TITLE

DIFFERENTIAL RESPONSES OF SORGHUM [SORGHUM BICQLOR (L.) MQENCH1

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GENOTYPES TO IRON NUTRITION

BY

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APPROVED **DATE**

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SCREENING SORGHUM [SORGHUM BICOLOR (L.) MOENCHl GENOTYPES FOR DIFFERENTIAL RESPONSES TO IRON NUTRITION

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University of Nebraska, 1980

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Experiments were conducted with sorghum [Sorghum bicolor (L.) Moench] to a) determine optimum conditions to screen for differential responses of genotypes to Fe deficiency in nutrient solutions, b) compare responses of nutrient solution-grown plants to soil-grown plants, and c) determine some of the physiological and chemical properties of genotypes considered to be both tolerant and susceptible to Fe deficiencies. Plants were grown in nutrient solutions and soils under growth chamber and greenhouse conditions. Iron deficiencies were imposed on the plants by 1) adding varied amounts of Fe, 2) adding higher than normal Levels of P, 3) adding high levels of $CaCO_3$, A) using different sources of N, and 5) using low Fe soils. Parameters used to measure some aspects of differential responses of the genotypes to Fe and the physiological and chemical properties were the degree Fe deficiency symptoms in the upper leaves, dry-matter yields, dry-matter produced/unit Fe, Fe concentrations and contents, top/root dry-matter and Fe ratios distribution of Fe among upper and lower leaves, pH changes in nutrient solutions, 'reductant' (phenolic compounds) released by roots in nutrient solutions, leaf surface areas and plant heights, leaf chlorophyll concentrations, and concentrations of P, K, Ca, Mg, S, Mn, Cu, and Zn and their possible interaction with Fe in leaves and roots.

In nutrient solution screening, plants grown with higher than normal P and with NO_3 as the sole source of N became Fe deficient more rapidly and gave wider differential responses to Fe deficiency than other treatments used to induce Fe deficiency. Extensive differences and intensity of Fe deficiency symptoms appeared in plants treated at 7 and 10 days of age but not in 14-day-old plants. Of the 46 U.S. and 10 Nigerian genotypes screened for differential Fe deficiency, SC 118-15E, Martin, Redlan, CK 60, TAM 428, SC 369-3-1JB, SC 500-6-1, SC 134, TX 415, TX 07, SC 29, and KS 57 (U.S.), and C 74, FFB-L, and HP 3 (Nigerian) were more ^{f}Fe-inefficient or susceptible to Fe deficiency, and SC 33-9-8-E4, Norghum, KS 5, Plainsman, a North Platte line, TX 412, SD 106, and SC 149 (U.S.), and KANO L-l, and RZ 1 (Nigerian) were more 'Fe-efficient' or tolerant to Fe deficiency. Most likely because of higher Mn and Cu in soils, genotypes grown on low Fe soils did not generally rank the same in Fe deficiency symptoms as they did when grown in nutrient solutions.

Selected genotypes which showed relatively wide differential Fe deficiency responses were used to study additional physiological and chemical, properties associated with Fe deficiency. The genotypes differed in the degree of Fe deficiency symptoms, dry-matter yields, Fe concentrations and contents, dry-matter produced/unit Fe, distribution of Fe, chlorophyll concentrations, leaf areas, plant heights, other element (especially Mn and Cu) concentrations, and 'reductant' released. Differences in nutrient solution pH did not distinguish differences in genotype response to Fe. SC 33-9-8-E4 ('Fe-efficient') had lower Mn and Mn/Fe ratios than SC 118-15E ('Fe-inefficient'). Iron concentration in Fe deficient tissue was not necessarily lower than in green tissue.

DIFFERENTIAL RESPONSES OF SORGHUM [*SORGHUM BICOLOR* (L.) MOENCH] GENOTYPES TO IRON NUTRITION

by

Yunusa Yusuf

A DISSERTATION

Presented to the Faculty of

The Graduate College in the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Doctor of Philosophy

Major: Agronomy

Under the Supervision of Professor Ralph B. Clark

Lincoln, Nebraska

November, 1980

ACKNOWLEDGMENTS

I wish to express my grateful appreciation and sincere thanks to my major Professor, Dr. R. B. Clark, for his guidance and helpful ideas in planning this study and writing this manuscript.

Special thanks are also expressed to Dr. M. Clegg and Dr. D. H. Sander for serving as the reading committee and providing some useful suggestions. Appreciation is also extended to Dr. W. M. Ross and Dr. E. Kinbacher for serving on the supervisory committee.

The author also wishes to express his profound appreciation and gratitude to the Kaduna State Government for giving him the opportunity to attain higher academic competence by granting him a scholarship and to his employers, Ahmadu Bello, University Zaria-Nigeria, for granting him a study fellowship. A note of thanks also to the University of Nebraska-Lincoln for the use of their facilities.

I also wish to thank all friends and colleagues who have helped in one way or the other and Ms. Grace Sobotka for the excellent job in typing this dissertation.

I am highly indebted to my wife, Zahra, and daughter, Jamila, for their love, patience, understanding, and moral support during the period of graduate study.

These acknowledgments would be incomplete without a mention of my late grandfather who had been the driving force behind me. To you, M. Bala Alhassan, I dedicate this dissertation.

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INTRODUCTION

The supply, absorption, movement, and use of chemical compounds needed for growth and metabolism may be defined as nutrition, and the chemical compounds required by an organism are termed nutrients. Iron is one of 19 nutrient elements essential for the growth and development of higher plants. The essentiality of Fe for higher plants was established about 140 years ago when Gris (1844) noted that low Fe caused a chlorosis in the leaves of vine and that specific cell inclusions now known as chloroplasts became abnormal in color and shape.

In the plant, Fe is a constituent of cytochrome a, b, and their function in the electron transport chain reactions of metabolism is vital. Iron is also a constituent of non-haem proteins such as ferredoxin which participates in the electron transport processes of photosynthesis, nitrite reduction, sulfate reduction, and N_2 assimilation. Besides photosynthetic processes, non-haem iron proteins are also associated with N_2 fixing and anaerobic bacteria reactions and in the hydrogenase systems.

Iron has also been found to be involved in the oxidation step from coproporphyrinogen to photoporphyrinogen in chlorophyll synthesis (Brown et al., 1980). Iron has been given a possible involvement in protein metabolism. Iron is also involved in nucleic acid metabolism, cell division, and chromosome structure. Recent evidence suggests that high amounts of Fe are located in leaf chloroplasts and plastids as phytoferritin (Seckbach, 1968, 1972).

From the above information on the importance of iron in plants, this nutrient element plays a significant role in the growth and metabolic processes of plants.

Sorghum [Sorghum bicolor (L.) Moench] is one of the most important cereals grown for food in many developing countries (especially in Africa, where it originated) and is also the third most widely grown cereal in the United States. Sorghum is grown to some extent in nearly all countries of the world, except those in the cool northwestern part of Europe. According to a 1975 Crop Census, the countries producing the most sorghum were the United States, India, Nigeria, Argentina, Mexico, and Sudan. In the U.S., the leading states in grain sorghum production are Texas, Kansas, Nebraska, Missouri, and Oklahoma (Agric. Stat., 1977).

Sorghum is well known for its susceptibility to Fe deficiency compared to other plant species (Brown and Jones, 1973, 1976, 1977). The soils where large amounts of sorghum are grown are often calcareous and high in pH, and the sorghum usually develops some degree of Fe chlorosis which limits productivity. These soils contain high amounts of Fe, but the Fe is not available for plant use. This is because the Fe in calcareous or alkaline soils is usually in the inactive ferric (Fe^{3+}) form. This form of Fe must be converted to the ferrous (Fe^{2+}) form before it becomes available for plant use (Chaney et al., 1972).

Since sorghum is the third most widely grown cereal in the U.S. and the fourth most widely grown cereal in the world, the need to identify sorghum genotypes that have greater ability to cope with Fe deficiencies becomes a matter of urgency.

With this urgency in mind, a series of experiments were conducted in nutrient solutions and in soils to provide information on this subject. The research was conducted with the following objectives in mind:

1. To develop a rapid and relatively simple method for growing large numbers of plants in nutrient solutions to determine Fe efficiency;
2. To screen sorghum genotypes for Fe efficiency using this method;
3. To correlate genotype responses to Fe in nutrient solutions to those in soil; and
4. To determine the effect of varied levels of Fe on certain physiological and chemical properties of 'Fe-efficient' and 'Fe-inefficient' sorghum genotypes.

LITERATURE REVIEW

Chlorosis is a general term which denotes leaf yellowing and a lack of chlorophyll in leaves. This condition is related to a large number of abnormalities or maladies. Iron chlorosis refers to the leaf yellowing that can be overcome by providing sufficient iron to plants. As such, these plants are said to be iron deficient.

Iron deficient plants can be found on both acid and alkaline soils in some plant species. Iron deficiency is more prevalent in plants grown on calcareous and alkaline soils where Fe is easily converted and maintained in unavailable forms (ferric compounds).

Many factors affect Fe availability or balance. Such factors as bicarbonate concentration, pH, macro- and micro-nutrient imbalances, level of soil organic matter, oxygen tension, and extreme moisture regimes have been associated with the severity of Fe deficiencies. Plants also have different capacities to make Fe available from the soil.

Genotypes of the same plant species when grown under Fe stress conditions differ in their susceptibility to Fe chlorosis. In some Fe uptake studies with PI-54619-5-1 soybeans (Glycine max L. Merr.), Thatcher Spring wheat (Triticum aestivum L.), Minnesota No. 800 hybrid corn [Zea mays (L.)], and Hawkeye soybean, only PI-54619-5-1 soybean failed to adsorb sufficient Fe from the calcareous Millville (pH 7.8, coarse silty, Typic Usfrochrept) soil to maintain growth. This led Brown et al. (1959) to conclude that the availability to plants of any Fe supply in the growth medium is dependent upon both the plant species and the growth medium.

Availability of Fe is directly dependent upon the solubility of the Fe compound applied, and this is dependent on soil pH. Lindsay (1974) estimated that in order for mass flow to transport sufficient Fe to the roots, the total solubility of Fe would have to be at least 10^{-6} M. This soluble inorganic Fe level is only achieved at pH 3. By raising the pH to just over 4, only 1% of the Fe demand would be met. At normal soil pH values (pH 5 to 7), Fe levels would be far below those required by plants. This would also be the case if the amount of diffused Fe is considered. It appears, therefore, that for plants growing in soil, the formation of soluble organic complexes (mainly chelates) will be important in the Fe supply. These compounds may originate from root exudates, soil organic matter, metabolic products of microorganisms, or as Fe chelate fertilizers added to the soil. Soluble Fe organic complexes are known to occur in soils. For example, Webley and Duff (1965) showed that α-ketogluconic acid excreted from the rhizosphere solubilized Fe which could then be taken up by plants. The significance of root exudates in the availability of Fe had been demonstrated by Raju and Marschner (1972). These workers observed a release of riboflavin from the roots of sunflower plants growing in culture solution under Fe deficiency. Conditions followed by the precipitation of Fe^{3+}-phosphate in the solution. The release of riboflavin was accompanied by a decrease in solution pH. The decrease in pH and the reducing effect of riboflavin mobilized precipitated Fe by reducing it to Fe^{2+}. Thus, Fe availability was improved and the plants became green again.

As mentioned earlier, crop cultivars differ considerably in their susceptibility to Fe deficiency. For example, in soybeans, the cultivar

Hawkeye (HA) is 'Fe-efficient' (i.e., capable of inducing some biochemical reactions to make Fe more available under Fe stress conditions), and PI-54619-5-1 (PI) is 'Fe-inefficient' (not capable of inducing biochemical reactions to make Fe more available under Fe stress conditions). Similarly, 'Fe efficient' and 'Fe-inefficient' cultivars of corn (Brown, 1967; Clark and Brown, 1974), tomatoes (Lycopersicum esculentum) (Brown et al., 1974), grapes (Vitis vinifera) (Sarlio, 1969), oat [Avena sativa (L.)] (Brown, 1979; MacDaniel and Dunphy, 1978), peanut (Arachis hypogea) (Hartzook et al., 1974), sorghum [Sorghum bicolor (L.) Moench] (Mikesell et al., 1973), pineapple [Ananas comosus (L.) Merr.] (Sideris and Young, 1956), and many other horticultural plants (Wallace and Lunt, 1960) have been identified. A tree species Eucalyptus vinimalis was also reported to be 'Fe-inefficient' (Ladiges, 1977). By reciprocal grafting between efficient and inefficient cultivars of soybeans, Brown (1961) showed that rootstocks were responsible for differences in Fe efficiency. It has also been established that 'Fe-efficient' plants can respond or adapt to Fe deficiency by increasing the efficiency of Fe utilization. This is achieved by enhancing the solubility and the rate of reduction of Fe^{3+} to Fe^{2+} by compounds ('reductants') such as riboflavin or phenols in the nutrient medium and by increasing citrate in the roots.

Iron efficiency factors have been reported to be genetically controlled. In soybeans, Weiss (1943) reported that differences in iron utilization of certain new introductions of soybeans were conditioned by a single dominant gene. Thus, the inefficiency factor was governed by a recessive gene. Performance of F_1 plants from crosses between efficient and inefficient cultivars indicated complete dominance of the Fe (efficient) allele over the Fe (inefficient) allele. However, in corn, Gorsline et al. (1963) observed additive gene actions for ear, leaf, and

grain concentrations for not only Fe, but also for P, K, Mg, Ca, Zn, Mn, and Al. These same workers also reported that the concentrations of Ca, Sr, Mg, and K were heritable.

Plant species also differ in the concentration of Fe required in the growth medium for growth processes and chlorophyll synthesis. In a study to determine Fe requirements of some plant species, Christ (1974) grew four monocotyledonous plant species (oat, wheat, rice, and corn) and three dicotyledonous species (tomato, cucumber, and soybean) in nutrient solutions. He found that the monocotyledonous plants required a substantially higher Fe concentration in the growth medium to attain maximum growth than did the dicotyledonous plants. Analyses showed that the monocotyledonous species were less efficient in Fe uptake. When the results obtained by using chelated forms of Fe were compared with results using inorganic forms of Fe, he showed that the inefficient species were equally inefficient in utilizing Fe^{3+}. However, when Fe^{2+} was used, the differences between the 'Fe-efficient' and the 'Fe-inefficient' plants disappeared. This confirmed the results of Ambler et al. (1971), Brown (1972), and Brown et al. (1961), who postulated that Fe^{3+} is reduced to Fe^{2+} before uptake of chelated Fe occurs in plant roots. Christ (1974) also reported that the efficiency of Fe uptake depended on the efficiency of the root system of a particular plant species to reduce Fe^{3+} to Fe^{2+}. The removal of Fe from the chelate complex after reduction seemed to present no difficulties in various plant species. Melsted et al. (1969) reported critical concentrations of Fe to be 25.0, 30.0, 25.0, and 30.0 mg/g in corn, soybeans, wheat, and alfalfa, respectively.

Even though Fe may be supplied to plant roots as Fe^{2+}, Fe^{3+}, or as Fe-chelates, absorption appears to be dependent on the ability of the roots to reduce Fe^{3+} to Fe^{2+} (Brown et al., 1961; Ambler et al., 1970; Ayed, 1970). According to Chaney et al. (1972), the reduction of Fe^{3+} to Fe^{2+} is essential (obligatory) before Fe can be absorbed, and they suggested that Fe^{3+} reduction at the outer plasmalemma is mediated by a source of electrons within the cell via cytochrome or flavin compounds.

Brown and Ambler (1974) and Ambler et al. (1970) reported that Fe reduction sites in tomato and soybean were predominantly in young lateral roots and between the region of root elongation and maturation in the primary root. The Fe moved through the protoxylem into the metaxylem of primary roots and then to the top of the plant as Fe-citrate (Brown and Ambler, 1974). Tiffin (1972) also observed that the major form of Fe translocated in soybean was Fe^{3+}-citrate. Rate of Fe uptake seems to be restricted to a narrow zone in the roots of barley (about 1-4 cm from the root tip).

Oliver and Barber (1966) reported that Fe diffusion in soils was the most important mechanism in which soybean roots were supplied Fe. When Fe-chelates were supplied to plant roots at the normally low Fe levels required by plants, a separation between Fe and chelate occurs prior to Fe absorption (Tiffin and Brown, 1961). However, at high levels of Fe-chelate, Jeffreys and Wallace (1968) were able to detect appreciable amounts of Fe-chelate in plant leaves. Evidence is sufficient to support the concept of active Fe uptake (Moore, 1972). Tiffin (1966) noted Fe concentrations in sunflower and soybean stem exudates to be 30 times greater than those in ambient solutions.

The uptake of Fe is influenced markedly by other cations. Thus, Fe nutrition of plants is most frequently disturbed in plants growing on calcareous soils. Chlorotic plants growing under these conditions are often referred to as having lime-induced chlorosis. The chlorosis may also be aggravated by high HCO_3^- levels in the soil solution. It may be possible that HCO_3^- raises the pH of the plant tissues and decreases the reduction of Fe^{3+} to Fe^{2+}. Calcium may also compete with Fe^{2+} for the same binding sites to reduce the availability of Fe.

Plant species show differences in their susceptibility to Fe deficiency chlorosis on calcareous soils. Iron deficiency is most commonly observed in calcifuge species such as blueberry, cranberry, and azalea. Among the important commercial crops affected by Fe deficiency are citrus, deciduous fruit trees, soybean, sorghum, ornamental shrubs, and trees and vines. Iron deficiency chlorosis has also been found in many other commercially important crop plants.

Lahar and Zipon (1978) suggested that high Ca concentrations near the root surface constituted a chemical barrier for the movement of Fe-EDTA toward roots. Singh and Sinha (1977) reported that Fe^{3+} was rapidly displaced in a calcareous soil by Ca^{2+} and Mg^{2+}. According to Burstrom (1968), high quantities of Ca in the soil solution or in the plant have a negative effect on physiologically active Fe. Calcium has been reported to interfere with Fe absorption and translocation by grain sorghum in the presence of P in calcareous soils of Texas (Onken and Walker, 1966). In a low Fe soil, Salardini and Murphy (1975) reported that Fe applications lowered Ca, Mg, Zn, and Mn concentrations in the plant.

Another macronutrient element that seriously interferes with Fe nutrition in plants is P which is taken up as an anion. In blueberry, Holmes (1960) noted that soluble Fe in a nutrient solution as acid as pH 4 was severely decreased by an increase in the soluble P. This was because in the presence of excess P, Fe was precipitated as insoluble Fe^{3+}-phosphate. In bushbeans, Wallace et al. (1978) reported that high P decreased Fe transport to the leaves both at high and low pH values. Brown et al. (1977) and Brown and Jones (1975) showed that sorghum cultivars that were 'P-efficient' were also 'Fe-inefficient' when grown in soils. Phosphate competes with the plant for Fe. Phosphate has also been reported to accentuate Fe^{2+} oxidation to Fe^{3+} (Brown and Olsen, 1980). Using corn and pinto beans as test crops, Watanabe et al. (1965) found that by increasing the P level at an Fe concentration of 4×10^{-5} M, the yields increased initially and then decreased because of P-induced Fe deficiency. The deficiency was not associated with changes in Fe concentration but was related to higher P concentrations in the tissue. The Fe deficiencies appeared when P/Fe ratios were greater than 60. DeKock (1955) emphasized P/Fe ratios in plants as useful indices of the plant status for Fe. P/Fe ratios have also been used to define 'active' Fe (DeKock et al., 1979). Excess P also interferes with the mobility and functioning of Fe in plants (Ayed, 1970). Biddulph (1951) found that bean plants grown in a nutrient solution at pH 4.0 were green when KH_2PO_4 was added at 10^{-4} M. However, when the pH of the solutions was increased to 7.0 with the addition of KH_2PO_4 at 10^{-3} M, the plants became chlorotic and Fe was precipitated on the surface of and within the roots. In studies with cowpeas [Vigna unguiculata (L.) Walp.],

Kashirad et al. (1978) reported maximum growth and highest grain yields when plants were supplied 50-100 µg/g P with 20 µg/g Fe in soils. Brown et al. (1959) used a split-medium technique to demonstrate phosphate-induced deficiency in soybeans. Ajakaiye (1979) found that high P concentration in the growth medium inhibited Fe absorption and translocation in both millet (Pennisetum typhoides) and sorghum. Millet was more tolerant of P-induced Fe deficiency than sorghum. For soybeans grown at an acid pH and with P at 0.001 N, precipitation of Fe in roots occurred, while 0.005 N P only inhibited the uptake of chelated Fe. High pH, high phosphate, and good aeration favor the oxidation of Fe^{2+} to Fe^{3+} and precipitation of Fe^{3+} salts. The precipitation of Fe^{3+}-phosphates may not only take place in the nutrient medium but also in the conducting tissues of the plant (Rediske and Biddulph, 1953).

Iron uptake is depressed by NO_3^- nutrition, whereas it is enhanced by NH_4^+ nutrition (Sideris and Young, 1956). This can probably be explained by the differences in pH at the plant root surfaces exerted by the two forms of N. When nitrates are assimilated (reduced) by plants or microorganisms, one OH^- is produced for every NO_3^- reduced. A portion of the OH^- may be released into the root medium to increase the pH value (Kirkby and Mengel, 1967). For NH_4^+, the reverse occurs. The incorporation of NH_4^+ results in the release of H^+ to lower the pH of the medium around the roots. The increased H^+ increases the availability of Fe.

Some reports indicate that cations such as Na^+, K^+, Mg^{2+}, and Ca^{2+} stimulate Fe uptake. Oertli and Opoku (1974) reported a stimulatory effect of K^+, Na^+, Mg^{2+}, and Ca^{2+} on the uptake of Fe by 11-day old corn plants. Using FeEDDHA [Fe-ethylenediamine di(o-hydroxyphenaylacetate)]

as the source of Fe, the stimulation of Fe uptake followed the sequence of K>Na>Mg>Ca. Anions also stimulated Fe uptake in the following order SO_4^{-2}>Cl^->NO_3^-. The stimulation was greater as the pH decreased during the absorption period.

Iron deficiency chlorosis may also occur because of high levels of heavy metals in the soil. A well known example of this is the effect of manganese. High Mn/Fe ratios in the nutrient medium gave rise to Fe deficiency symptoms. The Mn effect did not appear to relate to uptake but to a disturbance in the Fe enzyme activities. The mechanism of this disturbance is not clear. It has been proposed that Mn may compete for binding sites on the enzymes which are normally occupied by Fe. In rice (Oryza sativa L.), Tanaka and Navasero (1966) reported that an Fe/Mn ratio of 15-25 is necessary for normal plant growth. Agarwala et al. (1964) grew barley (Hordeum vulgare L. var K 12) at three levels of Mn and six levels of Fe in nutrient solutions. They reported wide Fe/Mn ratios for apparently normal growth and maximum yields of plants. Yields depended upon the actual levels of iron and manganese than on Fe/Mn ratios. Yields of plants increased with increased Fe supplies. Manganese supplies determined the magnitude of the yield increase and the range of Fe supply in which yields increased. In Fe deficient Hawkeye soybeans, Lingle et al. (1963) showed that Mn effectively reduced Fe uptake and transport when its concentration in the nutrient solution exceeded 2×10^{-6} M or at concentrations approximately equimolar with Fe. At lower Mn concentrations, Mn stimulated Fe uptake. Somers and Shive (1942) indicated that Mn appeared to oxidize Fe^{2+} to the more insoluble Fe^{3+} form. Dokiya et al. (1968) suggested that physiologically active Fe is rendered inactive

by high Mn concentrations. In an aerobic culture experiment with rice plants, Van der Vorm et al. (1979) reported an inhibition of Fe translocation by excessive Mn uptake at a high pH. A combination of high P and Mn levels in nutrient solutions reduced the translocation of Fe in rice roots to the shoots.

Another micronutrient element that influences the nutrition of Fe in plants is Mo. Berry and Reisenauer (1967) found that Fe uptake was depressed at both low and high levels of Mo. They observed maximal Fe accumulation at marginally adequate levels of Mo. Molybdenum starvation also limited the translocation of Fe from the veinal to the interveinal leaf tissues. High Mo levels decreased the solubilization of Fe_2O_3 x H_2O by reduction with hydroquinone. Since reduction is an important phase of Fe absorption by plants, high Mo could account for the decreased absorption of Fe. In a study designed to determine the effects of different levels of Mo, Fe, and Mn on the growth and nutrition of tomato plants, Kirsch et al. (1960) reported a three-way Fe x Mn x Mo interaction. At the lower Fe levels, added Mo decreased yields while yields were increased by the addition of Mo at higher Fe rates. Added Fe counteracted the yield-depressing effect of added Mn, but the amount of added Fe required to attain maximum yield increased as the Mo supply increased.

Zinc and copper also interfere with Fe nutrition. In soybean plants, Zn interfered with the translocation of Fe from the roots to the above ground parts (Ambler et al., 1970). Zinc also suppressed the production of 'reductant' by soybean roots and interfered with the reduction of Fe^{3+} added to overcome the effects of Zn on Fe translocation.

Earlier workers suggested that the main cause of iron chlorosis in citrus of Florida was the accumulation of Cu in the soil applied over several decades in sprays and fertilizers. Copper interference with Fe uptake in soybeans became effective when the Cu concentrations were 10^{-7} M to 5 x 10^{-6} M in the growth medium. At lower concentrations, Cu stimulated Fe absorption. The effectiveness of Cu and Zn as well as Ni, Cr, Co, Mn, and Mo to induce Fe chlorosis in oats was in the order of Ni>Cu>Co>Cr>Zn>Mo>Mn (Hunter and Vergnano, 1953). In sugar beets [Beta vulgaris (L.)], Hewitt (1948) showed that Cd, Cu, and Co were highly effective and Ni, CrO_4, Zn, Cr, and Mn were less effective in restricting Fe uptake. In rice, Kokiya et al. (1968) reported that even though Fe depressed Cu uptake, Cu showed no inhibitory effect on Fe. The data indicated that Cu accelerated Fe uptake under the conditions of the experiment. Both Cu and Zn are also known to displace Fe in heavy metal chelate complexes. This may be important in limiting Fe uptake and utilization by reducing Fe chelate translocation to roots or by the effect of heavy metal on centers of physiological activity of Fe within the plant.

Many other factors can induce iron deficiency in plants. These include high or low soil moisture (Burtch et al., 1948), extremes in temperature (Burtch et al., 1948), high or low soil organic matter (Takkar, 1968), and oxygen tension in the soil (Wallihan et al., 1961). Burtch et al. (1948) conducted experiments with bean plants to study the effect of light, soil temperature, and soil moisture on lime-induced Fe deficiency. They reported that plants were most chlorotic under red light through the severest chlorosis occurred with the combination of

full sunlight and cold temperatures. Chlorosis also tended to increase at high and low soil temperatures with a minimum of chlorosis at 25C. They observed that the higher the soil moisture, the greater the degree of chlorosis. Their results also indicated that a high moisture level together with low soil temperatures were the conditions most conducive to the development of lime-induced chlorosis. The climatic factors to induce Fe deficiency ranked in the following order: high soil moisture > high soil temperature > high light intensity. These authors concluded that chlorosis was most severe under low temperature, high moisture, and short-day treatments. They were of the opinion that much of the lime-induced chlorosis in the irrigated region of western U.S. could be alleviated by the proper use of irrigation water. Brown et al. (1979) observed that only small amounts of Fe^{3+} were reduced to Fe^{2+} at wavelengths above 420 nm. In addition, more Fe^{3+} was reduced to Fe^{2+} in solution under cool white fluorescent (CWF) lamps than under low pressure sodium (LPS) lamps. CWF lamps produce light at lower wavelengths than the LPS lamps. Chlorophyll levels were higher in leaves grown under CWF than under LPS and generally greater in leaves grown at 28C than at 22C.

Takkar (1968) observed that the level of organic matter in the soil regulated the amount of Fe available in soils. This is because the Fe is usually associated with organic matter in the soil.

Iron deficiency chlorosis in plants is often associated with soil conditions that appear to restrict the exchange of gases with the atmosphere. These conditions exist in fine-textured soils and in those that lack aggregation or have a discontinuity of profile due to plowsoles,

hardpans, claypans, or stratified deposits. These conditions enhance CO_2 accumulation in the soil. This is particularly the case in calcareous soils. Solution culture studies have indicated that $NaHCO_3$ can cause a marked reduction in Fe absorption with some plants. In a study to determine the effect of soil oxygen deficit on Fe nutrition, Wallihan et al. (1961) found that oxygen deficits resulted in significant reductions of plant growth, chlorophyll, and Fe concentrations in leaves and stems of citrus seedlings. A possible explanation for the oxygen deficit effect was that metabolic iron absorption was depressed at the low level of oxygen.

The availability of plant nutrients is closely related to soil pH. The activity of Fe, Mn, and Al increases as acidity increases. In general, the optimum pH for optimum growth of most plants is about 6.0 to 6.8. In this pH range, neither excess nor deficiency of available Fe usually occurs.

In a situation where plants do not get sufficient amounts of Fe, growth and productivity are greatly reduced. Twyman (1959) found that dry matter yields of tomato increased with increasing amounts of Fe. Agarwala et al. (1964) reported increased dry matter yields of barley with increasing levels of Fe. Pineapple plants grown in solution culture with ample Fe contained 2.15 times more chlorophyll and produced 2.0 more plant and fruit yields than when grown with low Fe (Sideris and Young, 1956). Under low Fe supply, isolated corn root mitochondria were reported to have a decreased oxygen uptake and reduced oxidative phosphorylation (Young and Wallace, 1971). In sunflower leaves, Jacobson and Oertli (1956) found good correlations between Fe supply and chlorophyll

concentrations. Similar results were obtained for cowpea (Marsh et al., 1963), corn, and radish (Agarwala et al., 1965).

Mikesell et al. (1973) reported greater shoot and root growth in sorghum with Fe^{2+}. Yields of cabbage grown in culture solution decreased in plants supplied with adequate Fe. Tobacco leaf discs receiving ample Fe in an incubation medium incorporated higher amounts of radioactive glycine into chlorophyll a and b at all stages of development than in leaf discs without Fe (Shetty and Miller, 1966). From comparisons of different Fe compounds in nutrient solution, nodulation and yields were highest when Trifolium pratense L. (Montgomery Red) was supplied with Fe as Fe^{3+}-EDTA (Van der Venter and Small, 1972).

In studying metabolic effects of mineral nutrients in plants, the development of a mineral deficiency is usually associated with changes in organic compounds. Iron also causes changes in organic acids. Clark et al. (1973) obtained a two-fold increase in malate and citrate contents and over a four-fold increase in aconitate content in the root saps of 'Fe-efficient' WF9 and 'Fe-inefficient' ys_1/ys_1 corn genotypes as the supply of Fe in the nutrient solution increased from 0.1 to 2.0 mg/l. An increase in citrate was noted in soybeans with increasing Fe (Brown and Tiffin, 1965). These authors reported that a decrease in Fe paralleled a decrease in citrate. A concomitant decrease of citrate in the stem exudates of soybeans and tomatoes with a decrease in Fe was also noted. Clark (1968) reported that total organic acids changed when Fe was limiting.

Other organic constituents affected by Fe supply are enzymes. Del Rio et al. (1978) reported increased catalase activity in pea plants

with increased Fe. They also observed low soluble protein contents in leaves of plants grown under low Fe. The activities of catalase, peroxidase, and aldolase in corn and radish were depressed under Fe deficient conditions (Agarwala et al., 1965). In addition, phosphorylase activity was depressed in radish grown under Fe deficiency conditions. Acid phosphatase and ribonuclease in both corn and radish, as well as transaminase in radish, were stimulated by iron deficiency. Barley supplied with various rates of Fe and Mn had decreased catalase activity under Fe deficient conditions irrespective of the Mn supply (Agarwala et al., 1964). These authors noted that at deficiency levels of Fe, peroxidase was depressed at normal and low Mn supply and generally increased at the high Mn. Increased Fe increased both catalase and peroxidase activities in grasses (O'Sullivan, 1969). Ulmer et al. (1971) reported a positive correlation between Fe supply and peroxidase activity in corn. Total peroxidase activity in soybean roots was reported to increase both at sufficient and extremely low concentrations of Fe (Elmstrom, 1969). Other enzymes whose activities have been reported to decrease under low Fe include photosynthetic pyridine nucleotide reductase in leaves of cowpea (Marsh et al., 1963) and nitrate reductase in tomato roots (Brown et al., 1974). Iron deficiency has also been reported to decrease proteins in corn (Perur et al., 1961), pineapple (Sideris and Young, 1956), and tobacco (Shetty and Miller, 1966).

The U.S. has nearly 12 million acres of crops, most of which are row crops which suffer from various degrees of Fe chlorosis. These crops are primarily soybeans and sorghum grown in the Great Plains states. In addition, millions of crop acres are not planted to these

crops to avoid Fe deficiency. This means that a large acreage cannot be used for production of certain crops because of the potential of Fe chlorosis. In order to make these areas productive, some corrective methods need to be employed. Factors employed to correct Fe deficiency in plants include genetic variation in plants, Fe chelates, and lowering the pH of the growth medium. In many crop species, 'Fe-efficient' cultivars have been identified. Examples of these are Hawkeye soybean, KS5 sorghum, and T3805FER tomatoes. 'Iron-efficient' cultivars or genotypes are those which are able to respond to Fe deficiency by inducing certain biochemical reactions to occur, thereby making Fe more available. Such reactions include the production of 'reductants' such as riboflavin (Marschner et al., 1978) and phenols (Olsen and Brown, 1980) which can increase the solubility and availability of Fe in the growth medium.

In the treatment of Fe chlorosis, the addition of inorganic Fe salts to the soil is mostly ineffective for the correction of Fe deficiency because Fe is rapidly made insoluble as oxides. Even foliar treatment with ferrous salts such as $FeSO_4$ is not always satisfactory. However, such salts have been used to correct Fe chlorosis in plants grown on calcareous soils (Hodgson et al., 1972). Thomas and Mathers (1979) corrected Fe chlorosis in grain sorghum grown on a calcareous soils with the addition of $FeSO_4$ and manure. From the dry-matter yields obtained, manure effectively reduced Fe deficiency. They hypothesized that manure could be used to correct Fe deficiency of grain sorghum on calcareous soils. Mathers (1970) used $FeSO_4$ and sulfuric acid to correct Fe deficiency on grain sorghum growing on a rich, fine sandy loam. The successful results of inorganic Fe applications to correct Fe deficiency

showed that large amounts of Fe salts would be required. Application of $FeSO_4$ at rates of 112 and 560 kg Fe/ha increased grain yields significantly. Banded application of $FeSO_4$, $Fe_2(SO_4)_3$ and FeEDTA (ethylenediaminetetraacetate) had no effect on grain sorghum yields in western Kansas (Murphy et al., 1970). The results also indicated that soil applications of Fe could be effective for varying periods of time depending upon soil composition and conditions of plant growth. However, the high rates of Fe involved make such practices expensive and applicable only to high economic value crops.

Schneider et al. (1968) pointed out that Fe deficiency must be corrected in the early stages of plant growth if maximum yield responses are to be obtained. They suggested soil applications of Fe be in combination with NH_4^+ fertilizers to increase the efficiency of Fe uptake.

Iron chelates are effective and more useful for correcting Fe deficiency when the crop plants are of sufficient value to warrant their use. Fruit, ornamental, and flower crops are examples where Fe chelates can be used economically, but the use of chelates on sorghum, corn, and rice is not generally economical (Wallace et al., 1966). Iron chelates can be used either as fertilizers or as foliar sprays. In soil applications it is important to consider the stability of the chelate relative to the soil pH. At higher soil pH levels, soil Ca^{2+} present in higher concentrations can displace Fe^{3+} from less stable chelates. Ca-chelates and Fe are precipitated as Fe oxide. Thus, Fe is rendered unavailable. Lindsay et al. (1967) showed that FeEDDHA was stable throughout a pH range of 4 to 10. This chelate also gave the highest sorghum yields. On the other hand, the stability of FeDTPA (Fe-diethyltriaminepentaacetate)

and FeEDTA falls above pH 7 and below 6, respectively, so that correspondingly lower sorghum yields were obtained with these chelates. Applications of about 10 to 20 g Fe/tree of Fe-chelate have proved satisfactory in citrus. Foliar applications of an Fe-polyflavonoid material were effective in overcoming chlorosis in grain sorghum in Arizona, but it was cautioned that under severe chlorotic conditions even foliar applications of Fe may be ineffective. Krantz and Brown (1967) concluded from their work in California that Fe treatment of grain sorghum and related crops can be best accomplished by applying a $FeSO_4$ solution as a foliar spray. Of five Fe chelates (EDTA, HEDTA (hydroxyethylethylene diaminetriacetate), CDTA, DTPA, and EDDHA) used to correct Fe deficiency, Brown and Holmes (1955) reported that only DTPA and EDDHA were effective in alleviating the deficiency in soybeans grown on 17 calcareous soils common to the western U.S. Stewart and Leonard (1957) found good responses to soil applications of FeEDTA by citrus trees in Florida.

Considering the various recommendations of Fe application, foliar applications seem to be more acceptable and efficient for treating Fe deficiencies than do soil applications. Wallace and North (1966) suggested the feasibility of applying FeEDDHA chelate in irrigation water for orange trees. The development of sprinkler irrigation raised the possibility of applying Fe through irrigation systems. The major problem with applying chelates, regardless of the method, is their cost.

Sulfur has been useful to prevent Fe deficiency. Upon oxidation of S, the H_2SO_4 formed can neutralize $CaCO_3$ and decrease soil pH to make Fe more available to plants. Elemental S application at the rate of 250 kg/ha increased cowpea yields significantly on a calcareous soil in

India (Bansal et al., 1975). Two disadvantages of using S are that the bacterial oxidation of S is too slow to correct Fe deficiencies experienced by seedlings if the S is applied with the seed and that high amounts of S are needed to sufficiently neutralize soils to correct or prevent Fe deficiency.

Sulfuric acid has the same net effect as elemental S except that its effect is immediate. Wallace and Mueller (1978) placed concentrated sulfuric acid at 3 cm depth at various rates to prevent Fe chlorosis in soybeans grown on a calcareous soil. They reported that small acidified spots of soil (equivalent to as little as 0.4% of $CaCO_3$) was sufficient to prevent Fe deficiency. By lowering the soil pH by the addition of HCl, the mobile ion in some Egyptian soils was reported to increase (Ibrahim et al., 1979). Olsen and Watanabe (1979) reported an increased uptake of Fe by sorghum grown on alkaline soils to which $CaSO_4$ was added. They observed that the increased Fe uptake was due to a decrease in Mo levels by the added $CaSO_4$. Mitchell and Anderson (1966) observed that the addition of trace amounts (0.2 ppm) of gibberellic acid (GA) to culture solutions increased the efficiency of Fe utilization by soybean plants grown at suboptimal Fe levels. These authors contended that GA affected the internal metabolism of the Fe and improved its activity. This was indicated by increased chlorophyll concentrations.

The application of other fertilizers indirectly influences Fe supplies to plants. Acid fertilizers, particularly NH_4^+ fertilizers, can depress deficiency symptoms. This may because of the lower pH around the root (Lucas et al., 1972). Machold (1968) showed evidence that NH_4^+ nutrition increased the levels of Fe^{2+} in plants. Applications of

organic fertilizers have also been reported to alleviate lime-induced chlorosis, possibly by the production of soluble Fe complexing compounds in the soil.

Inasmuch as many crop species are susceptible to Fe deficiency, and plants show Fe deficiencies on both alkaline and acid soils, plus the high cost of corrective measures for Fe deficiencies, more effective methods for overcoming the problems need to be found. One of the most promising methods would be to identify crop species that are efficient in the utilization of Fe. Plant breeders have shown that efficiency factors for certain nutrient elements are genetically controlled and can be transferred from less desirable and unproductive crop cultivars to those that are desirable and productive. Screening and identifying crop cultivars efficient in Fe utilization need to be accomplished, and this was an objective of the studies reported in this dissertation.

MATERIALS AND METHODS

A. Screening Genotypes for Fe Efficiency in Nutrient Solutions

Plants were grown in nutrient solutions using a method similar to that of Sullivan and Ross (1978). This consisted of growing a large number of seedlings (from 100 to 125) in the same nutrient solution of limited volume. Plants were suspended above nutrient solutions on 0.6 cm thick plastic plates. These plates were 27 cm wide x 32 cm long, rounded at the corners, and had 0.3 cm holes drilled in seven rows to allow seedling roots to suspend in solution (Fig. 1). The top of each hole was counter sunk with a rosette so that seedlings would remain in place. At each corner of the plate, a plastic coated wire was attached so that plates could be lowered or raised in the nutrient solution container to adjust for volume changes in various experiments. The containers for the nutrient solution were commercial dishpans (Fig. 1). In some experiments, fewer numbers of plants were grown on the plates than in others.

Seeds were germinated between moist paper towels and seedlings transferred at 4 days of age to 0.3-strength nutrient solution (without added Fe). Nine seedlings from each of 14 genotypes were suspended on the same plastic plate and bathed in 7.0 liters of nutrient solution. At 7 days of age, seedlings were thinned to five plants/genotype and plates were transferred to full-strength nutrient solutions containing limited Fe. The composition of full-strength nutrient solution was (mg/l): 135 Ca, 55 K, 147 NO_3^-, 17 NH_4^+, 26 Mg, 12 Cl, 11 S, 2.6 P, 0.47 Mn, 0.26 B, 0.15 Zn, 0.11 Mo, 0.04 Cu, and 0.13 Fe as FeHEDTA (ferric

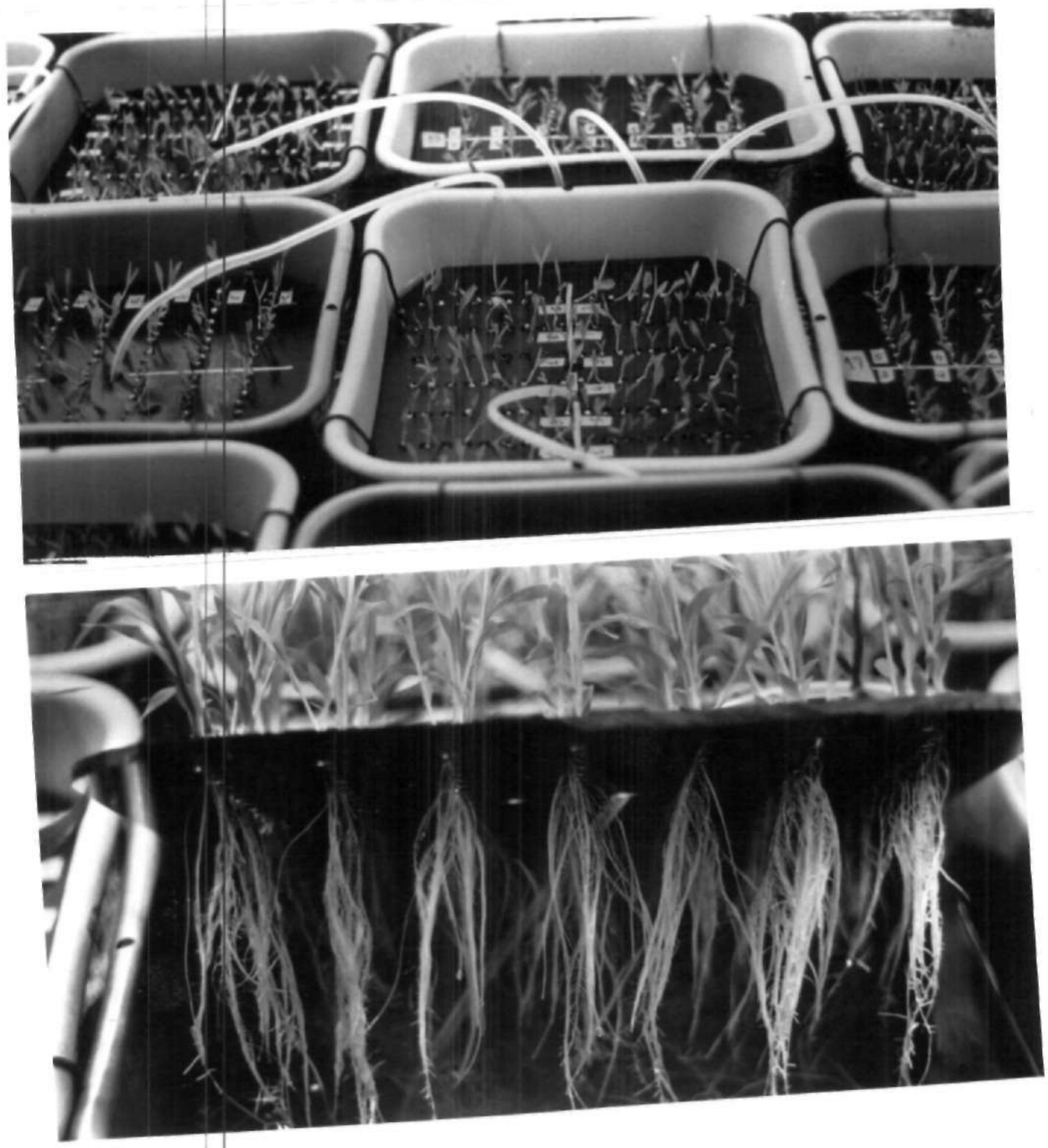


Fig. 1. Containers for growing sorghum genotypes in nutrient solutions. Top: Three day old seedlings. Bottom: Twenty-four day old seedlings showing roots and leaves.

hydroxyethylenediaminetriacetate). The initial pH of nutrient solutions was not adjusted but monitored three times weekly. Plants were grown in these solutions for 10 days before treatments were added to induce Fe deficiency.

When the treatments were added, plant roots were rinsed with distilled water and then placed into new pans with the appropriate nutrient solution. Experimental designs were complete randomized split-plots with two replications. Plants were grown in a growth chamber with 17 hours light (350 microeinsteins $m^{-2}sec^{-1}$) at 29C $\pm$ 1 and 7 hours darkness at 24C $\pm$ 1.

Visual Fe deficiency symptoms were noted daily after treatments were administered. Plants were rated for the degree of Fe deficiency on a scale of 0 to 4 where 0 = no Fe deficiency and 4 = severe Fe deficiency. Plants were grown for 7 days in the treatment solutions before experiments were terminated.

When the experiments were terminated, plant roots were rinsed thoroughly with distilled water and plants separated into roots, lower leaves, and upper leaves. The plant material was dried a minimum of 4 days at 70C in a forced-air oven, weighed, and ground in a stainless steel Wiley mill to pass a 0.5 mm (40-mesh) screen. Samples of the ground material were analyzed for Mg, P, S, K, Ca, Mn, Fe, Cu, and Zn by energy dispersive x-ray fluorescence (EDXRF) (Knudsen et al., 1981). This consisted of preparing a 1.3 cm diameter pellet from 100 mg of the ground material. Pellets were made in dyes held under 40,000 psi pressure for 1 minute. Pellets were then analyzed directly by EDXRF.

Treatments used to induce Fe deficiency were P added at 0.17 mM/l and 0.39 mM/l, $CaCO_3$ added at 0.15 mM, and NO_3^-, NH_4^+, and (NO_3^- + NH_4^+) as sources of N at 1.4 mM N/plant. When (NO_3^- + NH_4^+) was used, the ratio of NO_3^- to NH_4^+ was 8:1.

Genotypes screened for 'Fe-efficiency' with added P and $CaCO_3$ were CK 60, Redlan, SC 33-9-8-E4, SC 109-9, SC 118-15E, SC 134, SC 500-6-1, TAM 428, Wheatland, Redbine 60, KS 5, Martin, and a North Platte line (hereafter called NP). In addition to these U.S. genotypes, 10 Nigerian genotypes were also screened for 'Fe-efficiency.' The Nigerian materials were SK 5912, KANO L1, HP 3, C 7.4, YG 95760, FFB-L, L 1449, L 181, L 187, and RZ 1. When different sources of N were used, the U.S. genotypes listed above plus Plainsman, KS 56, KS 57, TX 414, TX 412, TX 07, TX 415, TX 7078, Norghum, Caprock, SD 102, SD 106, NB 3494, SC 29, SC 149, and SC 369-3-1JB were screened. The Nigerian genotypes were not screened in the various N solutions because of insufficient seed.

B. Relationship of Nutrient Solution and Soil Screening Methods

Many of the genotypes screened for 'Fe-efficiency' in nutrient solutions were also screened in low Fe soils to determine if their responses in nutrient solutions were similar to those in soil. The genotypes screened in soils were SC 118-15E, SC 134, SC 500-6-1, Wheatland, TAM 428, Redbine 60, Redlan, Plainsman, SC 109-9, CK 60, KS 5, Martin, NP, SC 33-9-8-E4, SC 369-3-1JB, TX 7078, TX 414, SD 106, KS 56, Norghum, TX 412, and TX 07. The genotypes SC 118-15E and SC 33-9-8-E4 were used as standards in the first experiment, and these two genotypes plus SC 500-6-1 and TAM 428 were used as standards in the second experiment. Two of the soils used were low in Fe and other was sufficient in Fe.

Bridget (pH 8.1, mesic Torriortheatic Haplustoll) from near North Platte, Nebraska, and Bridgeport (pH 8.1, mesic Fluevatic Haplustoll) from near Garden City, Kansas, were the soils low in Fe and Sharpsburg (pH 6.8, mesic Typic Argiudoll) was the soil sufficient in Fe. Some of the chemical properties and element analyses of these soils are given in Table 1.

The soils (ground to pass a 0.5 cm screen) were added to 15 cm diameter containers at 1.8 kg soil/pot. Each pot received fertilizer separately at rates of 100 N, 100 P, and 100 K kg/ha as NH_4NO_3, KH_2PO_4, and K_2SO_4. Micronutrients were added at rates of (kg/ha) 1.08 Mn, 0.38 B, 0.21 Zn, 0.05 Cu, and 0.05 Mo. The elements were added to the soils as liquids. The soils were allowed to dry, mixed thoroughly to ensure uniform distribution of the elements and put into the plastic containers. Completely randomized factorial experiments with four replications were conducted. Replications served as blocks. In the first experiment, each replication consisted of 42 pots (14 genotypes x 3 soils) representing all treatment combinations possible on a separate table. Plants were grown in the greenhouse during the months of March and April at a daytime temperature of 30C $\pm$ 1 and at a night temperature of 25C $\pm$ 1. Supplemental light was provided during the morning and evening to give 17 hours of light during the 24-hour period. In a second experiment, each replication consisted of 36 pots (12 genotypes x 3 soils). No supplemental light was necessary in the second experiment, since day lengths were sufficiently long to provide at least 17 hours of daylight (month of May).

A plastic bag encased each pot to catch excess water and leached nutrients. At planting, the soil in each pot was wetted completely with

Table 1. Analyses and description of soils used to grow sorghum genotypes for 'Fe-efficiency' screening.

Parameter	Units	Soil†		
		Bridget	Bridgeport	Sharpsburg
pH		8.1	8.1	6.8
O.M.	%	1.24	1.71	3.0
CEC	meq/100 g	11.9	12.4	22.5
Conductivity	mmhos	0.31	0.18	0.09
NO_3	µg/g	13.0	46.0	34.0
P	µg/g	3.7	3.0	14.0
K	meq/100 g	2.71	2.07	0.80
Ca	µg/g	11.8	11.6	8.8
Mg	µg/g	4.98	0.88	4.03
S	µg/g	21.5	5.8	7.6
Mn	µg/g	7.2	7.7	33.6
Zn	µg/g	0.80	0.40	1.32
Cu	µg/g	0.31	0.32	1.19
Fe	µg/g	1.3	1.2	61.5

† Bridget is a coarse silty mixed mesic Torriortheatic Haplustoll from near North Platte, NE.
Bridgeport is a fine silty mesic Fluevatic Haplustoll from near Garden City, KS.
Sharpsburg is a fine Montmorillonitic mesic Typic Argiudoll from near Lincoln, NE.

distilled water. The untreated seeds of a particular genotype were placed on top of the wet soil and 0.2 kg of soil removed earlier was poured over the seeds. The pots were covered with plastic bags to prevent water loss during germination.

Upon seedling emergence the plastic bags were removed. After 5 to 6 days, plants were thinned to four plants/pot and distilled water was added as needed. When Fe deficiency symptoms began to appear on the leaves (11 days), plants in each pot were rated daily for degree of Fe deficiency on a scale of 0 to 4; 0 = no Fe deficiency and 4 = severe Fe deficiency.

Termination of the first experiment was when plants were 23 days old and the second when plants were 25 days old. Plants were severed 1 cm above the soil and separated into lower and upper leaves. Plant parts were dried a minimum of 4 days at 70C in an air-forced oven and weighed.

C. Physiological Properties of 'Fe-efficient' and 'Fe-inefficient' Genotypes

Three experiments were conducted (two in nutrient solutions and one in soils) to determine physiological properties of various 'Fe-efficient' and 'Fe-inefficient' *sorghum* genotypes.

For experiments using nutrient solutions, seeds were soaked overnight in distilled water and then placed on a cheesecloth suspended over a shallow (3m deep) rectangular plastic container. The containers had distilled water and were covered with aluminum foil to prevent evaporation. After 2 days the aluminum foil was removed and seedlings allowed to grow 5 more days before six seedlings of each genotype were transferred to 0.3-strength nutrient solution in 3.5 liter plastic containers. Plants

were grown in this nutrient solution before adding the treatments. When treatments were administered, plants were thinned to four plants/pot. The roots were rinsed with distilled water and the plants transferred to full-strength nutrient solution. The composition of the nutrient solution was the same as described under A above. The experiments were conducted with treatments of varied Fe (FeHEDTA) at 0, 5, 11, 16, 22, and 27 μM Fe to pots containing 12-day-old plants in experiment 1 and 18, 36, and 54 μM Fe to pots containing 8-day-old plants in experiment 2. Plants were rated daily for visual symptoms of Fe deficiency rating on a scale of 0 to 4 as described earlier. The pH of the nutrient solutions was monitored daily. Every other day roots of plants grown in the same solution were separated from each other.

The genotypes used were: SC 33-9-8-E4, NP, and KS 5 ('Fe-efficient') and SC 118-15E, Martin, and Redlan ('Fe-inefficient') in experiment 1, SC 33-9-8-E4, NP, SC 118-15E, and Martin in experiment 2. The experimental design for the first experiment was a completely randomized 6 x 6 factorial with two replications. The design for the second experiment was a completely randomized 4 x 3 factorial with three replications.

Additional parameters measured on the plants before termination of the experiments were plant heights and 'reductant' in solution in experiment 2. Plants were harvested at 25 days of age in experiment 1 and at 26 days of age in experiment 2.

At harvest, plants were separated into roots, lower leaves, and upper leaves. Roots were thoroughly rinsed with distilled water, blotted dry, and all plant materials dried in a forced-air oven a minimum of 4

days at 70C, weighed, and ground in a stainless steel Wiley mill to pass a 0.5-cm (40-mesh) screen. Samples too small to be ground in a Wiley mill (less than 250 mg) were pulverized using a fast reciprocal vibrating shaker. This consisted of adding a small piece of teflon with the plant material in a 5-dram plastic vial, attaching this to the shaker, and letting the teflon piece pulverize the material during a 10 minute shaking. The pulverized plant material passed a 0.5 screen. All plant samples were made into 1.3-cm (100 mg) pellets for EDXRF analysis.

The amount of 'reductant' released into the nutrient solution was measured by the TPTZ (2,4,6-tripyridyl-s-triazine (specific for chelating Fe^{2+}) method (Collins et al., 1959). Aliquots of the nutrient solution from each container were taken every other day for analysis of 'reductant.' To each 20-ml aliquot of nutrient solution, the following reagents were added in the given order: 2.0 ml of 0.001 M TPTZ, 1.0 ml of 2 M sodium acetate at pH 4.4, and 2.0 ml of deionized water for a final volume of 25.0 ml. Iron standards of 10 and 20 µg Fe/g as $FeSO_4$ and blanks were used with each assay. The solutions were shaken, placed in the dark for 20-25 hours, and absorbance determined at 592 nm in a spectrophotometer.

The experiment (#3) using soil consisted of growing plants on low Fe and Fe-sufficient soils to determine certain physiological parameters of some genotypes. Selected genotypes from plants grown in the experiments described under B became experiment 3 in this section.

One day before termination of the experiments, plant heights and leaf area measurements were made. Leaf areas were measured on one representative plant from each pot in each replication using a Lycore

(Model 3100) leaf area meter.

Chlorophyll measurements were also made on samples from SC 118-15E, Martin, SC 33-9-8-E4, SC 500-6-1, TAM 428, NP, TX 7078, SD 106, KS 56, and Norghum. Leaf samples taken for chlorophyll determinations were from one representative plant in each pot. On the day of harvest, leaf areas and fresh weights were determined and immediately afterwards leaf samples for chlorophyll determinations (leaf numbers 5 and 6) were placed in an ice chest, frozen within 30 minutes after harvest, and freeze-dried (-42 to -44C). The freeze-dried samples were ground in a Wiley mill to pass a 0.5-mm screen and chlorophyll determinations made using the method of Specht et al. (1975). In brief, this determination consisted of extracting 5 mg leaf material with 1.0 ml 50% acetone by macerating the samples in a homogenator for 1 minute. The acetone homogenates were transferred to test tubes and the homogenate washed two times with acetone and the volume made up to 10.0 ml with additional acetone. The homogenates were centrifuged at 1,500 rpm for 5 minutes. Chlorophyll a and b were determined in the supernatant solution by measuring the absorbance at 663 nM (chlorophyll a) and 645 nM (chlorophyll b). Total chlorophyll was calculated by summing chlorophyll a and b.

RESULTS

A. Screening Sorghum for Differential 'Iron-efficiency' in Nutrient Solutions

Withholding Fe, growing plants in media near or above 7, the addition of many chemicals, and various environmental conditions may induce Fe deficiencies. One way to determine differences in 'Fe-efficiency' is to observe differential responses of genotypes that undergo Fe deficiency when plants are grown in a low Fe or induced Fe deficiency media. In these studies, Fe deficiencies were induced in sorghum plants growing in nutrient solutions. The methods used to induce Fe deficiency were added P and $CaCO_3$ and the use of different sources of N. In the latter case, NO_3^-, NH_4^+, or (NO_3^- + NH_4^+) were added to nutrient solutions as the source of N. With NO_3^-, the pH of nutrient solutions usually rises because of the more rapid plant uptake of NO_3^- compared to cations (Hiatt, 1974). The increase in solution pH causes Fe^{2+}, the available form of Fe to plants, to be converted to Fe^{3+}, the unavailable form of Fe to plants. The Fe^{3+} form may form insoluble Fe^{3+}-hydroxides and precipitate out of solution. With NH_4^+, the pH of nutrient solutions usually decrease because of the more rapid plant uptake of NH_4^+ compared to anions. Lowering the pH of nutrient solutions allows for greater reduction of Fe^{3+} to Fe^{2+}, thus increasing the availability of Fe to plants.

1. Growth of Plants

Because of growth space limitations, plants were grown in several experiments. Two experiments had nutrient solutions with added P and

$CaCO_3$ to induce Fe deficiencies in U.S. sorghum genotypes (Experiment 1) and Nigerian sorghum genotypes (Experiment 2). Three experiments were conducted to screen a greater number of U.S. genotypes, using various sources of N (Experiments 3, 4, and 5). One experiment had NO_3^- and added P in solution to observe the effect of plant age on the induction of Fe deficiency (Experiment 6).

The genotypes in each experiment appeared normal when grown in nutrient solutions until treatments were added. At the time treatments were added, the plants were 7 days old and were in the 6-leaf stage. Treatment effects on each genotype were different and associated with Fe deficiency.

2. Iron Deficiency Symptoms

Experiment 1: Fourteen U.S. genotypes (Table 2) were screened in this experiment for differential 'Fe-efficiency' when Fe deficiency was induced by added P and $CaCO_3$.

Some genotypes began to show Fe deficiency symptoms in the newly emerging leaves 2 days after the addition of treatments. When the experiments were terminated (7 days after treatments were added), the genotypes developed different degrees of Fe deficiency symptoms (Table 2). SC 118-15E had the most severe symptoms (very deep yellowing of the upper leaves) under the low P treatment and SC 33-9-8-E4, KS 5, and NP had little or no Fe deficiency symptoms. Under the high P treatment, only SC 33-9-8-E4 and Plainsman remained relatively green. Plants grown in the control solutions also showed some Fe deficiency chlorosis. In the control solutions, SC 118-15E, SC 500-6-1, and Redlan showed the most severe symptoms and SC 33-9-8-E4, KS 5, and SC 109-9 were green.

Table 2. The degree of Fe deficiency symptoms noted on the upper leaves of U.S. sorghum genotypes grown under $CaCO_3$- and P-induced Fe deficiency (Expt. 1).+

Genotypes	Treatment to induce Fe deficiency				
	Control	0.15 mM $CaCO_3$	0.17 mM P	0.39 mM P	Genotype means
SC 118-15E	2.3 a†	1.8 a	3.0 a	2.8 a	2.4 A
SC 134	1.0 bc	0.5 abc	1.0 bc	1.0 bcd	0.9 BCDE
SC 500-6-1	1.5 ab	0.8 abc	2.0 b	1.3 bcd	1.4 BCD
Wheatland	0.5 bc	0.0 c	1.5 bc	1.3 bcd	0.8 DE
TAM 428	1.06 bc	1.3 abc	1.5 bc	1.5 bc	1.3 BCD
Redbine 60	0.8 bc	0.3 bc	1.3 bc	1.0 bcd	0.8 DE
Redlan	1.5 ab	1.5 ab	2.0 b	1.3 bcd	1.6 B
Plainsman	0.5 bc	0.0 c	0.8 bc	0.3 cd	0.4 EF
SC 109-9	0.3 bc	1.3 abc	0.8 bc	1.3 bcd	0.9 BCDE
CK 60	1.3 abc	1.3 abc	1.5 bc	2.0 ab	1.5 BC
KS 5	0.3 bc	0.0 c	0.5 c	1.3 bcd	0.5 EF
Martin	1.0 bc	1.3 abc	1.3 bc	1.8 ab	1.3 BCD
NP	0.5 bc	0.3 bc	0.5 c	0.8 bcd	0.5 EF
SC 33-9-8-E4	0.0 c	0.3 bc	0.3 c	0.0 d	0.1 F
Treatment means	0.9 A	0.7 A	1.3 A	1.3 A	

+ 0 = No Fe deficiency (green); 4 = Severe Fe deficiency (severe interveinal chlorosis).

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

When the genotypes were grown in the $CaCO_3$ treatment, Wheatland, Plainsman, and KS 5 were completely green and SC 118-15E, Redlan, Martin, SC 109-9, and TAM 428 were moderately Fe deficient. From the Fe deficiency symptoms that appeared on the U.S. genotypes grown under P and $CaCO_3$ induced Fe deficiency, SC 118-15E, Redlan, and Martin could be considered 'Fe-inefficient,' and SC 33-9-8-E4, Plainsman, KS 5, and NP could be considered to be 'Fe-efficient.' At the treatment levels used, more severe Fe deficiency symptoms generally appeared when plants were brought under Fe deficiency by added P than by added $CaCO_3$.

Experiment 2: Ten Nigerian (Table 3) plus two U.S. (checks) genotypes were screened for 'Fe-efficiency' when Fe deficiency was induced by added P and $CaCO_3$. Plants grew well for 3 days before some genotypes started to show Fe deficiency symptoms. On the average, plants developed more severe Fe deficiency symptoms under added $CaCO_3$ and P than under the control (Table 3). Except for FFB-L, C 7.4, and SC 118-15E plants grown in the control solutions remained green. Under the $CaCO_3$ treatment, only H.P 3, L 1449, C 7.4, L 187, and SK 5912 became moderately Fe deficient. Under the P treatments, several genotypes developed severe Fe deficiency symptoms. The genotypes that developed the least Fe deficiency symptoms were RZ 1, SC 33-9-8-E4, L 181, FFB-L, and YG 5760 under the $CaCO_3$ treatment; SC 33-9-8-E4, RZ 1, and KANO L.1 under the low P treatment and SC 33-9-8-E4, and KANO L.1 under the high P treatment. On the basis of the above observations, FFB-L, H.P 3, C 7.4, and SC 118-15E could be considered 'Fe-inefficient' and KANO L.1, SC 33-9-8-E4, and RZ 1 'Fe-efficient.'

Table 3. The degree of Fe deficiency symptoms noted on the upper leaves of Nigerian sorghum genotypes grown under $CaCO_3$- and P-induced Fe deficiency (Expt. 2).+

Genotypes	Treatment to induce Fe deficiency				
	Control	0.15 mM $CaCO_3$	0.17 mM P	0.39 mM P	Genotype means
SK 5912	0.0 a†	1.0 bc	2.0 ab	1.3 de	1.1 AB
KANO L.1	0.0 a	0.8 bc	0.5 e	0.5 f	0.5 CD
H.P 3	0.0 a	1.3 a	1.3 cd	2.0 bc	1.1 AB
YG 5760	0.0 a	0.5 cd	2.0 ab	1.8 bcd	1.1 AB
FFB-L	0.5 a	0.5 cd	2.3 a	2.8 a	1.5 A
L 1449	0.0 a	1.3 ab	1.5 bc	0.8 ef	0.9 BC
C 7.4	0.5 a	1.0 abc	2.0 ab	2.3 ab	1.4 A
L 181	0.0 a	0.5 cd	1.3 cd	0.8 ef	0.6 CD
L 187	0.0 a	1.5 a	0.8 de	1.4 cde	0.9 BC
RZ 1	0.0 a	0.0 d	0.5 e	0.9 ef	0.4 CD
SC 33-9-8-E4	0.0 a	0.5 cd	0.3 e	0.3 f	0.3 D
SC 118-15E	0.5 a	0.7 bcd	1.8 abc	2.3 ab	1.3 A
Treatment means	0.1 C	0.8 B	1.3 AB	1.4 A	

+ 0 = No Fe deficiency (green); 4 = Severe Fe deficiency (severe interveinal chlorosis).

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

The treatment x genotype interactions were significant. L 187 was more Fe deficient under the $CaCO_3$ treatment than under the low P treatment. RZ 1 was completely green under $CaCO_3$ treatment but developed slight Fe deficiency symptoms under both P treatments. While most genotypes developed more severe Fe deficiency symptoms under the high P than under the low P treatment, SC 118-15E, H.P 3, and FFB-L had more severe symptoms under the low P treatment. KANO L.1 was equally Fe deficient under both P treatments.

Experiments 3, 4, and 5: Thirty-two U.S. genotypes were screened for 'Fe-efficiency' when plants were grown with different sources of N. Because of limitations in growth space, the genotypes were grown in three experiments (Tables 4, 5, and 6). In experiment 3, Fe deficiency symptoms appeared in some genotypes after 2 days in treatment solutions. Martin, SC 118-15E, SC 500-6-1, Redbine 60, and NP (a North Platte line) began to show Fe deficiency first in NO_3^- solutions. The remaining genotypes did not show Fe deficiency symptoms until after 4-5 days in NO_3^- solution. In NH_4^+ solutions, SC 118-15E, SC 500-6-1, Wheatland, Redbine 60, and SC 109-9 became Fe deficient within 2 days after plants were put into nutrient solutions. SC 33-9-8-E4 and NP did not show any Fe deficiency symptoms until after they had been in the treatments for 5 days. The remaining genotypes became Fe deficient within 3 days. Of those genotypes grown with (NO_3^- + NH_4^+) or control, Fe deficiency symptoms developed in Redbine 60 and SC 109-9 within 2 days; in SC 118-15E, Wheatland, TAM 428, and Redlan after 3 days; in Martin, SC 33-9-8-E4, SC 500-6-1, and CK 60 after 4 days; in SC 134, KS 5, and NP after 5 days; and in Plainsman after 6 days. By harvest, differences in Fe

Table 4. The degree of Fe deficiency symptoms observed on the upper leaves of sorghum genotypes grown with three sources of N (Expt. 3).+

Genotypes	Source of N			
	NO_3^-	NH_4^+	$(NO_3^- + NH_4^+)$	Genotype means
SC 118-15E	3.0 abcd†	2.3 abc	1.8 bcd	2.3 DEF
SC 134	2.5 cdef	2.5 ab	1.3 cde	2.1 EF
SC 500-6-1	2.8 bcde	2.5 ab	2.0 abc	2.4 CDE
Wheatland	3.0 abcd	2.8 ab	1.8 bcd	2.5 BCDE
TAM 428	3.3 abc	2.3 abc	2.3 ab	2.6 ABCD
Redbine	2.5 cdef	2.0 bc	1.3 cde	1.9 FG
Redlan	3.8 a	2.8 ab	2.3 ab	2.9 AB
Plainsman	2.0 ef	1.0 d	0.5 e	1.2 E
SC 109-9	3.5 ab	2.8 ab	2.3 ab	2.8 ABC
CK 60	3.5 ab	2.3 abc	2.0 abc	2.6 ABCD
KS 5	2.3 def	1.0 d	1.0 de	1.4 H
Martin	3.3 abc	3.0 a	2.8 a	3.0 A
NP	2.3 def	1.5 cd	1.0 de	1.6 GH
SC 33-9-8-E4	1.8 f	1.3 d	1.0 de	1.3 H
Treatment means	2.8 A	2.1 AB	1.6 B	

+ 0 = No Fe deficiency (green); 4 = Severe Fe deficiency (severe interveinal chlorosis).

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 5. The degree of Fe deficiency symptoms of sorghum genotypes grown with three sources of N (Expt. 4).+

Genotypes	Source of N			
	NO_3^-	NH_4^+	$(NO_3^-+NH_4^+)$	Genotype means
KS 56	1.5 b†	1.0 ab	0.2 a	1.3 B
TX 414	1.2 b	0.7 abc	0.2 a	1.0 B
TX 7078	1.2 b	0.7 abc	0.2 a	1.0 B
TX 07	0.8 bc	0.5 bc	0.0 a	0.7 C
Norghum	0.2 cd	0.5 bc	0.0 a	0.4 CD
Caprock	1.2 b	0.7 abc	0.0 a	1.0 B
SD 102	0.3 cd	0.3 bc	0.2 a	0.3 CD
TX 412	0.0 d	0.0 c	0.0 a	0.0 D
SC 369-3-1JB	2.2 a	1.3 a	0.2 a	1.8 A
Treatment means	0.9 A	0.6 A	0.1 B	

+ 0 = No Fe deficiency (green); 4 = Severe Fe deficiency (severe *interveinal chlorosis*).

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 6. The degree of Fe deficiency symptoms observed on the upper leaves of plants grown with three sources of N (Expt. 5).+

Genotypes	Source of N			
	NO_3^-	NH_4^+	(NO_3^-+NH_4^+)	Genotype means
KS 57	3.2 ab†	1.3 ab	2.5 ab	2.3 AB
SC 29	3.2 ab	1.2 b	2.5 ab	2.3 AB
TX 7078	3.3 a	1.2 b	2.0 b	2.2 ABC
TX 07	3.0 abc	1.5 ab	2.7 ab	2.4 AB
NB 9434	2.8 abc	1.5 ab	1.0 c	1.8 CD
SC 149	2.3 c	0.8 b	1.0 c	1.4 D
SD 106	2.3 c	0.8 b	1.0 c	1.4 D
TX 412	2.5 bc	1.3 ab	2.2 b	2.0 BC
TX 415	2.7 abc	2.0 a	3.0 a	2.6 A
Treatment means	2.8 A	1.3 C	2.0 B	

+ 0 = No Fe deficiency (green); 4 = Severe Fe deficiency (severe interveinal chlorosis).

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

deficiency symptoms were noted between NO_3^- and the (NO_3^- + NH_4^+) treatments (Table 4). Differences in the degree of Fe deficiency symptoms between NO_3^- and NH_4^+ treatments were insignificant. The genotypes also showed some differences. Martin, CK 60, SC 109-9, Redlan, TAM 428, Wheatland, and SC 118-15E developed severe Fe deficiency symptoms in these solutions and SC 33-9-8-E4, NP, KS 5, and Plainsman developed only slight Fe deficiency symptoms (Table 4).

In Experiment 4, KS 56, TX 414, TX 7078, Norghum, and SC 369-3-1JB showed Fe deficiency symptoms in NO_3^- solutions within 2 days. The remaining genotypes did not show Fe deficiency symptoms until after 5-6 days in NO_3^- solutions. Similarly, KS 56, SC 369-3-1JB, TX 414, and TX 7078 developed Fe deficiency in the NH_4^+ solution by the third day, and the remaining genotypes developed the symptoms only after 6 days. For plants grown in the (NO_3^- + NH_4^+) solutions, only SC 369-3-1JB became Fe deficient on the third day. TX 7078 and Norghum developed some P deficiency symptoms when grown in NO_3^- solutions. Roots of all genotypes were yellowish-red for plants grown in NH_4^+ solutions. Though plants did not become severely Fe deficient at the time the experiment was terminated, the treatments differed (Table 5). Only five genotypes showed slight symptoms of Fe deficiency in the (NO_3^- + NH_4^+) solution, and five genotypes were slightly to moderately Fe deficient in the NO_3^- solution. Only TX 412 remained green in the NO_3^- and NH_4^+ solutions. In contrast, TX 07, Norghum, Caprock, and TX 412 were green in (NO_3^- + NH_4^+) solutions.

In Experiment 5, some genotypes started to show Fe deficiency symptoms within 2 days in each of the N solutions. TX 07, TX 412, and TX 415 developed Fe deficiency in NO_3^- solutions within this time. On

the fourth day, KS 57, TX 7078, and SD 106 also showed Fe deficiencies. NB 3494 and SC 149 became Fe deficient on the fifth day, and SC 29 developed Fe deficiency symptoms only after 6 days in NO_3^- solutions. In NH_4^+ solutions, the first genotypes to develop Fe deficiency symptoms were TX 7078, TX 07, NB 3494, SC 149, SD 106, and TX 415 after 2 days in solution. SC 29 became Fe deficient after 3 days and TX 412 and KS 57 showed Fe deficiency symptoms after 4 days. For plants grown with (NO_3^- + NH_4^+), NB 3494, TX 07, TX 7078, SC 149, and SD 106 developed Fe deficiency symptoms within 2 days; TX 415 and KS 57 within 4 days; and SC 29 and TX 412 within 6 days. When the experiment was terminated, the genotypes differed in the severity of Fe chlorosis in each N solution (Table 6). Plants were generally more Fe deficient when grown in NO_3^- solutions than in NH_4^+ or (NO_3^- + NH_4^+) solutions.

3. pH Changes in Nutrient Solutions

When plants are grown in nutrient solutions, the pH of the solution usually decreases with time unless the solution has NO_3^- only as a source of N or certain chemicals such as high $CaCO_3$ and other buffer salts are added. In Experiment 1, the decreases in the pH of the control and treatment solutions were similar (Fig. 2). The decrease in the pH noted for solutions treated with $CaCO_3$ was unexpected, since $CaCO_3$ added to nutrient solutions usually causes the pH to rise. Apparently insufficient carbonate was added to cause solution pH increases. Nevertheless, Fe deficiency symptoms appeared in plants grown in $CaCO_3$ solutions. Figure 3 shows the pH changes with time for Experiment 2. The pH of the treatment solutions decreased gradually up to day 4 after

Fig. 2. Changes in pH of nutrient solutions for sorghum genotypes grown under various Fe stress (mean average of 14 genotypes).

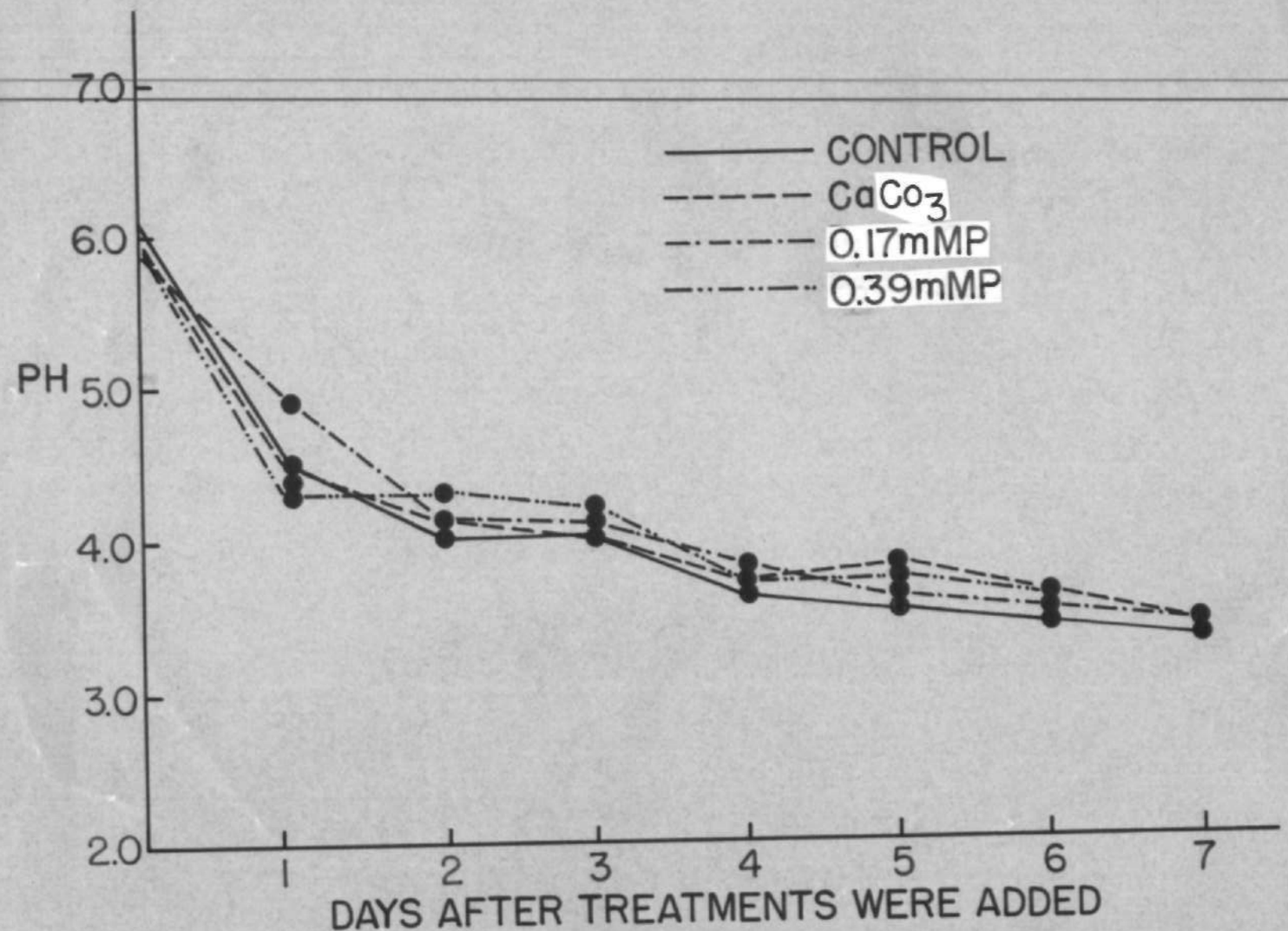


Fig. 3. pH changes in nutrient solution for sorghum genotypes grown under various Fe stress (mean average of 12 genotypes).

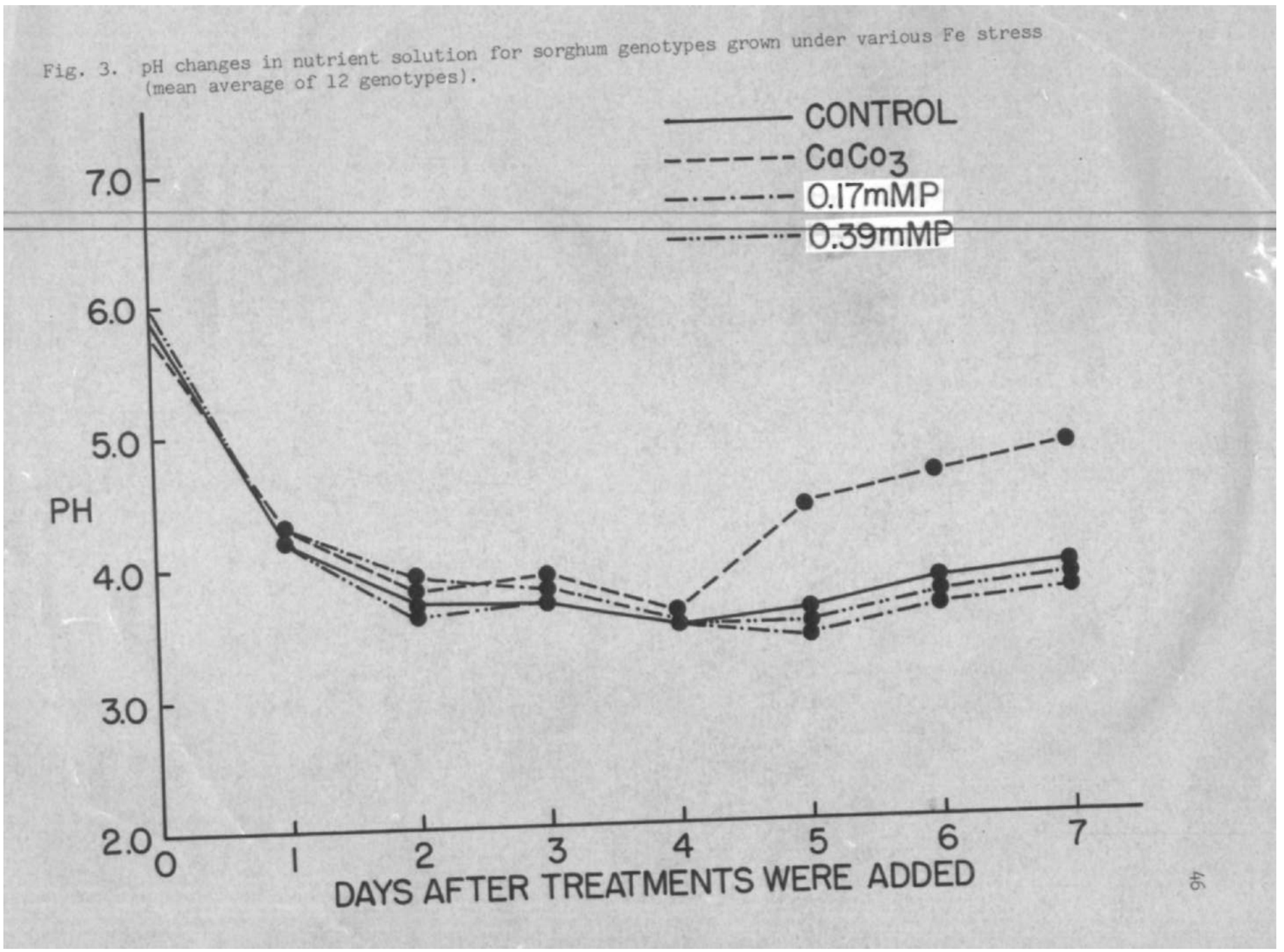


Fig. 5. pH changes in nutrient solution for sorghum genotypes grown with three sources of nitrogen (mean average of 9 genotypes).

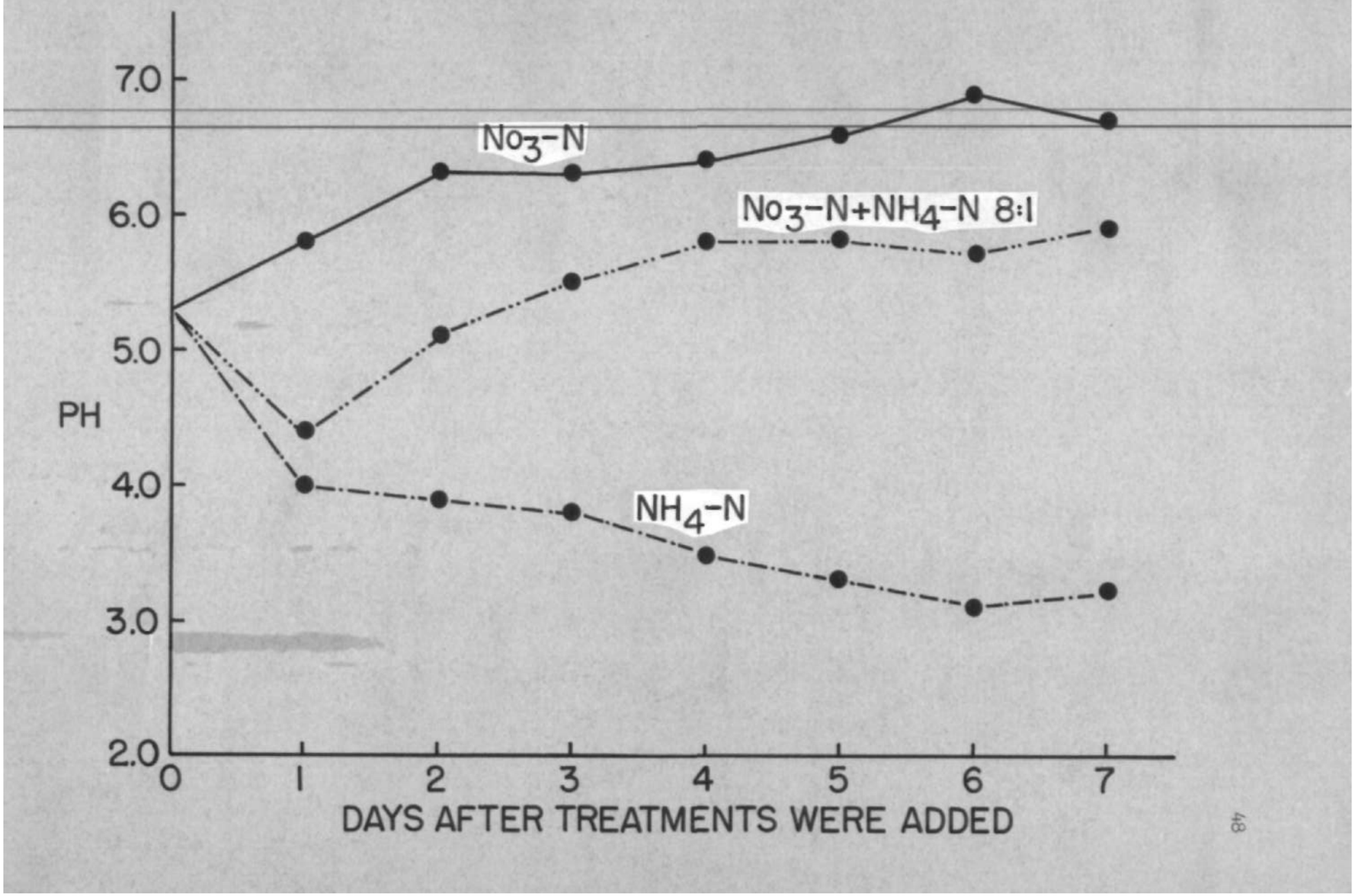
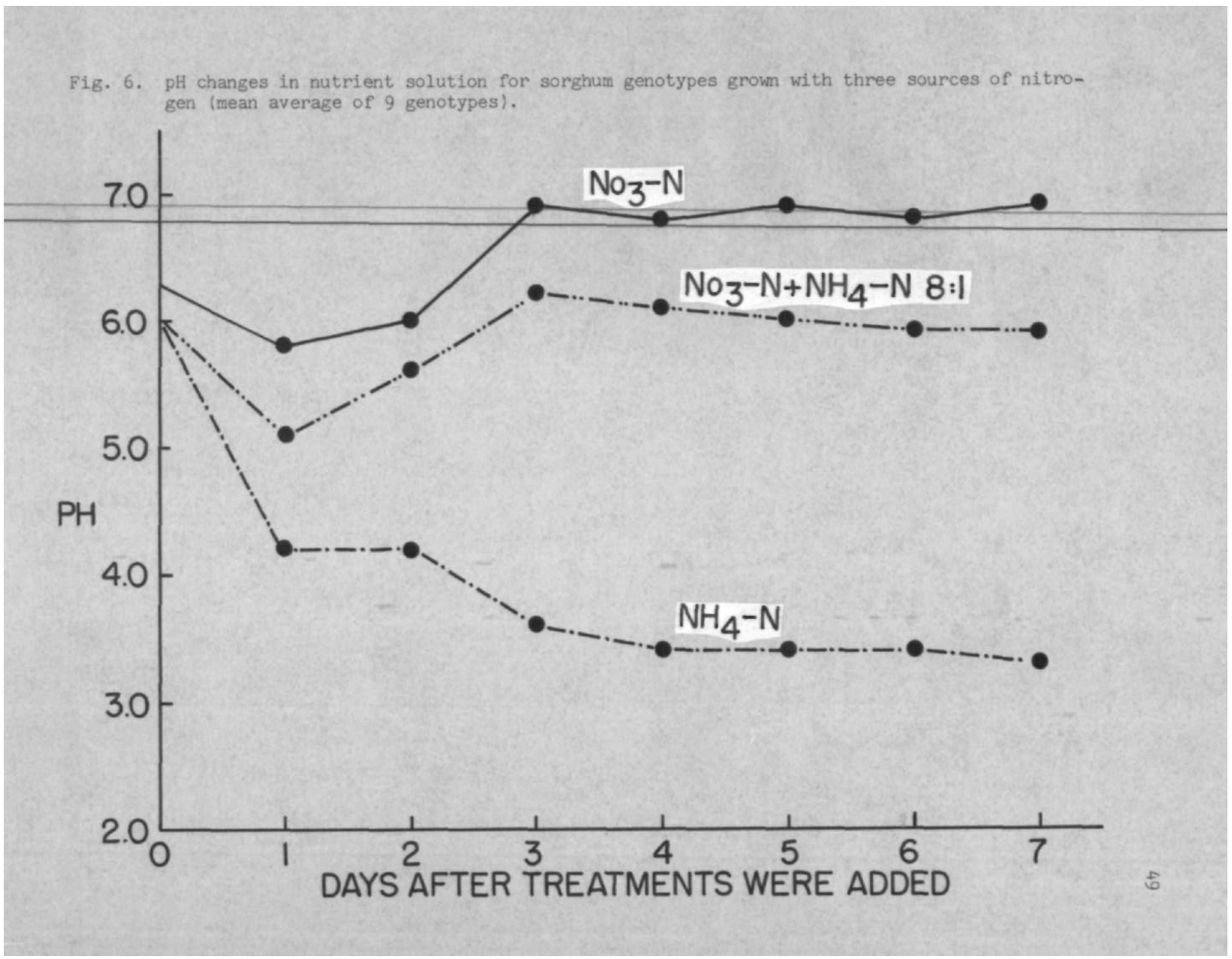


Fig. 6. pH changes in nutrient solution for sorghum genotypes grown with three sources of nitrogen (mean average of 9 genotypes).



which the pH increased under the $CaCO_3$ and control treatments decreased under the low P treatment and did not change under the high P treatment. When the experiment was terminated, the pH was highest under the $CaCO_3$ treatment (4.8) and was essentially the same under the control and both P treatments (3.7 to 3.9).

Figure 4 shows the pH changes in nutrient solutions with time in Experiment 3. The pH of the NO_3^- solutions increased gradually, while the pH of the NH_4^+ solutions decreased. The greatest decrease in pH occurred within 3 days, and the sharpest rise in pH occurred within 2 days after plants were placed in them. The pH of solutions with (NO_3^- + NH_4^+) decreased the first day, stabilized the following day, then increased gradually thereafter. Similar changes in pH were noted in Experiments 3 and 4 (Fig. 5 and 6) for the other genotypes.

4. Dry-matter Yields

Top, root, and total dry-matter yields for genotypes grown in Experiment 1 are shown in Tables 7 and 8. Differences in dry-matter yields among genotypes were significant. SC 118-15E and Martin had the highest dry-matter yields, and SC 33-9-8-E4 and Plainsman had the lowest. Genotype x treatment interactions were not significant.

The addition of $CaCO_3$ or P decreased top dry-matter yields for most genotypes compared to the control. However, for SC 500-6-1, TAM 428, Redlan, Plainsman, Martin, and KS 5, the addition of $CaCO_3$ increased top dry-matter yields over those of the control solutions and the addition of low P increased top dry-matter yields for Martin. Except for Plainsman, KS 5, and NP, root dry-matter yields were higher

Table 7 . Top and root dry matter yields of U.S. sorghum genotypes grown under $CaCO_3$- and P-induced Fe deficiency (Expt. 1).

Genotypes	Treatment to induce Fe deficiency									
	Top yield					Root yield				
	Control	0.15 mM $CaCO_3$	0.17 mM P	0.39 mM P	Genotype means	Control	0.15 mM $CaCO_3$	0.17 mM P	0.39 mM P	Genotype means
	mg/plant					mg/plant				
SC 118-15E	138 a†	118 b	130 ab	122 a	127 A	93 a	56 ab	67 a	60 a	69 A
SC 134	118 a	79 cd	79 c	76 bcde	88 C	64 bcd	44 bcd	52 ab	40 abcd	50 BC
SC 500-6-1	88 bc	97 bc	70 cd	70 cdef	81 CD	57 cde	52 abc	37 bc	29 bcd	44 BCD
Wheatland	82 cd	49 e	67 cd	64 bcde	66 EF	49 cde	27 cde	25 bc	32 bcd	33 DEF
TAM 428	74 cde	84 cd	48 d	77 bcde	71 E	42 def	51 abcd	24 c	37 abcd	39 CDE
Redbine 60	60 cdef	58 de	57 cd	53 ef	57 FG	35 ef	35 bcde	28 bc	28 bcd	31 DEF
Redlan	112 ab	117 b	106 b	83 bcd	105 B	67 bcd	56 ab	41 bc	38 abcd	50 BC
Plainsman	33 f	42 e	56 cd	44 f	44 G	21 f	25 de	32 bc	31 bcd	27 EF
SC 109-9	77 cde	51 e	48 d	51 ef	57 FG	52 cde	25 de	25 bc	24 cd	31 DEF
CK 60	119 a	104 bc	106 b	91 bc	105 B	73 abc	57 ab	42 bc	40 abcd	53 B
KS 5	49 ef	62 de	54 cd	57 def	55 FG	36 ef	33 bcde	27 bc	53 ab	37 DE
Martin	116 a	145 a	142 a	100 ab	126 A	84 ab	76 a	69 a	54 ab	71 A
NP	58 def	59 de	50 cd	50 ef	54 FG	32 ef	32 bcde	28 bc	50 abc	36 DE
SC 33-9-8-E4	64 cde	34 e	47 d	42 f	47 G	30 ef	17 e	22 c	23 d	23 F
Treatment means	85 A	78 A	76 A	70 A		52 A	42 A	39 A	37 A	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 8 . Total dry matter yields and top/root dry matter ratios of U.S. sorghum genotypes grown under $CaCO_3$- and P-induced Fe deficiency (Expt. 1).

Genotypes	Treatment to induce Fe deficiency									
	Total yield					Top/root ratio				
	Control	0.15 mM $CaCO_3$	0.17 mM P	0.39 mM P	Genotype means	Control	0.15 mM $CaCO_3$	0.17 mM P	0.39 mM P	Genotype means
	mg/plant									
SC 118-15E	230 a†	174 b	197 a	182 a	196 A	1.5 b	2.1 a	2.0 cde	2.0 ab	1.9 ABCD
SC 134	182 bc	123 cd	131 bc	116 bcde	138 BC	1.8 b	1.8 a	1.5 e	1.9 ab	1.8 BCD
SC 500-6-1	145 cd	149 bc	108 bcd	99 cdef	125 CD	1.6 b	1.9 a	1.9 cde	2.4 a	1.9 ABCD
Wheatland	131 de	76 e	92 cd	96 cdef	99 EF	1.7 b	1.8 a	2.6 ab	2.0 ab	2.0 ABC
TAM 428	117 def	134 bc	72 d	115 bcde	109 DE	1.8 b	1.7 a	2.1 abcd	2.0 ab	1.9 ABCD
Redbine 60	95 efg	92 de	86 d	80 def	88 FG	1.7 b	1.7 a	2.1 abcd	1.9 ab	1.9 ABCD
Redlan	180 bc	173 b	147 b	122 bcd	156 B	1.7 b	2.1 a	2.7 a	2.2 a	2.2 A
Plainsman	54 g	68 e	88 cd	71 ef	70 G	1.6 b	1.7 a	1.8 de	1.5 b	1.6 D
SC 109-9	129 def	75 e	73 d	76 ef	88 FG	1.6 b	2.0 a	2.0 cde	2.1 ab	1.9 ABCD
CK 60	191 ab	161 bc	148 b	131 bc	158 B	1.6 b	1.8 a	2.4 abc	2.3 a	2.0 ABC
KS 5	85 g	92 de	80 d	85 def	86 FG	1.4 b	1.8 a	2.3 abcd	2.0 ab	1.9 ABCD
Martin	200 ab	224 a	211 a	155 ab	197 A	1.5 b	1.9 a	2.0 cde	1.8 ab	1.8 BCD
NP	90 efg	91 de	79 d	75 ef	84 FG	1.8 b	1.8 a	1.8 de	2.0 ab	1.8 BCD
SC 33-9-8-E4	94 ef	51 e	68 d	65 f	69 G	2.4 a	2.1 a	2.1 abcd	1.9 ab	2.1 AB
Treatment means	137 A	120 A	113 A	105 A		1.7 B	1.9 A	2.1 A	2.0 A	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

for plants grown in the control solutions than with added P or $CaCO_3$. Similar observations could be made for total dry-matter yields.

The Nigerian genotypes in Experiment 2 also showed differences in their top, root, and total dry-matter yields (Tables 9 and 10). FFB-L and YG 5760 produced the highest amounts of top dry-matter; YG 5760, FFB-L, and C 7.4 produced the highest root dry-matter; and YG 5760 and FFB-L produced the highest total dry-matter. Root dry-matter production of plants grown in the control solutions and with added P or $CaCO_3$ did not differ. However, plants produced higher top dry-matter yields when grown in the control solutions than under the high P treatment.

In Experiment 3, top dry-matter yields of plants grown with (NO_3^- + NH_4^+) were higher than the yields of plants grown with NO_3^- or NH_4^+ (Tables 11 and 12).

For Experiments 4 and 5, the top dry-matter produced by plants grown in the three treatments were similar (Tables 13 and 15). Genotypes, however, showed yield differences. In Experiment 3, Redlan and Martin outyielded the other genotypes in top dry-matter, and SC 33-9-8-E4 had the lowest top dry-matter yield. Some genotype x treatment interactions were significant indicating that the genotypes did not behave the same way under all N treatments. Under the NO_3^- treatment, Martin gave the highest yields, and under both NH_4^+ and (NO_3^- + NH_4^+) treatments, Redlan produced the most top dry-matter. Redlan produced the most top dry-matter. Except for SC 33-9-8-E4, TAM 428, Wheatland, and SC 134, the other genotypes produced higher top dry-matter under

Table 9 . Top and root dry matter yields of Nigerian sorghum genotypes grown under $CaCO_3$- and P-induced Fe deficiency (Expt. 2).

Genotypes	Treatment to induce Fe deficiency									
	Top yield					Root yield				
	Control	0.15 mM $CaCO_3$	0.17 mM P	0.39 mM P	Genotype means	Control	0.15 mM $CaCO_3$	0.17 mM P	0.39 mM P	Genotype means
	mg/plant					mg/plant				
K 5912	190 b†	122 bc	156 ab	166 ab	158 B	92 b	87 b	85 a	127 b	98 BC
KANO L.1	52 e	78 d	77 bc	56 d	66 FG	28 c	50 bc	50 bc	35 d	41 EF
H.P 3	119 d	133 bc	53 c	77 cd	95 CDE	62 b	79 b	29 c	62 c	58 DE
YG 5760	247 a	142 ab	168 a	145 ab	176 AB	135 a	112 a	100 a	119 b	117 AB
FFB-L	264 a	174 a	181 a	177 a	199 A	128 ab	115 a	92 a	187 a	131 A
L 1449	143 c	158 a	151 ab	141 ab	148 B	65 b	98 ab	98 a	104 b	91 C
C 7.4	193 b	163 ab	177 a	125 bc	164 B	131 a	131 a	114 a	98 bc	119 A
L 181	91 de	74 d	81 b	54 d	75 EFG	43 c	40 cd	40 bc	39 d	40 EF
L 187	131 cd	91 cd	117 b	97 c	109 CD	73 b	60 bc	67 b	62 c	65 D
RZ 1	124 cd	75 d	82 bc	55 d	84 DEF	60 bc	59 bc	42 bc	40 d	50 DE
SC 33-9-8-E4	48 e	58 d	46 c	53 d	51 G	23 c	28 d	20 c	25 d	24 F
SC 118-15E	121 c	113 b	111 b	106 c	113 C	57 b	71 bc	56 bc	73 c	64 D
Treatment means	144 A	115 AB	117 AB	104 B		75 A	78 A	66 A	81 A	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 10. Total dry-matter yields and top/root dry-matter ratios of Nigerian sorghum genotypes grown under $CaCO_3$- and P-induced Fe deficiency (Expt. 2).

Genotypes	Treatment to induce Fe deficiency									
	Total yield					Top/root ratio				
	Control	0.15 mM $CaCO_3$	0.17 mM P	0.39 mM P	Genotype means	Control	0.15 mM $CaCO_3$	0.17 mM P	0.39 mM P	Genotype means
	mg/plant									
SK 5912	280 bc†	209 abc	241 abc	293 a	256 BC	1.3 cd	1.4 b	1.8 b	2.1 a	1.7 BC
KANO L.1	81 e	128 cd	127 de	92 d	107 EF	1.6 bc	1.5 b	1.6 b	1.8 ab	1.6 BC
H.P 3	181 cd	212 abc	82 de	138 d	153 DE	1.3 cd	1.7 ab	1.8 b	2.0 a	1.7 BC
YG 5760	382 a	254 ab	268 abc	264 ab	292 AB	1.2 d	1.3 b	1.7 b	1.9 a	1.5 CD
FFB-L	393 a	289 a	273 ab	314 a	317 A	1.0 d	1.5 b	2.0 ab	2.1 a	1.6 BC
L 1449	208 cd	255 ab	249 abc	246 abc	239 C	1.4 b	1.6 b	1.6 b	2.2 a	1.7 BC
C 7.4	323 ab	294 a	293 a	173 bcd	271 ABC	1.3 cd	1.4 b	1.6 b	1.5 b	1.4 D
L 181	134 de	114 cd	121 de	93 d	256 BC	1.4 b	1.9 a	2.0 ab	2.2 a	1.9 B
L 187	204 cd	151 bcd	184 bcd	159 cd	174 D	1.6 bc	1.5 b	1.8 b	1.8 ab	1.7 BC
RZ 1	184 cd	199 abc	125 de	94 d	150 DE	1.4 c	1.3 b	1.9 b	2.1 a	1.7 BC
SC 33-9-8-E4	72 e	86 d	66 e	78 d	75 F	2.1 a	2.1 a	2.4 a	2.1 a	2.2 A
SC 118-15E	154 de	184 bcd	168 cde	178 bcd	171 D	1.5 c	1.7 ab	2.0 ab	2.1 a	1.8 B
Treatment means	216 A	198 A	183 A	177 A		1.4 C	1.6 BC	1.8 AB	2.0 A	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 11. Top and root dry-matter yields of sorghum genotypes grown with different sources of N to induce Fe deficiency in nutrient solutions (Expt. 3).

Genotypes	Source of N							
	Top yield				Root yield			
	NO_3^-	NH_4^+	$(NO_3^-+NH_4^+)$	Genotype means	NO_3^-	NH_4^+	$(NO_3^-+NH_4^+)$	Genotype means
	mg/plant				mg/plant			
SC 118-15E	160 cd†	143 b	208 c	171 CD	72 b	59 bc	119 bc	83 DEF
SC 134	128 de	163 b	177 c	157 D	85 b	76 b	94 c	85 DE
SC 500-6-1	181 c	153 b	255 b	196 BC	89 b	57 bc	146 ab	97 BCD
Wheatland	146 cd	229 a	258 b	211 B	88 b	109 a	136 b	111 B
TAM 428	137 d	141 b	205 c	161 D	73 b	67 bc	139 ab	93 CDE
Redbine 60	145 cd	136 b	191 c	157 D	89 b	57 bc	92 c	79 EF
Redlan	279 a	239 a	321 a	280 A	131 a	93 a	167 a	130 A
Plainsman	112 de	89 c	138 d	113 E	62 b	42 c	76 c	60 GH
SC 109-9	180 c	164 b	297 a	213 B	101 a	67 b	128 b	99 BCD
CK 60	236 b	165 b	246 b	216 B	108 a	77 b	112 bc	99 BCD
KS 5	113 de	97 c	143 d	118 E	75 b	58 b	72 c	68 FG
Martin	308 a	229 a	224 bc	254 A	108 a	108 a	107 b	108 BC
NP	109 de	78 c	120 d	103 E	60 bc	37 c	71 c	56 GH
SC 33-9-8-E4	81 e	87 c	140 d	103 E	38 c	35 c	67 c	47 H
Treatment means	165 B	151 B	209 A		84 AB	67 B	109 A	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 12. Total dry-matter yields and top/root dry-matter ratios of sorghum genotypes grown with different sources of N to induce Fe deficiency in nutrient solutions (Expt. 3).

Genotypes	Source of N							
	Total yield				Top/root ratio			
	NO_3^-	NH_4^+	$(NO_3^-+NH_4^+)$	Genotype means	NO_3^-	NH_4^+	$(NO_3^-+NH_4^+)$	Genotype means
	mg/plant							
SC 118-15E	232 de[†]	202 bcd	277 def	237 D	2.2 bc	2.5 ab	1.8 ab	2.1 ABCD
SC 134	213 de	239 b	273 def	242 D	1.6 d	2.2 b	2.0 a	1.9 CDE
SC 500-6-1	270 d	211 bc	401 bc	294 C	2.0 bc	2.7 a	1.8 ab	2.2 ABCD
Wheatland	234 de	338 a	394 bc	322 C	1.7 d	2.2 b	1.9 ab	1.9 CDE
TAM 428	210 de	208 bc	344 cd	254 D	1.9 bc	2.1 bc	1.5 b	1.8 E
Redbine 60	233 de	196 bcd	283 de	237 D	1.7 d	2.4 ab	2.1 a	2.0 BCDE
Redlan	409 ab	332 a	487 a	410 A	2.2 bc	2.6 a	1.9 ab	2.2 ABCD
Plainsman	174 ef	131 de	214 efg	173 E	1.8 cd	2.1 bc	1.8 ab	1.9 CDE
SC 109-9	281 cd	231 b	425 ab	312 C	1.8 cd	2.4 ab	2.3 a	2.2 ABCD
CK 60	344 bc	242 b	358 bc	315 C	2.2 bc	2.1 bc	2.2 a	2.2 ABCD
KS 5	188 ef	155 cde	215 efg	186 E	1.6 d	1.7 c	2.0 a	1.8 E
Martin	416 a	336 a	331 cd	361 B	2.8 a	2.2 ab	2.1 a	2.4 A
NP	170 ef	115 e	192 g	159 E	1.8 cd	2.1 ab	1.7 ab	1.9 CDE
SC 33-9-8-E4	119 f	122 e	208 fg	149 E	2.3 b	2.6 a	2.1 a	2.3 AB
Treatment means	250 B	218 B	314 A		2.0 A	2.3 A	1.9 A	

[†] Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 13. Top and root dry-matter yields of sorghum genotypes grown with different sources of N to induce Fe deficiency in nutrient solutions (Expt. 4).

Genotypes	Source of N							
	Top yield				Root yield			
	NO_3^-	NH_4^+	$(NO_3^-+NH_4^+)$	Genotype means	NO_3^-	NH_4^+	$(NO_3^-+NH_4^+)$	Genotype means
	mg/plant				mg/plant			
KS 56	375 a[†]	356 a	377 a	369 A	139 ab	147 a	161 a	149 A
TX 414	326 b	315 ab	268 bc	302 B	168 a	152 a	101 c	140 A
TX 7078	273 c	246 c	300 b	273 BC	112 bc	99 c	149 a	120 B
TX 07	240 c	194 d	205 c	213 E	102 c	82 c	87 c	90 B
Norghum	336 b	263 b	234 c	278 BC	135 b	98 c	92 c	108 B
Caprock	244 c	222 c	329 ab	265 BCD	101 c	90 c	148 a	113 B
SD 102	241 c	302 b	181 c	241 CDE	103 c	140 ab	79 cd	107 BC
TX 412	255 c	206 d	224 c	228 DE	78 dc	110 bc	119 bc	113 B
SC 369-3-1JB	273 c	261 b	128 d	220 E	93 c	116 bc	47 d	85 C
Treatment means	285 A	263 A	249 A		118 A	115 A	109 A	

[†] Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

NO_3^- and (NO_3^- + NH_4^+) than under NH_4^+ alone.

In experiment 4, KS 56 produced the highest top dry-matter (369.4 mg/plant) and TX 07 produced the lowest top dry-matter (212.9 mg/plant) (Table 13). The genotype x treatment interactions were significant with KS 56 outyielding all the other genotypes under all treatments. In experiment 5, NB 3494 and KS 57 gave much higher yields than the remaining genotypes tested in this experiment (Table 15). TX 07 and TX 7078 produced the lowest top dry-matter yields.

The treatment effects on root dry-matter yields were significant only for the genotypes in experiment 3 (Table 11). Plants grown with (NO_3^- + NH_4^+) produced higher root dry matter than plants grown with either NO_3^- or NH_4^+. Root dry-matter production for the N treatments were similar for the genotypes in experiments 4 and 5 (Tables 13 and 15). However, within each experiment, the genotypes differed in root dry-matter yields. Roots of Redlan and Wheatland were higher than most of the genotypes in experiment 3 (Table 11); KS 56 and TX 414 had higher root weights than the remaining genotypes in experiment 4 (Table 13) and KS 57 and TX 415 gave higher root weights than most of the genotypes in experiment 5 (Table 15). Similar observations were noted for total dry-matter yields (Tables 12, 14, and 16). In experiment 3, yields differed among treatments. In the three experiments, genotypes showed differences in total dry-matter production.

5. Top/Root Dry Matter Ratios

Top/root dry-matter ratios reflect how the roots or aerial organs of the plant have been affected by the treatments and differences among genotypes in the production of root or top material.

Table 14. Total dry-matter yields and top/root dry-matter ratios of sorghum genotypes grown with different sources of N to induce Fe deficiency in nutrient solutions (Expt. 4).

Genotypes	Source of N							
	Total yield				Top/root ratio			
	NO_3^-	NH_4^+	$(NO_3^-+NH_4^+)$	Genotype means	NO_3^-	NH_4^+	$(NO_3^-+NH_4^+)$	Genotype means
	mg/plant							
KS 56	514 a†	504 a	537 a	518 A	2.7 ab	2.4 b	2.4 ab	2.5 ABC
TX 414	450 abc	434 ab	367 bc	420 B	1.9 c	2.1 bc	2.6 a	2.2 CD
TX 7078	352 cd	345 bc	448 ab	381 BCD	2.4 b	2.5 a	2.0 b	2.3 BCD
TX 07	341 d	276 c	292 c	303 E	2.4 b	2.4 a	2.4 ab	2.4 ABC
Norghum	471 ab	361 bc	326 c	386 BC	2.5 b	2.7 a	2.5 a	2.6 AB
Caprock	345 cd	291 c	477 a	371 BCD	2.4 b	2.5 a	2.2 b	2.4 ABC
SD 102	344 cd	442 ab	259 cd	348 CDE	2.3 bc	2.2 bc	2.3 ab	2.3 BCD
TX 412	333 d	283 c	343 bc	320 DE	2.3 bc	1.9 c	1.9 b	2.0 D
SC 369-3-1JB	366 bcd	377 bc	175 d	306 E	3.0 a	2.3 b	2.7 a	2.7 A
Treatment means	392 A	368 A	358 A		2.4 A	2.3 A	2.4 A	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Fig. 4. pH changes in nutrient solution for sorghum genotypes grown with three sources of nitrogen (mean average of 14 genotypes).

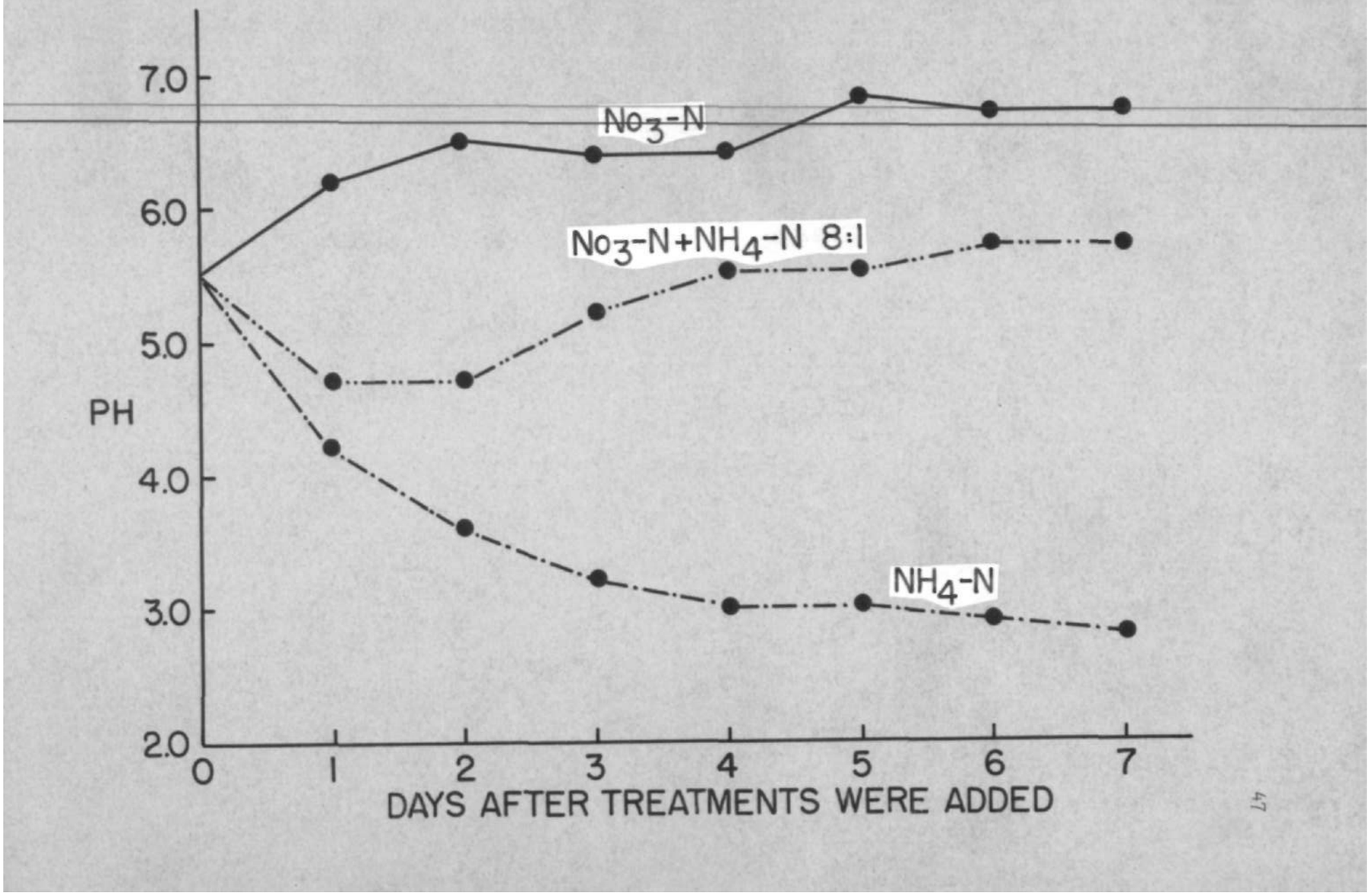


Table 15. Top and root dry-matter yields of sorghum genotypes grown with different sources of N to induce Fe deficiency in nutrient solutions (Expt. 5).

Genotypes	Source of N							
	Top yield				Root yield			
	NO_3^-	NH_4^+	$(NO_3^-+NH_4^+)$	Genotype means	NO_3^-	NH_4^+	$(NO_3^-+NH_4^+)$	Genotype means
	mg/plant				mg/plant			
KS 57	228 ab†	282 a	253 bc	254 A	134 a	136 a	137 ab	136 A
SC 29	169 cd	205 b	231 cd	201 BC	86 d	85 c	105 cd	92 C
TX 7078	167 cd	156 c	143 e	155 D	99 cd	77 c	92 d	89 C
TX 07	137 d	172 c	140 e	150 D	91 d	83 c	82 d	85 C
NB 9434	261 a	264 ab	288 a	270 A	118 cd	120 ab	132 abc	123 AB
SC 149	198 bc	172 c	162 e	178 CD	123 bc	95 bc	94 d	105 BC
SD 106	184 bc	229 b	205 d	206 BC	80 d	98 bc	102 bcd	93 C
TX 412	263 a	209 b	223 cd	232 AB	138 a	113 ab	116 bcd	123 AB
TX 415	219 b	214 b	275 ab	236 AB	143 a	113 ab	146 a	134 A
Treatment means	203 A	215 A	213 A		113 A	103 A	112 A	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 16. Total dry-matter yields and top/root dry-matter ratios of sorghum genotypes grown with different sources of N to induce Fe deficiency in nutrient solutions (Expt. 5).

Genotypes	Source of N							
	Total yield				Top/root ratio			
	NO_3^-	NH_4^+	$(NO_3^-+NH_4^+)$	Genotype means	NO_3^-	NH_4^+	$(NO_3^-+NH_4^+)$	Genotype means
	mg/plant							
KS 57	363 ab†	417 a	390 a	390 A	1.7 b	2.1 ab	1.9 ab	1.9 B
SC 29	255 c	296 cd	335 b	295 BCD	2.0 ab	2.5 a	2.2 a	2.2 A
TX 7078	266 c	233 d	235 c	245 CD	1.7 b	2.1 ab	1.6 b	1.8 B
TX 07	230 c	254 d	222 c	236 D	1.6 b	2.1 ab	1.8 ab	1.8 B
NB 9434	379 a	357 b	420 a	383 A	2.3 a	2.2 ab	2.2 a	2.2 A
SC 149	321 b	267 d	253 c	282 BCD	1.6 b	1.9 b	1.7 ab	1.7 B
SD 106	264 c	327 bc	310 b	300 BC	2.3 a	2.3 ab	2.0 ab	2.2 A
TX 412	402 a	322 bc	305 b	343 AB	1.9 ab	1.9 b	1.9 ab	1.9 B
TX 415	362 ab	327 bc	421 a	370 A	1.6 b	1.9 b	1.9 ab	1.8 B
Treatment means	316 A	315 A	321 A		1.8 A	2.1 A	1.9 A	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

In both experiments 1 and 2, significant differences among treatments were observed for top/root dry-matter ratios (Tables 8 and 10). Ratios were higher when plants were grown with added P than when they were grown under the control conditions. The differences between the control and the two P treatments could have been caused by enhanced top growth under the P treatments. The genotypes also differed, Redlan had a much higher ratio than SC 134, Martin, NP, and Plainsman in the first experiment, and SC 33-9-8-E4 had the highest ratio (2.2), and C 7.4 had the lowest ratio (1.4) in the second experiment.

Nitrogen treatment effects on top/root dry-matter ratios were not different (Tables 12, 14, and 16). However, genotypes differed in each experiment. In experiment 3, the top/root dry-matter ratios were highest for Martin and lowest for TAM 428 and KS 5. SC 369-3-1JB had a higher top/root dry-matter ratio than the remaining genotypes in experiment 4, and SC 29, NB 3494, and SD 106 had higher top/root dry-matter ratios than the remaining genotypes in experiment 5. In experiments 3, 4, and 5, treatment x genotype interactions were not significant.

6. Effect of Plant Age on Screening for 'Fe-efficiency'

This experiment was conducted to determine the effect of plant age (7, 10, and 14-day-old seedlings) on the induction of Fe deficiency of plants screened for 'Fe-efficiency.' Two treatments were used to induce Fe deficiencies in the plants: (1) NO_3^- as a source of N at 1.4 mM N/plant and (2) P added at 0.39 mM.

a. Iron deficiency symptoms

When treatments were added to 7 and 10-day seedlings, most

genotypes developed Fe deficiencies earlier when grown with NO_3^- than when P was added. Plants became Fe deficient within 3 days when grown with NO_3^- compared to 5 days when grown with added P. Under the NO_3^- treatment, 7- and 10-day old seedlings of SC 118-15E, Wheatland, TAM 428, Redbine 60, and Redlan became Fe deficient 3 days after treatments had been added; whereas only SC 109-9 was Fe deficient under the added P treatment. Three genotypes (SC 109-9, CK 60, and Martin) and four genotypes (SC 118-15E, SC 500-6-1, TAM 428, and Redlan) developed some Fe deficiency under NO_3^- and P, respectively, after 4 days. After the plants had been in solution for 5 days, SC 134 and SC 500-6-1 developed some Fe deficiency in NO_3^- solutions and Wheatland, CK 60, Martin, and SC 134 became Fe deficient in P treated solutions. Plainsman, KS 5, NP, and SC 33-9-8-E4 did not become Fe deficient in NO_3^- solutions until after 6 days. Concomitantly, Redbine 60, Plainsman, KS 5, NP, and SC 33-9-8-E4 took 6 days to become Fe deficient when grown in the added P solutions. Iron deficiency ratings of the genotypes at 14 and 17 days of age (termination of the experiment) are given in Tables 17 and 18. The genotypes differed within each treatment. In the NO_3^- treatment, the most severe Fe deficiency symptoms were noted on SC 118-15E, Wheatland, and TAM 428. SC 33-9-8-E4, NP, SC 109-9, and Plainsman had the least severe Fe deficiency symptoms. In the P treatment, SC 118-15E, Wheatland, Redlan, and Redbine 60 had the most severe Fe deficiency symptoms, while SC 33-9-8-E4, NP, KS 5, CK 60, SC 109-9, and Plainsman had the least Fe deficiency symptoms. Of the plants treated at 10 days of age, the genotypes also differed within each treatment (Table 18). SC 118-15E and Redlan developed the most severe Fe deficiency symptoms in NO_3^-

Table 17. The degree of Fe deficiency in the upper leaves and top/root dry-matter ratios of sorghum genotypes treated with NO_3^- and P to induce Fe deficiency in 7-day-old seedlings (Expt. 6).

Genotypes	Treatment to induce Fe deficiency			
	Fe deficiency rating+		Top/root ratio	
	NO_3^-	0.39 mM P	NO_3^-	0.39 mM P
SC 118-15E	3.8 a†	1.8 a	1.6 a	2.1 b
SC 134	1.5 def	1.0 abc	1.4 a	1.8 b
SC 500-6-1	2.3 bcd	1.0 abc	2.0 a	2.5 b
Wheatland	3.5 a	1.3 ab	1.6 a	2.2 b
TAM 428	3.0 ab	0.8 bc	1.5 a	1.8 b
Redbine 60	2.0 cde	1.3 ab	1.5 a	2.2 b
Redlan	2.5 bc	1.3 ab	1.9 a	2.2 b
Plainsman	1.0 fg	0.5 bc	1.7 a	1.8 b
SC 109-9	1.0 fg	0.5 bc	2.0 a	2.3 b
CK 60	2.0 cde	0.5 bc	2.0 a	1.9 b
KS 5	1.3 efg	0.5 bc	1.4 a	2.5 b
Martin	2.3 bcd	0.8 bc	1.6 a	6.9 a
NP	1.0 fg	0.5 bc	1.8 a	1.8 b
SC 33-9-8-E4	0.5 g	0.3 c	1.7 a	2.2 b
Treatment means	2.0 A	0.8 B	1.7 A	2.4 A

+ 0 = No Fe deficiency (green); 4 = Severe Fe deficiency (severe interveinal chlorosis).

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 18. The degree of Fe deficiency in the upper leaves and top/root dry-matter ratios of sorghum genotypes treated with NO_3^- and P to induce Fe deficiency in 10-day-old seedlings (Expt. 6).

Genotypes	Treatment to induce Fe deficiency			
	Fe deficiency rating+		Top/root ratio	
	NO_3^-	0.39 mM P	NO_3^-	0.39 mM P
SC 118-15E	3.5 a†	2.3 abc	1.9 b	3.1 ab
SC 134	1.8 cde	1.8 abcd	1.8 b	2.0 ab
SC 500-6-1	2.3 bcd	1.5 bcde	2.3 b	2.4 ab
Wheatland	2.0 bcde	2.0 abc	2.0 b	2.5 ab
TAM 428	2.5 abc	2.5 ab	4.5 a	2.8 ab
Redbine 60	2.0 bcde	2.5 ab	2.0 b	2.2 ab
Redlan	3.0 ab	2.8 a	2.5 b	3.2 ab
Plainsman	1.3 de	0.5 e	2.2 b	1.9 ab
SC 109-9	2.4 bc	1.3 cde	1.8 b	3.0 ab
CK 60	1.3 de	1.3 cde	2.2 b	2.5 ab
KS 5	1.3 de	0.8 de	1.6 b	2.5 ab
Martin	2.3 bcd	2.0 abc	1.9 b	2.7 ab
NP	1.5 cde	0.5 e	2.0 b	1.7 b
SC 33-9-8-E4	1.0 e	0.8 de	1.9 b	3.7 a
Treatment means	2.0 A	1.6 A	2.2 A	2.6 A

+ 0 = No Fe deficiency (green); 4 = Severe Fe deficiency (severe interveinal chlorosis).

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 19. The degree of Fe deficiency in the upper leaves and top/root dry-matter ratios of sorghum genotypes treated with NO_3^- and P to induce Fe deficiency in 14-day-old seedlings (Expt. 6).

Genotypes	Treatment to induce Fe deficiency			
	Fe deficiency rating+		Top/root ratio	
	NO_3^-	0.39 mM P	NO_3^-	0.39 mM P
SC 118-15E	0.0 a†	3.0 ab	1.8 b	2.2 a
SC 134	0.0 a	2.0 cde	1.6 b	2.4 a
SC 500-6-1	0.0 a	2.3 cd	2.0 b	2.4 a
Wheatland	0.0 a	3.0 ab	1.5 b	2.6 a
TAM 428	0.0 a	1.8 def	1.5 b	2.2 a
Redbine 60	0.0 a	2.5 bc	1.5 b	2.6 a
Redlan	0.0 a	3.3 a	1.8 b	2.3 a
Plainsman	0.0 a	1.3 f	1.9 b	1.9 a
SC 109-9	0.5 a	2.3 cd	1.9 b	2.6 a
CK 60	0.0 a	1.5 ef	1.8 b	3.0 a
KS 5	0.0 a	1.5 ef	1.8 b	2.5 a
Martin	0.3 a	3.5 a	2.1 ab	2.5 a
NP	0.0 a	2.0 cde	3.1 a	2.7 a
SC 33-9-8-E4	0.0 a	1.5 ef	1.7 b	2.2 a
Treatment means	0.05 B	2.2 A	1.9 A	2.4 A

+ 0 = No Fe deficiency (green); 4 = Severe Fe deficiency (severe interveinal chlorosis).

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

solutions, while SC 33-9-8-E4, KS 5, CK 60, and Plainsman had the least Fe deficiency symptoms. In the P treatment, only Redlan developed severe Fe deficiency symptoms, and Plainsman, KS 5, NP, and SC 33-9-8-E4 had only slight Fe deficiency.

When P treatments were added to 14-day-old seedlings, 10 of the 14 genotypes had Fe deficiency symptoms within 2-3 days. Two of the remaining genotypes (CK 60 and SC 33-9-8-E4) developed Fe deficiency on the fourth day and the other two genotypes (TAM 428 and Plainsman) developed Fe deficiency symptoms only after the fifth day. In the NO_3^- treatment, only two genotypes (SC 109-9 and Martin) showed any Fe deficiency at the end of 21 days (termination of the experiment). Treatment effects were markedly different for 7- and 10-day-old plants compared to 14-day-old plants (Tables 17, 18, and 19). For plants that received treatments at 7 days of age, those grown with NO_3^- were 2.5 times more Fe deficient as those grown with P. For 10-day-old seedlings, the treatment effects were similar in terms of Fe deficiency symptoms (Table 18). Plants treated at 14 days of age became Fe deficient when grown in the added P treatment but remained green when grown in NO_3^- solution (Table 19). Only SC 109-9 and Martin developed slight Fe deficiency in NO_3^- solutions, and essentially no differences were noted among genotypes. In the P treatment, SC 118-15E, Wheatland, Redlan, and Martin developed severe Fe deficiency symptoms; whereas Plainsman, CK 60, KS 5, and SC 33-9-8-E4 developed only slight Fe deficiency symptoms.

b. pH of nutrient solutions

Figures 7, 8, and 9 show the changes in pH of the growth media with time after plants were put into nutrient solutions. The trends of

Fig. 7. Changes in pH of nutrient solution for sorghum genotypes grown with either nitrate-N or phosphorus added when plants were 7 days old (mean average of 14 genotypes).

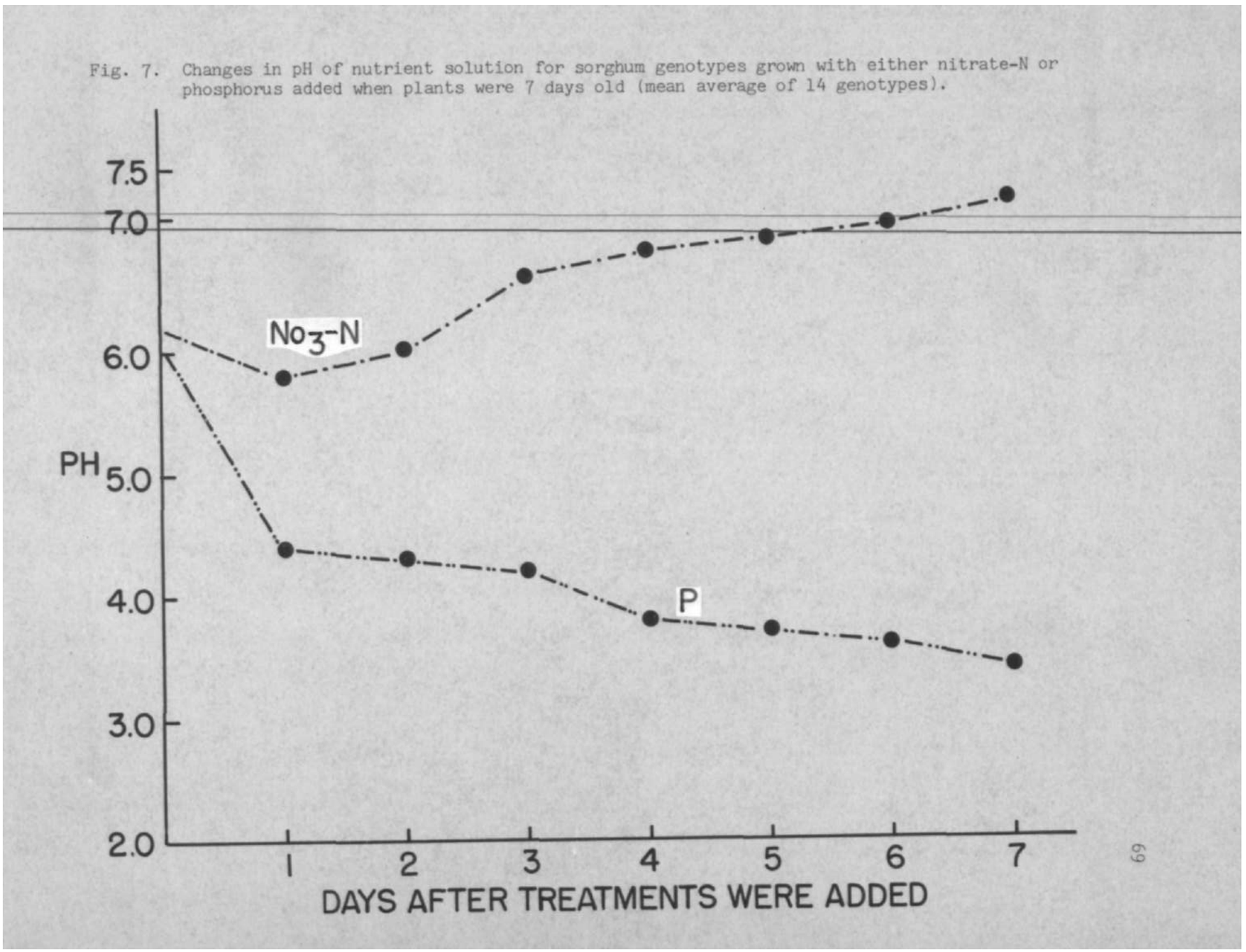


Fig. 8. Changes in pH of nutrient solution for sorghum genotypes grown with either nitrate-N or phosphorus added when plants were 10 days old (mean average of 14 genotypes).

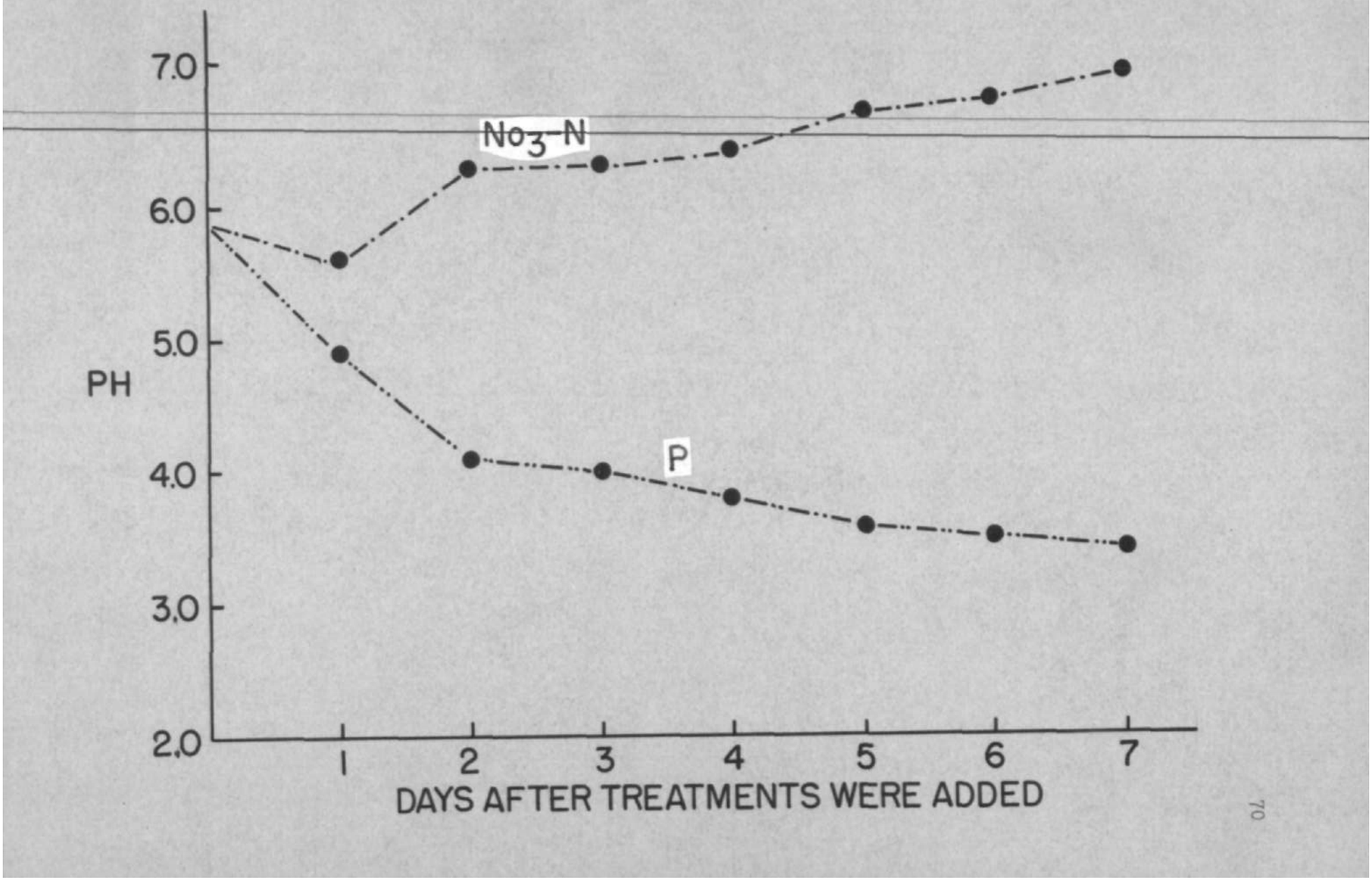
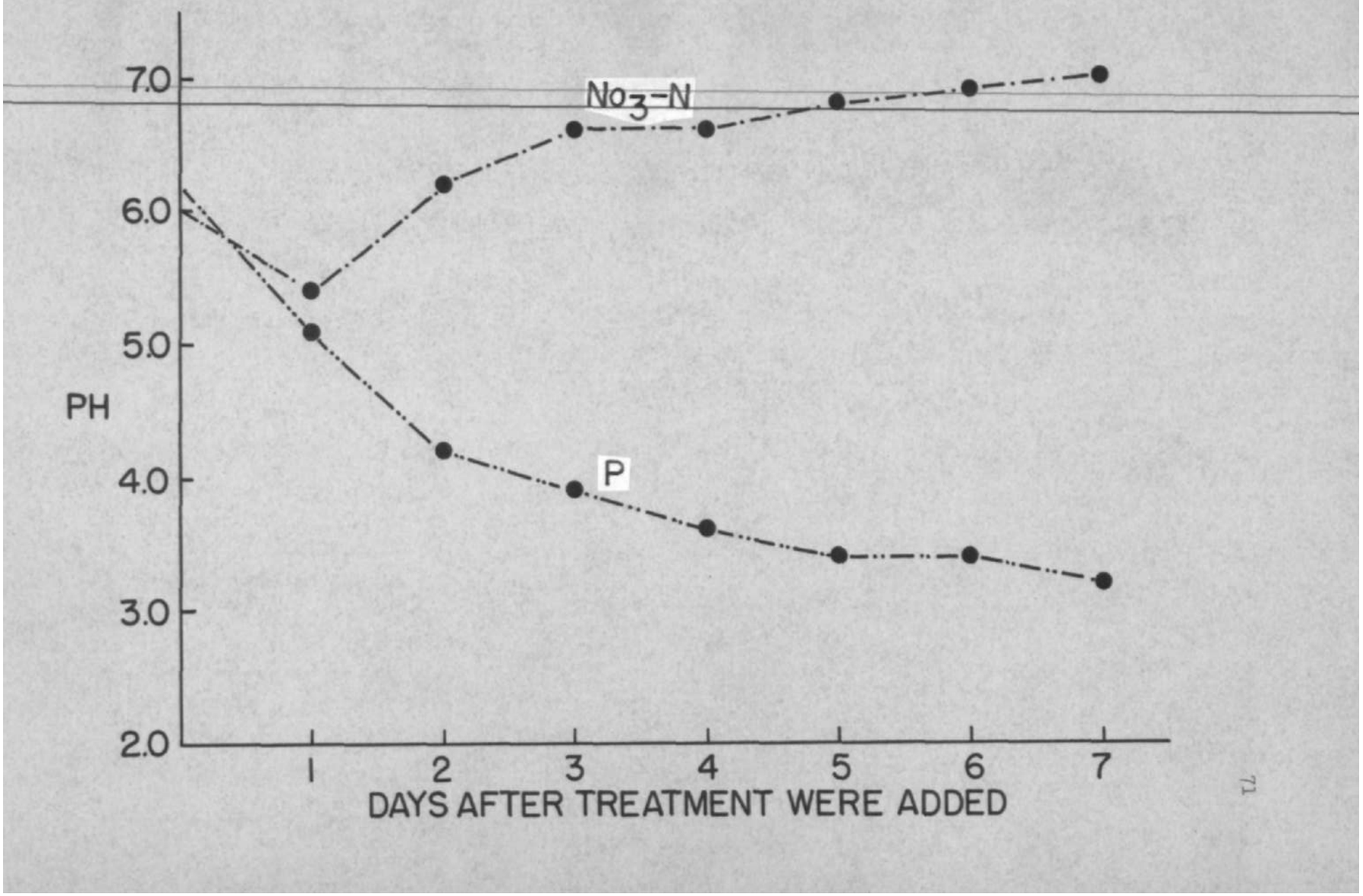


Fig. 9. Changes in pH of nutrient solution for sorghum genotypes grown with either nitrate-N or phosphorus added when plants were 14 days old (mean average of 14 genotypes).



both treatments were similar irrespective of seedling age. The pH decreased in solutions with added P treatment and increased in NO_3^- solutions after the second day.

c. Dry-matter yields

The 7-day-old seedlings produced higher top dry-matter yields when treated with P than when grown with NO_3^- (Table 20). However, root and total dry-matter production was similar under the two treatments. Iron deficiency appears to affect top growth much more than root growth. Treatment effects for 10- and 14-day-old seedlings were not different (Tables 21 and 22). Regardless of age and the treatment used to induce Fe deficiency, the genotypes differed in top, root, and total dry-matter yields. At 7 days, Redlan outyielded the other genotypes for top and total dry-matter under both treatments. Redlan also outyielded the other genotypes for root dry-matter when plants were grown in the P treatment but not in the NO_3^- treatment. In the NO_3^- treatment, root dry-matter yields of Redlan were similar to many of the other genotypes.

In the P treatment, TAM 428 and Redlan outyielded the remaining genotypes for top dry-matter. Martin produced the highest root dry-matter. Total dry-matter was higher for Redlan than the other genotypes. Plainsman had the lowest total dry-matter yields.

When 14-day-old seedlings received treatments, Redlan had higher top and total dry-matter yields than the other genotypes. In the P treatment, Redlan root dry-matter yields were similar to those produced by SC 118-15E but higher than those of the other genotypes. SC 33-9-8-E4 had the lowest top dry-matter yields in NO_3^- solutions, and Plainsman had the lowest top dry-matter yields in the P treated solutions. The lowest

Table 20. Top, root and total dry-matter yields of sorghum genotypes treated with NO_3^- and P to induce Fe deficiency in 7-day-old seedlings (Expt. 6).

Genotypes	Treatment to induce Fe deficiency					
	Top		Root		Total	
	NO_3^-	0.39 mM P	NO_3^-	0.39 mM P	NO_3^-	0.39 mM P
	mg/plant					
SC 118-15E	38 b[†]	45 bc	23 abc	21 b	61 b	66 b
SC 134	32 bc	39 cd	23 abc	22 b	54 bc	61 bc
SC 500-6-1	30 bcd	35 cde	15 cde	15 bcd	45 cde	50 cd
Wheatland	35 b	42 bc	22 abc	19 bcd	56 bc	61 bc
TAM 428	30 bcd	36 cde	21 abcd	20 bc	50 bcd	56 bc
Redbine 60	30 bcd	40 cd	16 bcde	19 bcd	50 bcd	58 bc
Redlan	54 a	71 a	28 a	33 a	82 a	104 a
Plainsman	22 cd	26 efg	13 de	14 bcd	35 ef	40 de
SC 109-9	31 bcd	33 def	16 bcde	15 bcd	46 cde	47 cde
CK 60	35 b	36 cde	18 bcde	19 bcd	53 bc	60 bc
KS 5	22 cd	39 cd	16 bcde	16 bcd	37 def	54 bc
Martin	39 bc	53 b	24 ab	15 cd	63 b	68 b
NP	19 d	22 g	11 e	12 d	30 f	34 e
SC 33-9-8-E4	23 cd	24 gf	13 e	11	36 def	35 e
Treatment means	31 B	39 A	18.4 A	18 A	50 A	56 A

[†] Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 21. Top, root and total dry-matter yields of sorghum genotypes treated with NO_3^- and P to induce Fe deficiency in 10-day-old seedlings (Expt. 6).

Genotypes	Treatment to induce Fe deficiency					
	Top		Root		Total	
	NO_3^-	0.39 mM P	NO_3^-	0.39 mM P	NO_3^-	0.39 mM P
	mg/plant					
SC 118-15E	118 b†	103 ab	65 ab	34 abc	182 b	136 abc
SC 134	87 bce	83 abc	48 bc	41 abc	135 bc	124 bcd
SC 500-6-1	97 bc	83 abc	43 cd	34 abc	141 bc	117 bcd
Wheatland	97 bc	88 abc	47 bc	35 abc	143 bc	122 bcd
TAM 428	83 bcd	120 a	23 d	43 ab	107 cd	163 ab
Redbine 60	82 bcd	67 bc	40 cd	33 abc	122 cd	100 cd
Redlan	178 a	115 a	72 a	44 abc	250 a	186 a
Plainsman	58 cd	46 c	27 cd	24 bc	85 cd	70 d
SC 109-9	66 cd	82 abc	38 cd	28 bc	104 cd	110 bcd
CK 60	90 bcd	98 ab	43 cd	40 abc	133 bc	138 abc
KS 5	66 cd	66 bc	40 cd	27 bc	106 cd	96 cd
Martin	121 b	110 ab	64 ab	52 a	185 b	162 ab
NP	48 d	53 c	25 d	32 abc	73 d	85 cd
SC 33-9-8-E4	65 cd	78 abc	33 cd	20 c	96 cd	97 cd
Treatment means	90 A	85 A	43 A	35 B	133 A	122 A

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 22. Top, root and total dry-matter yields of sorghum genotypes treated with NO_3^- and P to induce Fe deficiency in 14-day-old seedlings (Expt. 6).

Genotypes	Treatment to induce Fe deficiency					
	Top		Root		Total	
	NO_3^-	0.39 mM P	NO_3^-	0.39 mM P	NO_3^-	0.39 mM P
	mg/plant					
SC 118-15E	202 bc†	211 bc	118 bcd	109 ab	320 b	320 bc
SC 134	144 de	194 cd	87 cdefg	85 bc	232 bc	279 bcd
SC 500-6-1	164 cd	205 bcd	93 bcdefg	87 bc	257 bc	292 bc
Wheatland	208 bc	203 bcd	143 ab	80 bc	351 b	283 bcd
TAM 428	209 bc	158 cdef	138 bc	76 bc	348 b	234 bcd
Redbine 60	139 de	169 cdef	98 bcdefg	66 bc	237 bc	235 bcd
Redlan	327 a	341 a	187 a	152 a	515 a	493 a
Plainsman	119 de	95 g	63 efg	50 c	333 b	145 d
SC 109-9	154 cde	148 defg	80 defg	56 bc	233 bc	204 bcd
CK 60	145 de	182 cde	81 defg	62 bc	226 bc	244 bcd
KS 5	142 de	123 fg	81 defg	49 c	224 bc	172 d
Martin	239 b	253 b	113 bcde	100 bc	352 b	353 b
NP	114 de	133 efg	43 g	49 c	157 c	182 d
SC 33-9-8-E4	97 e	120 fg	57 g	56 bc	154 c	176 d
Treatment means	172 A	181 A	99 A	77 A		

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

root dry-matter was produced by NP and KS 5 under the NO_3^- and P treatments, respectively.

d. Top/Root Dry-Matter Ratios

Irrespective of plant age, treatment effects on top/root dry-matter were similar. The ratios tended to be slightly higher for plants grown in the P treatment than for plants grown in the NO_3^- treatment. Seven-day-old treated genotypes did not differ in top/root dry-matter ratios when grown in the NO_3^- treatment (Table 17). However, in the P treatment, Martin had a higher ratio than other genotypes. When NO_3^- treatment was added to 10-day-old seedlings, TAM 428 had a higher top/root dry-matter ratio than the other genotypes (Table 18). The top/root dry-matter ratios also differed among genotypes that received treatments at 14 days (Table 19). Of plants grown in NO_3^- treatment, NP had a higher top/root dry-matter ratio than the other genotypes.

7. Discussion

Many nutrient imbalances such as high $CaCO_3$, Mn, Zn, Cu, P, and other environmental factors such as light quality (Brown et al., 1979), temperature, moisture, and oxygen tension (Burtch et al., 1948; Wallihan et al., 1961; Wallace et al., 1981; Clark et al., 1981) will induce Fe deficiency in many plants. With these factors being optimum, cultivars of many crop species have been identified for tolerance to Fe deficiency. For example, Hawkeye soybean (Brown et al., 1960), Coker 227 and Coker 74-22 oat cultivars (MacDaniel and Dunphy, 1978), sorghum (Mikesell et al., 1973), WF 9 corn (Clark and Brown, 1974), and T 3238FER tomato (Brown et al., 1974) have been identified as 'Fe-efficient.'

Sorghum is one of the more susceptible crop plants to Fe deficiency (Brown et al., 1975). Cultivars or genotypes more tolerant to low Fe would be helpful in solving this problem in many of the sorghum growing areas of the world. In an effort to identify more 'Fe-efficient' sorghum genotypes, screening methods for 'Fe-efficiency' were devised and evaluated. Iron deficiencies were imposed on sorghum plants by the addition of $CaCO_3$ and P and growing plants with different sources of N in nutrient solutions.

In Experiments 1 and 2, sorghum genotypes differed in susceptibility to Fe deficiency depending upon the method used to induce the Fe stress. Since genotype x treatment interactions were significant, differences in genotype responses would be expected. When the plants were grown in $CaCO_3$ or P treatments, SC 118-15E developed the most severe Fe deficiency symptoms out of the U.S. genotypes used and SC 33-9-8-E4 developed the least severe Fe deficiency symptoms. The Nigerian genotypes were usually more Fe deficient under the high P treatment than under the $CaCO_3$. Genotypes, however, showed Fe deficiency symptoms earlier under $CaCO_3$ than under P treatments. Under both P treatments, FFB-L had the most severe Fe deficiency symptoms and L 187 had the least Fe deficiency chlorosis under the same P treatments of the Nigerian genotypes screened. From these two experiments, the P treatment to induce Fe deficiency symptoms in sorghum plants was a better method for screening sorghum genotypes for 'Fe-efficiency.' Both P treatments were about as effective (Table 23).

In Experiments 3, 4, and 5, plants developed more severe Fe deficiency chlorosis when supplied with NO_3^- alone than when they received

Table 23. Distribution of genotypes based on the degree of Fe deficiency symptoms induced in various Fe stress treatments.

Fe deficiency ratings after 7 days	Fe stress treatments				
	0.17 mM P	0.39 mM P	0.15 mM $CaCO_3$	NO_3^-	NH_4^+
	No. of genotypes in each category+				
0 -0.5	6	4	11	3	4
0.6-1.0	3	6	6	1	8
1.1-1.5	9	8	8	4	9
1.6-2.0	6	4	1	2	2
2.1-2.5	1	2	0	8	5
2.6-3.0	1	2	0	6	4
3.1-3.5	0	0	0	7	0
3.6-4.0	0	0	0	1	0

+ 26 genotypes were screened by the addition of P and $CaCO_3$ and 32 were screened by using different N sources.

either NH_4^+ or (NO_3^- + NH_4^+). The Fe deficiency symptoms also appeared earlier in plants grown with NO_3^- than in plants that received NH_4^+ or both N sources. The most Fe deficient genotypes were Redlan, CK 60, SC 109-9, KS 56, TX 414, Caprock, KS 57, TX 7078, and SC 29 when the plants were grown with NO_3^-. The most Fe deficient genotypes when plants were grown with NH_4^+ were SC 109-9, Redlan, Wheatland, KS 56, SC 369-3-1JB, TX 415, TX 07, and NH 3494. Genotypes with the least severe Fe deficiency symptoms, when grown with NO_3^-, were SC 33-9-8-E4, Plainsman, TX 412, Norghum, SD 102, and SC 149. When grown with NH_4^+, KS 56, Plainsman, SC 33-9-8-E4, TX 412, SD 102, Norghum, SD 106, and SC 149 had the least Fe deficiency symptoms.

In experiment 6, younger seedlings (7 and 10 days old) became Fe deficient faster when grown with NO_3^- than with added P. In addition, the 7-day-old seedlings were more Fe deficient in the NO_3^- treatment than in the P treatment. Plants treated with NO_3^- at 14 days developed only slight Fe deficiency. Phosphorus treated plants showed good differential Fe deficiency symptoms even at 14 days of age. These observations can be possibly explained by how the two treatments induced Fe deficiency in the sorghum genotypes. The NO_3^- effect was through pH increases in the growth medium, and excess P induced Fe deficiency by making Fe unavailable by the forming insoluble Fe-P compounds and subsequent precipitation of the Fe in the growth medium (Mengel and Kirkby, 1979). Phosphorus may have also inactivated Fe within the plant root tissue. Table 24 shows the frequency distribution of the genotypes within each Fe deficiency class rating. The distributions were only similar for 10-day-old seedlings. The plants treated at 14 days of age had the ability to get more Fe or make more Fe available because of their larger root systems than in the younger plants.

24. Distribution of genotypes based on the degree of Fe deficiency symptoms at 7, 10 and 14 days of age.

Fe deficiency rating after 7 days	Seedling age (days)	Fe stress treatments	
		NO_3^-	0.39 mM P
0 -0.5	7	1	6
0.6-1.0	7	3	4
1.1-1.5	7	2	3
1.6-2.0	7	2	1
2.1-2.5	7	3	0
2.6-3.0	7	1	0
3.1-3.5	7	1	0
3.6-4.0	7	1	0
0 -0.5	10	0	2
0.6-1.0	10	1	2
1.1-1.5	10	4	3
1.6-2.0	10	3	3
2.1-2.5	10	4	3
2.6-3.0	10	1	1
3.1-3.5	10	1	0
3.6-4.0	10	0	0
0 -0.5	14	14	0
0.6-1.0	14	0	0
1.1-1.5	14	0	4
1.6-2.0	14	0	2
2.1-2.5	14	0	3
2.6-3.0	14	0	2
3.1-3.5	14	0	2
3.6-4.0	14	0	0

If NO_3^- is to be used as a screening method, plants younger than 14 days old should be used or plants need to remain longer than 7 days in the NO_3^- solutions before 'Fe-efficiency' is assessed. Seven- to 14-day-old plants could be screened in P treatments with good results.

Reductions in dry matter caused by Fe deficiency were significant only when plants were grown with 0.39 mM P in solution but were not large because of the limited time the Fe stress was imposed. To use dry-matter yields as a parameter of 'Fe-efficiency' in young plants, a longer Fe deficiency stress period should be used. In Experiments 1 and 2, genotypes that produced higher top dry-matter yields tended to have higher Fe deficiency ratings. This is to be expected due to a dilution effect. The treatments had little or no effect on root dry-matter yields. Plants grown with (NO_3^- + NH_4^+) produced higher top dry-matter yields than plants grown with either NO_3^- or NH_4^+ alone. The root dry-matter yields were higher in the (NO_3^- + NH_4^+) and NO_3^- treatments than in the NH_4^+ treatment. The lower root dry-matter yields, despite increased Fe availability in the NH_4^+ treatment, could have been caused by either NH_3^- toxicity or the acid pH. Some elements are known to be limited for plant use under these conditions.

Table 23 shows the frequency distribution of the genotypes screened under the various treatments. It is evident from this table that the frequency distribution for the genotypes screened in Experiments 1 and 2 was similar under the two P treatments. However, the distribution was different for the $CaCO_3$ treatment. Most genotypes fell within the lowest Fe deficiency rating. Only one genotype received a rating higher than 1.5 in the $CaCO_3$ treatment, but eight genotypes got a higher Fe deficiency rating in the P treatments.

Table 25. Ranking of sorghum genotypes based on the degree of Fe deficiency ratings in the Fe stress treatments.

Treatment	Expt. No.	Genotype classes	
		'Fe efficient'	'Fe inefficient'
0.15 mM $CaCO_3$	1	SC 33-9-8-E4, Plainsman, KS 5	SC 118-15E, Redlan, Martin
	2	RZ 1, L 181, FFB-L	H.P 3, L 187, L 1449
0.17 mM P	1	SC 33-9-8-E4, NP, KS 5	SC 118-15E, Redlan, SC 500-6-1
	2	RZ 1, KANO L.1, L 187	FFB-L, C 7.4, SK 5912
0.39 mM P	1	SC 33-9-8-E4, NP, Plainsman	SC 118-15E, Martin, CK 60
	2	RZ 1, L 181, KANO L.1	FFB-L, C 7.4, H.P 3
NO_3^-	3	Plainsman, SC 33-9-8-E4	Redlan, CK 60, SC 109-9
	4	TX 412, Norghum, SD 102	KS 56, TX 414, Caprock
	5	SD 102, SC 149	KS 57, TX 7078, SC 29
NH_4^+	3	KS 5, Plainsman, SC 33-9-8-E4	SC 109-9, Redlan, Wheatland
	4	TX 412, SD 102, Norghum	KS 56, SC 369-3-1JB
	5	SD 106, SC 149	TX 415, TX 07, NB 9434

Table 26. Fe efficiency ranking of sorghum genotypes based on total dry-matter produced under various Fe stress treatments.

Category	Dry-matter yields	Treatment			
		$CaCO_3$	0.39 mM P	NO_3^-	NH_4^+
	(% of highest)				
Fe efficient	86-100	Martin, C 7.4, FFB-L, L 1449, YG 5760	SC 118-15E, FFB-L, SK 5912	Redlan, Martin, CK 60, KS 56, Norghum, TX 414, NB 9434, TX 412, KS 57, TX 415	Martin, Redlan, Wheatland, KS 56, TX 414, SD 102, KS 57, NB 9434
	71-85	SC 118-15E, CK 60, SC 500-6-1, TAM 428, Redlan, SK 5912, H.P 3	Martin, CK 60, L 1449, YG 5760	SC 29	SC 134, CK 60, SC 369-3-1JB, SD 106, TX 415, TX 412, SC 29
	56-70	RZ 1	SC 134, TAM 428, Redlan	SC 118-15E, SC 500-6-1, Wheatland, Redbine 60, SC 109-9, TX 7078, TX 07, Caprock, SD 106, SC 369-3-1JB	TAM 428, SC 118-15E, SC 500-6-1, Redbine 60, SC 109-9, TX 7078, Norghum, TX 07, SC 149
Fe inefficient	41-55	SC 134, Redbine 60, KS 5, NP, L 187, KANO L.1	Redbine 60, NP, Wheatland, KS 5, L 187, C 7.4	SC 134, KS 5, TAM 428, Plainsman	Caprock
	0-40	Wheatland, Plainsman, SC 109-9, SC 33-9-8-E4, L 181	Plainsman, SC 33-9-8-E4, L 181, RZ 1	NP, SC 33-9-8-E4	Plainsman, NP, SC 33-9-8-E4, KS 5

In comparing the NO_3^- and NH_4^+ treatments, many genotypes received high Fe deficiency rating in the NO_3^- solutions, while most genotypes received the low ratings in the NH_4^+ solutions. Of the 32 genotypes grown with either source of N, 22 genotypes received an Fe deficiency rating higher than 2.0 in the NO_3^- treatment, but only nine genotypes received a similar rating when grown with NH_4^+. No genotype received a rating higher than 3.0 in the NH_4^+ treatment solution as compared to eight genotypes that received a rating higher than 3.0 in the NO_3^- treated solutions. Based on Fe deficiency ratings, the genotypes considered to be more 'Fe-efficient' and 'Fe-inefficient' when grown with the various treatments are shown in Table 25.

From these experiments, Fe deficiency can be induced in sorghum genotypes by the addition of excess $CaCO_3$ or P and by growing plants in NO_3^- or NH_4^+ treated solutions. The effectiveness of these treatments depends upon the rates used, the length of time plants are allowed to grow in treatment solutions, and the sorghum genotypes.

Using the total dry-matter produced under the various Fe stress treatments as a basis of 'Fe-efficiency,' Martin, Redlan, and SC 118-15E were the most 'Fe-efficient' genotypes (Table 26). TAM 428 could also be considered as 'Fe-efficient' among the U.S. genotypes. FFB-L and SK 5912 were the most 'Fe-efficient' among the Nigerian genotypes.

B. Relationship of Nutrient Solution to Soil Screening for 'Fe-Efficiency'

Screening sorghum for 'Fe-efficiency' in nutrient solutions allows for closer control of the growth medium conditions and for reduction of many complicating factors in soils. However, sorghum production

occurs in soils and the results obtained in nutrient solutions and soils must be related if the screening method is to be of value. The purpose of these experiments was to screen sorghum genotypes in soils that had previously been screened in nutrient solutions. These experiments were conducted in a greenhouse (see Materials and Methods).

Two low Fe (Bridget and Bridgeport) and one sufficient Fe (Sharpsburg) soils were used to grow the sorghum genotypes. The properties of each soil are given in Table 1. The low Fe soils are from western Nebraska and Kansas where Fe deficiency is a common problem to many crop plants. Both of the low Fe soils had high pH values (8.1) and low DTPA-extractable Fe. The sufficient Fe soil had a lower pH (6.8) and nearly 50 times more DTPA-extractable Fe than the low Fe soils. Although some differences in chemical properties were noted for each soil, the Fe level and pH were the most pronounced differences. The Bridget soil had about two times more Zn than the Bridgeport soil, and this element could possibly affect Fe uptake and use.

1. Growth of Plants

The genotypes were grown in two experiments. Fourteen genotypes were screened in the first experiment and 12 in the second. Seed germination was good except for SC 109-9, SC 369-3-1JB, TAM 428, and Norghum on Bridget soil. Plants grew well until Fe deficiencies developed. Iron deficiency was the only problem noted on plants grown in the low Fe soil. Some P deficiencies were noted on plants grown in the Sharpsburg soil.

2. Iron Deficiency Symptoms

Iron deficiencies began to appear in plants grown on the low Fe soils 5 days after plant emergence. Of the plants grown on the Bridget soil, SC 134, Wheatland, Redbine 60, SC 109-9, NP, SC 33-9-8-E4, SC 369-3-1JB, Norghum, and TX 07 developed Fe deficiency symptoms first. Redlan and Plainsman began to show Fe deficiency the next day and Martin the following day. Genotypes that developed Fe deficiency last in the Bridget soil were SC 118-15E, TAM 428, SD 106, KS 5, TX 7078, TX 414, and SC 500-6-1 (8-10 days after emergence). On the Bridgeport soil, Wheatland, SC 109-9, SC 369-3-1JB, TX 07, Norghum, and SC 33-9-8-E4 developed some Fe deficiency symptoms 5 days after emergence. SC 134 and SC 118-15E became Fe deficient the next day. Martin, Redbine 60, Redlan, Plainsman, and CK 60 developed the symptoms on day 9. Genotypes to show Fe deficiency last (days 10-13) in this soil were TAM 428, TX 7078, SD 106, KS 5, NP, and SC 500-6-1. Plants grown in the Sharpsburg soil remained green throughout the experiment. When the experiments were terminated, plants developed moderate to severe Fe deficiency symptoms (Tables 27 and 28). Plants were more Fe deficient on the Bridget soil than on the Bridgeport soil. The genotypes also differed in intensity of Fe deficiency symptoms. SC 109-9, SC 369-3-1JB, KS 56, Norghum, and SC 118-15E had more severe Fe deficiency symptoms than the other genotypes. The genotypes with least severe Fe deficiency symptoms were TAM 428, SC 500-6-1, and SD 106. The genotype x soil interactions were significant.

Table 27. Dry-matter yields of tops and the degree of Fe deficiency symptoms observed on the upper leaves of sorghum genotypes grown on Fe-sufficient and low Fe soils in the greenhouse (Expt. 1).

Genotype	Top yield				Average Fe deficiency ratings			
	Fe deficient soil		Fe-sufficient soil	Genotype means‡				
	Bridget+	Bridgeport+	Sharpsburg		Bridget+	Bridgeport+	Sharpsburg	Genotype means‡
	mg/plant							
SC 118-15E	87 a†	186 a	280 a	137 A	2.8 ab	1.6 abc	0.0 a	2.2 a
SC 134	61 c	120 c	219 c	91 D	1.8 d	0.8 de	0.0 a	1.3 B
SC 500-6-1	101 a	181 a	235 bc	141 A	0.4 e	0.3 ef	0.0 a	0.4 C
Wheatland	75 b	132 b	276 ab	104 CD	2.5 abc	1.8 ab	0.0 a	2.2 A
TAM 428	102 a	112 d	205 cd	107 CD	0.9 e	0.0 f	0.0 a	0.5 C
Redbine 60	71 b	114 d	180 d	93 D	2.0 cd	0.6 def	0.0 a	1.3 B
Redlan	75 b	126 cd	202 cd	101 CD	1.8 d	1.0 cd	0.0 a	1.4 B
Plainsman	50 c	124 cd	197 cd	87 D	1.8 d	1.0 cd	0.0 a	1.4 B
SC 109-9	41 c	60 e	170 d	51 E	2.9 a	2.3 a	0.0 a	2.6 A
CK 60	50 c	144 bc	165 d	97 D	2.0 cd	0.8 de	0.0 a	1.4 B
KS 5	82 a	190 a	228 bc	136 A	1.9 cd	0.8 de	0.0 a	1.4 B
Martin	77 b	159 b	253 ab	118 ABC	2.1 bcd	1.0 cd	0.0 a	1.6 B
NP	67 bc	162 ab	194 cd	115 BC	1.8 d	0.3 ef	0.0 a	1.1 B
SC 33-9-8-E4	93 a	155 b	288 a	124 AB	2.8 ab	1.3 bcd	0.0 a	2.1 A
Soil means	74 C	140 B	221 A		1.9 A	0.9 B	0.0 C	

+ Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 28. Dry-matter yields of tops and the degree of Fe deficiency symptoms observed on the upper leaves of sorghum genotypes grown on Fe-sufficient and low Fe soils in the greenhouse (Expt. 2).

Genotype	Top yield				Average Fe deficiency ratings			
	Fe deficient soil		Fe-sufficient soil	Genotype means‡				Genotype means‡
	Bridget+	Bridgeport+	Sharpsburg		Bridget+	Bridgeport+	Sharpsburg	
	mg/plant							
SC 369-3-1JB	28 c†	100 d	175 b	64 E	4.0 a	2.8 a	0.0 a	3.4 A
TX 7078	56 ab	135 b	193 ab	96 BC	3.8 ab	0.8 cd	0.0 a	2.3 B
TX 414	50 bc	154 b	224 a	104 B	2.8 cd	1.2 bc	0.0 a	2.0 C
SD 106	71 a	194 a	210 a	133 A	2.4 d	0.4 d	0.0 a	1.4 D
KS 56	36 c	124 cd	180 b	80 C	3.4 abc	2.5 a	0.0 a	3.0 A
Norghum	39 c	138 b	158 c	89 C	3.8 ab	2.4 a	0.0 a	3.1 A
TX 412	40 bc	159 b	181 b	100 B	3.4 abc	1.6 b	0.0 a	2.5 B
TX 07	32 c	107 d	179 b	70 D	2.6 d	1.3 bc	0.0 a	2.0 C
TAM 428	60 ab	87 d	194 ab	74 D	1.8 e	0.4 d	0.0 a	1.1 D
SC 500-6-1	68 ab	182 a	206 ab	125 A	3.3 bc	1.0 bcd	0.0 a	2.2 C
SC 118-15E	56 ab	201 a	195 ab	129 A	3.4 abc	2.4 a	0.0 a	2.9 AB
SC 33-9-8-E4	41 b	142 bc	194 ab	92 BC	3.4 abc	1.5 b	0.0 a	2.5 B
Soil means	48 C	144 B	191 A		3.1 A	1.5 B	0.0 C	

+ Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

3. Dry-Matter Yields

Only the above ground portions of plants were harvested. Dry-matter production of plants grown in the Sharpsburg soil was 2 to 3 times higher than that of plants grown in Bridget and Bridgeport soils (Tables 27 and 28). Plants grown in the Bridgeport soils produced about two times more dry matter than plants grown in the Bridget soil. The genotypes also differed in dry-matter yields. In the low Fe soils, SC 118-15E, SC 500-6-1, and SD 106 had the highest dry-matter yields and SC 109-9 and SC 369-3-1JB had the lowest.

4. Discussion

Using Fe deficiency ratings and dry-matter yields as criteria for classifying sorghum genotypes into 'Fe-efficient' or 'Fe-inefficient,' the rankings of the genotypes are given in Tables 29 and 30.

Considering these criteria for 'Fe-efficiency' the most 'Fe-efficient' genotypes when grown in the low Fe soils were SC 500-6-1 and SD 106. TAM 428 might also be considered as one of the more 'Fe-efficient' genotypes since it had low Fe deficiency ratings when grown on both low Fe soils and had good growth when grown on the Bridget soil. However, TAM 428 had poor growth when grown on the Bridgeport soil. The most 'Fe-inefficient' genotypes when grown on the low Fe soils were SC 109-9 and SC 369-3-1JB.

When the results of screening sorghum genotypes in nutrient solutions were compared with the results of screening in low Fe soils, genotypes did not respond the same. If Fe deficiency ratings of genotypes in nutrient solutions were compared with those in soils, SC 118-15E, Wheatland, SC 369-3-1JB, SC 109-9, KS 56, and TX 07 would be considered

Table 29. Ranking of sorghum genotypes on the basis of the degree of Fe deficiency ratings in the low Fe soils.

Soil	Expt. No.	Fe inefficient	Moderately Fe inefficient	Moderately Fe efficient	Fe efficient
Bridgeport	1	SC 118-15E, Wheatland, SC 33-9-8-E4, SC 109-9	SC 134, Redlan, Plainsman, CK 60, KS 5, Redbine 60, Martin	SC 500-6-1, NP	TAM 428
	2	SC 369-3-1JB, KS 56, Norghum, SC 118-15E	TX 414, TX 412, TX 07, SC 33-9-8-E4	TAM 428, SD 106, SC 500-6-1	
Bridget	1	SC 118-15E, Wheatland, Redbine 60, SC 109-9, CK 60, KS 5, Martin, SC 134, Plainsman, NP, SC 33-9-8-E4	TAM 428	SC 500-6-1	
	2	SC 369-3-1JB, TX 7078, TX 414, SD 106, KS 56, Norghum, TX 412, TX 07, SC 118-15E, SC 500-6-1, SC 33-9-8-E4	TAM 428		

Table 30. Rankings of genotypes based on top dry-matter produced on the low Fe soils.

Category	Dry-matter yields	Soil	
		Bridget	Bridgeport
	(% of highest)		
Fe efficient	86-100	TAM 428, SD 106, SC 500-6-1	KS 5, SC 118-15E, SD 106, SC 500-6-1
	71-85	SC 118-15E, KS 5, TX 7078, Martin, Wheatland, Redlan, SC 33-9-8-E4	NP, Martin, TX 412, TX 414, SC 33-9-8-E4, CK 60
	56-70	Plainsman, NP, SC 134, TX 412, *Norghum*	Wheatland, KS 56, Redlan, SC 134, *Plainsman*, TX 7078, Redbine 60
Fe inefficient	41-55	KS 56, TX 414, CK 60, TX 07	TAM 428, TX 07, SC 369-3-1JB
	0-40	SC 109-9, SC 369-3-1JB	SC 109-9

'Fe-inefficient' in either screening method. However, TAM 428 and SC 500-6-1 would be considered moderately 'Fe-efficient' to 'Fe-efficient' when grown in both low Fe soils, but they could not be considered 'Fe-efficient' when grown in nutrient solutions. The genotypes SC 33-9-8-E4, NP, Norghum, Plainsman, and TX 412 were moderately 'Fe-efficient' in low Fe soils. SD 106 was 'Fe-efficient' when grown in NH_4^+-treated solutions as well as when grown on the Bridgeport soil.

On the basis of dry-matter yields of the genotypes in nutrient solutions and on low Fe soils, Martin, SC 118-15E, Redlan, Wheatland, and TX 7078 could generally be considered 'Fe-efficient.' One genotype, SC 109-9, would be considered 'Fe-inefficient.'

It is not surprising that plants grown in nutrient solutions and in soils did not respond the same since the growth conditions in nutrient solutions can be controlled more precisely than in soils. The supply of elements like P, Mn, Cu, and Zn, which can interfere with Fe uptake and translocation, can be controlled in nutrient solutions but not as easily in soils. In addition, Fe in nutrient solutions would be more readily available for plant use than in a soil because of root accessibility and the ease in changing the pH of a solution compared to a soil. Genotypes that have low Fe requirements should compete more readily for Fe in solution but may not be able to obtain sufficient Fe when grown on a low Fe soil. Bridget soil contained higher levels of Zn and this might partially explain why plants grown on this soil had more severe Fe deficiency symptoms and lower dry-matter yields than plants grown on the Bridgeport soil. Nutrient solution experiments are invaluable for studying mechanisms involved in uptake and utilization of

nutrients, but most plants grown for food production are grown in soils. Thus, screening responses in nutrient solution need to be correlated with screening results in soils.

C. Physiological Properties of Sorghum Genotypes Showing Differential Responses to Fe Deficiency

Several experiments were conducted in nutrient solutions and in low Fe and Fe-sufficient soils under growth chamber and greenhouse conditions to determine differences in physiological properties of genotypes considered to be 'Fe-efficient' and 'Fe-inefficient.' Studies were conducted to determine genotype differences or effects on (1) varied Fe levels, (2) production of 'reductant' in nutrient solutions, (3) pH of nutrient solutions, (4) plant heights and leaf areas, (5) leaf chlorophyll, (6) mineral element concentrations and ratios, and (7) dry-matter produced per unit Fe taken up.

1. Genotype Response to Varied Levels of Fe

a. Plant growth

SC 33-9-8-E4, NP, KS 5, SC 118-15E, Redlan, and Martin were grown in separate containers with NO_3^- as a source of N and with 0, 5, 11, 16, 22, and 27 mM Fe. Plants that received the 0 Fe treatment had no Fe added to the initial growth solution and other Fe treatments had a low amount of Fe added to the initial solutions. Seedlings were normal before treatments were added. Plants grown without Fe became Fe deficient within 3 days and grew poorly thereafter. Plants grew progressively better with increasing levels of Fe. The highest Fe level appeared

adequate for maximum growth even though slight Fe deficiency symptoms appeared in some of the genotypes.

b. Iron deficiency symptoms

Without added Fe, plants of each genotype developed Fe deficiencies within 3 days, and the deficiency symptoms became progressively worse with time. Differences among genotypes could be detected for plants grown without Fe, but few differences could be detected among genotypes when Fe was added at any level. In solutions with added Fe, SC 118-15E had the most severe Fe deficiency. Genotypes showed the greatest differences in Fe deficiency symptoms 5 days after treatments were added. Except for SC 118-15E, genotype differences for Fe deficiency symptoms were small at the time the experiment was terminated (21 days). Plants developed the same degree of Fe deficiency symptoms when they were grown with the various amounts of Fe in solution.

c. pH increases in nutrient solution

Table 31 shows changes in the nutrient solution pH with each level of Fe and each genotype. The pH increased with time for each level of Fe and for each genotype, but differences due to Fe levels or genotype were not statistically significant. Changes of pH in solutions without Fe tended to be lower than in solutions with added Fe. The initial pH of the nutrient solutions was 5.6 and varied by only 0.5 pH units from 0 to the high Fe level.

d. Dry-matter yields

Top, root, and total dry-matter yields are given in Tables 32 and 33. Dry-matter yields generally increased as Fe increased in the growth

Table 31. The degree of Fe deficiency symptoms observed on the upper leaves and increases in pH of the nutrient solution for selected sorghum genotypes grown at varied levels of Fe.

Genotypes	Fe level (mM)						
	0	5	11	16	22	27	Genotype means
	Fe deficiency rating+						
SC 33-9-8-E4	4.0 a†	0.0 c	0.0 d	-	-	0.0 c	0.7 C
NP	3.5 a	0.0 c	0.5 b	0.5 d	0.0 d	1.0 b	0.9 BC
KS 5	3.5 a	1.0 b	1.5 a	1.0 c	1.0 c	1.0 b	1.5 B
SC 118-15E	2.5 b	2.5 a	1.0 b	1.5 b	2.5 a	2.5 a	2.1 A
Redlan	2.0 bc	0.0 c	1.0 b	3.0 a	1.5 b	1.0 b	1.4 B
Martin	1.5 c	0.5 c	0.5 c	0.0 e	0.0 d	0.0 c	0.4 C
Treatment means	3.2 A	0.7 B	0.8 B	0.9 B	0.9 B	0.9 B	
	Increase in solution pH						
SC 33-9-8-E4	1.1 b	1.5 ab	1.7 a	1.6 ab	1.4 a	1.5 ab	1.5 A
NP	0.8 b	1.5 ab	1.6 a	1.5 ab	1.7 a	1.8 a	1.5 A
KS 5	1.5 a	1.4 ab	1.6 a	1.2 b	1.5 a	1.5 ab	1.5 A
SC 118-15E	0.8 b	1.5 ab	1.6 a	1.2 b	1.5 a	1.3 b	1.3 A
Redlan	0.9 b	1.3 b	1.7 a	1.5 ab	1.6 a	1.4 ab	1.6 A
Martin	1.4 a	1.8 a	1.6 a	1.8 a	1.6 a	1.5 ab	1.6 A
Treatment means	1.1 A	1.5 A	1.6 A	1.5 A	1.6 A	1.5 A	

+ 0 = No Fe deficiency (green); 4 = Severe Fe deficiency (severe interveinal chlorosis).

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 32. Top and root dry-matter yields of selected sorghum genotypes grown under varied levels of Fe.

Genotypes	Fe level (mM)						
	0	5	11	16	22	27	Genotype means
	mg/plant						
	Top yield						
SC 33-9-8-E4	30 b†	172 cd	115 e	224 c	233 d	195 c	178 C
NP	33 b	255 b	293 b	332 b	343 b	235 c	282 B
KS 5	45 b	124 e	166 d	307 b	292 c	315 b	208 C
SC 118-15E	43 b	203 c	186 d	219 c	250 d	201 c	184 C
Redlan	43 b	154 de	240 c	256 c	255 d	305 b	209 C
Martin	251 a	378 a	390 a	526 a	521 a	545 a	435 A
Treatment means	74 C	214 B	248 B	311 A	316 A	333 A	
	Root yield						
SC 33-9-8-E4	9 c	71	71	105	94	78	71 D
NP	12 bc	133 b	140 b	170 b	159 b	204 b	136 B
KS 5	14 bc	58 d	73 c	139 b	138 bc	168 c	98 C
SC 118-15E	17 b	86 c	92 c	92 c	122 cd	82 d	82 CD
Redlan	13 bc	58 d	85 c	99 c	101 d	115 d	79 D
Martin	108 a	178 a	192 a	285 a	279 a	293 a	222 A
Treatment means	29 C	97 B	109 B	148 A	148 A	157 A	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 33. Total dry-matter yields and top/root dry-matter ratios of selected sorghum genotypes grown under varied levels of Fe.

Genotypes	Fe level (mM) 0	5	11	16	22	27	Genotype means
	mg/plant						
Total yield							
SC 33-9-8-E4	39 b†	243 d	289 de	330 cd	327 d	273 d	250 D
NP	45 b	387 b	433 b	453 b	451 b	639 b	418 B
KS 5	53 b	182 e	360 c	445 b	429 b	432 c	306 C
SC 118-15E	60 b	289 c	278 e	310 d	371 c	283 d	265 D
Redlan	57 b	212 de	324 cd	355 c	357 cd	421 c	288 D
Martin	359 a	556 a	532 a	810 a	796 a	788 a	657 A
Treatment means	103 C	311 B	357 B	459 A	464 A	490 A	
Top/root ratio							
SC 33-9-8-E4	3.2 a	2.4 b	3.1 a	2.2 b	2.5 a	2.5 ab	2.6 A
NP	3.4 a	2.2 b	2.3 b	2.2 b	2.2 ab	2.1 b	2.3 B
KS 5	3.3 a	2.1 b	2.3 b	2.3 ab	2.2 ab	2.4 ab	2.4 AB
SC 118-15E	2.6 b	2.2 b	2.4 b	2.4 ab	2.0 b	2.5 ab	2.4 AB
Redlan	3.3 a	2.9 a	2.6 b	2.7 a	2.6 a	2.7 a	2.8 A
Martin	2.3 b	2.1 b	1.8 c	2.2 b	1.9 b	2.1 b	2.1 B
Treatment means	3.0 A	2.4 B	2.3 B	2.3 B	2.3 B	2.3 B	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

medium. Plants given 5 μM Fe in the growth medium had dry-matter increases of about 200% over plants grown without Fe. Doubling the amount of Fe in the nutrient solution to 11.0 μM Fe increased dry-matter yields by only another 32%. Further increases in Fe gave only small or no increases in dry matter. Iron at levels below 5.0 μM inhibited growth and with Fe above this level, the increases in dry matter were relatively small. The trends in dry-matter increases were similar for both top and roots.

The genotypes differed in dry-matter yields (Tables 32 and 33). Regardless of Fe level, Martin outyielded the other genotypes. In fact, in solutions with no Fe, Martin had over 6-fold higher dry matter than the next highest yielding genotype. SC 33-9-8-E4 produced the lowest top and root dry-matter when no Fe was added.

Even though added Fe increased dry matter of all genotypes, the increases were different for each genotype. Dry-matter increases from 0 to 5 μM Fe were greatest for NP and least for Martin, but each genotype showed marked increases. At Fe levels above 5 μM, increases in dry matter for each genotype were relatively small. From these observations, NP was the most responsive genotype to added Fe and Martin was the least.

For maximum dry-matter production, the genotypes required different amounts of Fe in the growth media. SC 33-9-8-E4 and KS 5 needed 16 μM Fe, SC 118-15E and Martin required 22 μM Fe, and Redlan and NP required 27 μM Fe. Martin produced more dry matter at the low Fe and appeared to be the most efficient genotype for dry-matter production at low Fe levels.

e. Top/root dry-matter ratios

Top/root dry-matter ratios of sorghum genotypes grown without added Fe were higher than for plants grown with Fe (Table 33). These ratios were unchanged for plants grown with Fe at 5 to 27 μM. In solutions with no added Fe, root growth was generally inhibited more than top growth to give higher top/root ratios. Martin had the lowest top/root ratio. The other genotypes had similar top/root ratios.

f. Mineral element concentrations

Nutrient element concentrations for five of six Fe levels are given in Tables 34, 35, 36, and 37. Only micronutrient elements and P data are reported here.

The concentration of Fe in the upper leaves and roots increased with increasing level of Fe in the growth medium. The level of Fe had little or no effect on the Fe concentration in the lower leaves. At each Fe level, genotypes differed in Fe concentration in all plant parts except for plants grown with 16 μM which had similar Fe concentrations in the lower leaves. The Fe concentrations were generally higher in the roots than in both upper and lower leaves.

The amount of Mn accumulated in the upper and lower leaves and roots decreased as the level of Fe in the growth medium increased except for plants grown with 22 μM Fe in solution which had the highest Mn concentrations in the roots. Manganese concentrations were in the order of lower leaves > upper leaves > roots.

The level of Fe in the growth medium had little effect on the amount of Cu accumulated by plants in the upper and lower leaves.

Table 34. Micronutrient element concentrations in the upper leaves of sorghum genotypes grown with various Fe levels in nutrient solutions.

Genotype	Fe level (μM) 0	5	11	16	22	Genotype means	0	5	11	16	22	Genotype means
	μg/gm						μg/gm					
	Fe						Mn					
SC 33-9-8-E4	--	89 b†	30 c	77 a	68 a	66 B	--	122 c	159 b	89 b	192 b	140 B
NP	39 b	37 c	76 b	66 ab	50 a	57 B	295 a	188 b	91 c	174 a	248 a	175 A
KS 5	--	59 c	44 c	77 a	68 a	62 B	--	121 c	205 a	88 b	145 c	140 B
SC 118-15E	--	181 a	60 bc	84 a	15 b	85 A	--	231 a	176 ab	166 a	215 ab	197 A
Redlan	74 a	34 c	67 bc	35 b	63 a	50 B	177 b	168 b	94 c	113 b	229 ab	151 B
Martin	14 c	52 c	112 a	49 b	49 a	66 B	189 b	135 bc	90 c	185 a	208 b	155 B
Fe level means	42 C	75 A	65 AB	65 AB	52 BC		220 A	161 B	136 B	136 B	206 A	
	Cu						Zn					
SC 33-9-8-E4	--	27 ab	25 a	28 a	35 a	29 A	--	89 b	114 a	75 c	89 b	92 A
NP	36 a	22 b	25 a	25 a	32 a	26 A	136 a	121 a	72 b	104 ab	118 a	104 A
KS 5	--	29 ab	25 a	25 a	32 a	28 A	--	109 ab	107 a	82 bc	120 a	104 A
SC 118-15E	--	34 a	27 a	29 a	19 b	27 A	--	130 a	96 ab	100 b	112 ab	110 A
Redlan	33 a	28 ab	23 a	21 a	30 a	26 A	128 a	123 a	75 b	83 bc	120 a	100 A
Martin	30 a	25 ab	28 a	25 a	26 ab	26 A	134 a	82 b	97 ab	125 a	110 ab	104 A
Fe level means	33 A	28 A	25 A	25 A	29 A		133 A	109 B	94 B	95 B	112 B	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 35. Micronutrient element concentrations in the lower leaves of selected sorghum genotypes grown with various Fe levels in nutrient solutions.

Genotype	Fe level (µM) 0	5	11	16	22	Genotype means	0	5	11	16	22	Genotype means
	µg/gm						µg/gm					
	Fe						Mn					
SC 33-9-8-E4	--	70 b†	66 b	73 bc	117 a	81 AB	--	362 b	228 b	202 c	63 e	214 D
NP	65 b	91 a	68 b	88 ab	82 a	82 AB	541 a	328 b	216 bc	346 a	297 c	297 B
KS 5	--	87 ab	82 b	66 c	95 a	83 AB	--	247 c	234 b	215 c	190 d	222 CD
SC 118-15E	--	72 ab	71 b	68 c	50 ab	65 B	--	430 a	316 a	307 b	336 b	347 A
Redlan	63 b	75 ab	79 b	106 a	77 ab	84 AB	398 b	185 d	237 b	205 c	382 a	252 C
Martin	119 a	75 ab	135 a	76 bc	100 a	97 A	427 b	231 c	181 c	184 c	296 c	223 CD
Fe level means	82 A	78 A	87 A	76 A	87 A		455 A	297 B	239 CD	222 D	269 BC	
	Cu						Zn					
SC 33-9-8-E4	--	41 a	34 a	30 ab	28 a	33 A	--	142 a	129 a	104 b	89 b	116 A
NP	34 a	37 a	28 a	35 ab	34 a	34 A	103 b	140 a	129 a	137 ab	135 a	135 A
KS 5	--	43 a	33 a	27 b	36 a	35 A	--	145 a	124 a	129 ab	124 a	133 A
SC 118-15E	--	39 a	37 a	30 ab	24 a	33 A	--	144 a	124 a	137 ab	130 a	136 A
Redlan	37 a	35 a	31 a	26 b	38 a	30 A	109 b	135 a	122 a	158 a	130 a	136 A
Martin	42 a	38 a	36 a	45 a	30 a	37 A	144 a	119 a	121 a	132 ab	122 ab	124 A
Fe level means	38 A	39 A	34 A	31 A	32 A		119 A	138 A	124 A	132 A	122 A	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 36. Micronutrient element concentrations in the roots of selected sorghum genotypes grown with varied levels of Fe.

Genotype	Fe level (μM) 0	5	11	16	22	Genotype means	0	5	11	16	22	Genotype means
	μg/gm						μg/gm					
	Fe						Mn					
SC 33-9-8-E4	--	110 a†	64 c	215 a	130 a	130 A	--	60 c	68 c	48 d	59 d	59 D
NP	56 b	68 b	123 ab	51 d	85 b	82 B	134 a	167 b	62 c	165 b	195 c	147 B
KS 5	--	101 a	48 c	98 c	54 c	75 B	--	95 c	137 b	45 d	181 c	114 BC
SC 118-15E	--	59 b	107 b	134 b	66 bc	91 B	--	255 a	211 a	209 a	368 a	261 A
Redlan	119 a	67 b	155 a	43 d	77 bc	86 B	102 b	91 c	59 c	108 c	285 b	136 BC
Martin	45 b	88 ab	121 b	61 d	63 bc	83 B	50 c	83 c	59 c	84 c	180 c	102 C
Fe level means	73 B	82 AB	103 A	100 A	69 B		95 B	125 B	99 B	110 B	242 A	
	Cu						Zn					
SC 33-9-8-E4	--	68 d	213 a	213 a	165 b	164 AB	--	110 ab	85 ab	79 ab	91 bc	91 BC
NP	36 b	210 a	156 b	208 a	212 a	197 A	124 ab	89 b	53 b	86 ab	94 bc	80 C
KS 5	--	66 d	204 a	200 a	206 a	169 AB	--	116 ab	82 ab	66 b	117 ab	95 B
SC 118-15E	--	116 c	194 ab	210 a	203 a	181 AB	--	134 a	115 a	112 a	117 ab	121 A
Redlan	--	209 a	197 ab	170 ab	213 a	197 A	144 a	117 ab	81 ab	70 b	130 a	100 B
Martin	208 a	163 b	78 c	138 b	158 b	134 B	108 b	97 ab	52 b	72 b	77 c	75 C
Fe level means	122 C	139 BC	173 AB	190 A	198 A		125 A	111 A	78 B	81 B	107 A	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

However, plants grown with higher Fe levels tended to accumulate higher amounts of Cu in the roots. The Cu concentrations were higher in the roots than in the upper and lower leaves.

In the upper leaves, the higher the level of Fe in the growth medium, the lower the amount of Zn accumulated by plants. The level of Fe did not influence Zn concentrations in the lower leaves and in the roots, Zn concentrations tended to decrease as the level of Fe in solution increased. Zinc concentrations were generally higher in the upper and lower leaves than in the roots.

The genotypes showed significant differences for Mn, Cu, and Zn concentrations at each Fe level except for plants grown with 5 and 11 µM Fe which had similar Cu and Zn concentrations in the lower leaves. Also, plants grown with 0, 11, and 16 µM Fe did not differ in Cu concentrations in the upper leaves.

Plants grown without added Fe had higher P concentrations in the upper leaves than plants grown with added Fe (Table 37). No differences in P concentrations were noted for genotypes grown with added Fe. In the lower leaves, the level of Fe in the growth medium did not affect P concentrations. In the roots, P concentrations decreased with increasing level of Fe in solution up to 16 µM Fe and then increased for plants grown with 22 µM Fe.

On the average, when the genotypes were grown with added Fe, they accumulated similar amounts of P in the upper and lower leaves and in the roots. The differences amongst genotypes in P concentrations at each Fe level were small. In comparing plant parts, P concentrations were higher in the lower leaves. The order of P concentration in the

Table 37. Phosphorus concentrations in the upper and lower leaves and roots of selected sorghum genotypes grown with varied levels of Fe.

Genotype	Fe level (μM)											
	0	5	11	16	22	Genotype means	0	5	11	16	22	Genotype means
	%						%					
				UL						LL		
SC 33-9-8-E4	--	0.6 a†	0.5 a	0.5 ab	0.5 a	0.5 A	--	2.1 a	1.7 a	1.5 bc	0.9 c	1.6 A
NP	1.3 a	0.5 a	0.4 a	0.5 ab	0.6 a	0.5 A	1.6 ab	1.8 a	1.4 a	2.1 a	1.8 a	1.8 A
KS 5	--	0.6 a	0.5 a	0.4 b	0.5 a	0.5 A	--	1.6 ab	1.5 a	1.2 c	1.4 a	1.4 A
SC 118-15E	--	0.7 a	0.5 a	0.6 ab	0.4 a	0.6 A	--	1.7 ab	1.6 a	1.7 ab	1.3 bc	1.6 A
Redlan	1.4 a	0.5 a	0.4 a	0.4 b	0.7 a	0.5 A	1.7 a	1.3 b	1.7 a	1.3 c	1.7 ab	1.5 A
Martin	1.0 a	0.5 a	0.5 a	0.8 a	0.4 a	0.6 A	1.2 b	1.4 b	1.4 a	1.3 c	1.3 bc	1.3 A
Fe level means	1.2 A	0.6 B	0.5 B	0.6 B	0.5 B		1.5 A	1.7 A	1.6 A	1.4 A	1.4 A	
				R								
SC 33-9-8-E4	--	0.7 a	0.8 a	0.7 a	0.7 b	0.7 A						
NP	1.4 a	0.8 a	0.8 a	0.8 a	1.0 b	0.9 A						
KS 5	--	0.8 a	0.7 ab	0.7 a	1.5 a	0.9 A						
SC 118-15E	--	0.8 a	0.7 ab	0.7 a	0.8	0.8 A						
Redlan	1.6 a	0.7 a	0.5 b	1.0 a	1.0 b	0.8 A						
Martin	0.5 b	0.9 a	0.9 a	0.7 a	1.0 b	0.7 A						
Fe level means	1.2 A	0.8 B	0.7 C	0.8 B	1.1 AB							

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

plant parts was lower leaves > roots > upper leaves.

g. Nutrient element concentration ratios

The P:Fe, Mn:Fe, Fe:Cu, and Zn:Fe ratios in the upper and lower leaves and roots are shown in Tables 38, 39, and 40.

The P:Fe ratios in all plant parts were much higher in plants grown without added Fe. This was also the case for Mn:Fe ratios in the upper and lower leaves and the Zn:Fe ratios in the lower leaves and roots. The Fe:Cu ratios generally increased with increasing Fe level in the growth medium.

Differences in these ratios were also noted amongst genotypes. When plants were grown with added Fe, SC 118-15E generally had higher P:Fe and Mn:Fe ratios than the other genotypes. This genotype also had higher Mn:Fe ratios in the roots and higher Zn:Fe ratios in the upper and lower leaves than the other genotypes.

Table 41 shows the Fe ratios amongst the various plant parts. The level of Fe in the growth medium did not significantly affect the UL/LL Fe ratios as well as the R/UL and R/LL Fe ratios. The genotypes, however, differed. The UL/LL Fe ratios were higher for SC 118-15E and the R/LL and R/UL Fe ratios were higher for SC 33-9-8-E4.

h. Total Fe content

Total Fe content in all plant parts increased with increasing Fe level in the growth medium (Table 42). The contents were generally higher in the upper leaves than in the lower leaves or roots. At each Fe level, genotypes differed. Averagely, when plants were grown with added Fe, Martin had much higher Fe content in all plant parts than the other genotypes.

Table 38. Nutrient element concentration ratios in the upper leaves of selected sorghum genotypes grown with varied levels of Fe.

Genotype	Fe level (μM)											
	0	5	11	16	22	Genotype means	0	5	11	16	22	Genotype means
	P:Fe						Mn:Fe					
SC 33-9-8-E4	--	62 c†	173 a	67 c	78 c	95 BC	--	1.4 c	5.3 a	1.2 d	2.8 d	2.7 B
NP	337 b	140 a	57 c	77 c	110 b	96 BC	7.6	5.1 a	1.2 c	2.6 bc	5.0 b	3.5 B
KS 5	--	101 b	117 b	66 c	69 c	88 C	--	2.0 b	4.6 a	1.1 d	2.1 d	2.2 B
SC 118-15E	--	38 d	89 b	76 c	265 a	117 A	--	1.3 c	2.9 b	2.0 c	14.5 a	4.7 A
Redlan	194 c	134 a	60 c	115 b	110 b	105 AB	2.4	4.9 a	1.4 c	3.2 ab	3.7 c	3.3 B
Martin	688 a	92 b	41 c	169 a	87 c	97 BC	13.1	2.6 b	0.8 c	3.9 a	4.3 bc	2.9 B
Fe level means	406 A	94 B	90 B	95 B	120 B		7.7 A	2.9 C	2.7 C	2.3 C	5.4 B	
	Fe:Cu						Zn:Fe					
SC 33-9-8-E4	--	3.3 b	1.2 d	2.8 ab	2.0 a	2.3 A	--	1.0 cd	3.8 a	1.0 b	1.3 c	1.8 B
NP	1.1 b	1.7 c	3.1 ab	2.7 ab	2.3 a	2.5 A	3.5 b	3.2 a	1.0 c	1.6 b	2.4 b	2.1 B
KS 5	--	2.0 c	1.8 cd	3.1 a	2.1 a	2.3 A	--	1.8 b	2.4 b	1.1 b	1.8 bc	1.8 B
SC 118-15E	--	5.4 a	2.2 bc	2.9 a	0.8 b	2.8 A	--	0.7 d	1.6 c	1.2 b	7.5 a	2.8 A
Redlan	2.3 a	1.2 c	2.9 b	1.6 c	2.1 a	2.0 A	1.7 c	3.6 a	1.1 c	2.4 a	1.9 bc	2.3 AB
Martin	0.5 c	2.1 bc	4.0 a	1.9 bc	1.9 a	2.5 A	9.3 a	1.6 b	0.9 c	2.6 a	2.3 b	1.9 B
Fe level means	1.3 C	2.6 A	2.5 A	2.5 A	1.8 BC		4.8 A	2.0 B	1.9 B	1.7 B	2.9 B	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 39. Nutrient element concentration ratios in the lower leaves of selected sorghum genotypes grown with varied levels of Fe.

Genotype	Fe level (μM) 0	5	11	16	22	Genotype means	0	5	11	16	22	Genotype means
	P:Fe						Mn:Fe					
SC 33-9-8-E4	--	302 a†	256 a	205 b	77 d	210 B	--	5.2 a	3.4 a	2.8 ab	0.5 c	3.0 B
NP	239 a	199 bc	206 b	237 ab	219 b	215 B	8.3 a	3.6 b	3.2 a	3.9 a	3.6 b	3.6 B
KS 5	--	180 c	182 c	182 c	148 c	173 CD	--	2.8 b	2.8 ab	3.3 a	2.0 bc	2.7 B
SC 118-15E	--	237 b	227 ab	251 a	258 a	243 A	--	6.0 a	4.5 a	4.5 a	6.7 a	5.4 A
Redlan	271 a	174 c	214 bc	123 d	227 ab	183 C	6.3 b	2.5 b	3.0 a	1.9 b	5.0 a	3.1 B
Martin	103 b	186 c	104 d	171 c	131 c	148 D	3.6 c	3.1 b	1.3 b	2.4 b	3.0 b	2.5 B
Fe level means	204 A	174 B	198 B	195 B	176 B		6.1 A	3.9 B	3.0 B	3.1 B	3.5 B	
	Fe:Cu						Zn:Fe					
SC 33-9-8-E4	--	1.7 a	1.9 b	2.4 b	4.2 a	2.6 AB	--	2.0 a	1.9 a	1.4 a	0.8 c	1.5 AB
NP	1.9 b	2.4 a	2.4 b	2.5 b	2.5 c	2.5 AB	1.6 a	1.5 a	1.9 a	1.6 a	1.6 b	1.7 AB
KS 5	--	2.1 a	2.5 b	2.4 b	2.6 c	2.4 AB	--	1.6 a	1.5 ab	2.0 a	1.3 bc	1.6 AB
SC 118-15E	--	1.8 a	1.9 b	2.5 b	2.1 c	2.1 B	--	2.0 a	1.8 a	2.0 a	2.6 a	2.1 A
Redlan	1.7 b	2.1 a	2.6 b	3.5 a	2.0 c	2.6 AB	1.7 a	1.8 a	1.5 ab	1.5 a	1.7 ab	1.6 AB
Martin	2.8 a	2.0 a	3.8 a	2.9 ab	3.3 b	3.0 A	1.2 a	1.6 a	0.9 b	1.7 a	1.2 bc	1.3 B
Fe level means	2.1 B	2.0 B	2.5 AB	2.7 A	2.8 A		1.5 A	1.8 A	1.6 A	1.7 A	1.5 A	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 40. Nutrient element concentration ratios in the roots of selected sorghum genotypes grown with varied levels of Fe.

Genotype	Fe level (μM)											
	0	5	11	16	22	Genotype means	0	5	11	16	22	Genotype means
	P:Fe						Mn:Fe					
SC 33-9-8-E4	--	60 c†	125 a	31 c	55 d	67 E	--	0.5 d	1.1 b	0.2 c	0.5 c	0.6 C
NP	255 a	118 ab	68 b	163 a	117 c	117 C	2.4 a	2.4 b	0.5 c	3.2 a	2.3 b	2.1 B
KS 5	--	79 c	153 a	75 b	273 a	145 A	--	0.9 cd	2.9 a	0.5 c	3.3 b	1.9 B
SC 118-15E	--	139 a	65 b	54 bc	118 c	94 D	--	4.4 a	2.0 a	1.6 b	5.6 a	3.4 A
Redlan	130 b	111 a	32 c	166 a	135 bc	111 C	0.9 b	1.4 c	0.4 c	1.8 b	3.7 b	1.8 B
Martin	120 b	101 b	76 b	163 a	164 b	126 B	1.1 b	0.9 cd	0.5 c	1.4 b	2.9 b	1.4 BC
Fe level means	168 A	101 B	92 B	107 B	144 A		1.5 B	1.8 B	1.2 B	1.5 B	3.1 A	
	Fe:Cu						Zn:Fe					
SC 33-9-8-E4	--	1.6 a	0.3 bc	1.0 a	0.8 a	0.9 A	--	1.0 b	0.4 c	0.7 c	1.3 a	0.9 A
NP	1.6 a	0.3 b	0.8 b	0.2 b	0.4 a	0.4 B	2.2 a	1.3 b	1.7 a	1.1 bc	0.4 b	1.1 A
KS 5	--	1.5 a	0.2 c	0.5 b	0.3 a	0.6 AB	--	1.1 b	0.7 bc	2.2 a	1.7 a	1.4 A
SC 118-15E	--	0.5 b	0.6 bc	0.6 b	0.3 a	0.5 AB	--	2.4 a	0.8 bc	1.8 ab	1.1 a	1.5 A
Redlan	0.2 b	0.3 b	0.8 b	0.3 b	0.4 a	0.4 AB	1.2 b	1.7 ab	1.6 a	1.7 ab	0.5 b	1.4 A
Martin	0.9 a	0.5 b	1.5 a	0.4 b	0.4 a	0.7 AB	2.4 a	1.1 b	1.2 ab	1.2 bc	1.1 a	1.0 A
Fe level means	0.9 A	0.8 AB	0.7ABC	0.5 BC	0.4 C		1.9 A	1.4 AB	1.1 B	1.5 AB	0.9 B	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 41. Fe concentration ratios for selected sorghum genotypes grown with varied levels of Fe.

Genotype	Fe level (μM)											
	0	5	11	16	22	Genotype means	0	5	11	16	22	Genotype means
	UL/LL						R/UL					
SC 33-9-8-E4	--	1.3 b†	0.5 b	1.0 a	0.6 ab	0.9 A	--	1.2 a	2.1 a	2.8 a	1.9 b	2.0 A
NP	0.6 b	0.4 c	1.1 a	0.8 ab	0.6 ab	0.7 A	1.4 b	1.8 a	1.6 ab	0.8 c	1.7 b	1.5 A
KS 5	--	0.7 c	0.5 b	1.2 a	0.7 ab	0.8 A	--	1.7 a	1.1 b	1.3 bc	0.8 c	1.2 A
SC 118-15E	--	2.5 a	0.8 ab	1.2 a	0.3 b	1.1 A	--	0.3 b	1.8 ab	1.6 b	4.4 a	2.0 A
Redlan	1.2 a	0.5 c	0.8 ab	0.3 b	0.8 a	0.6 A	1.6 b	1.9 a	2.3 a	1.2 bc	1.2 bc	1.7 A
Martin	0.1 c	0.7 c	0.8 ab	0.6 ab	0.5 ab	0.7 A	3.1 a	1.7 a	1.1 b	1.3 bc	1.3 bc	1.4 A
Fe level means	0.6 A	1.0 A	0.8 A	0.9 A	0.6 A		2.0 A	1.4 A	1.7 A	1.5 A	1.8 A	
	R/LL											
SC 33-9-8-E4	--	1.6 a	1.0 bc	2.9 a	1.1 a	1.7 A						
NP	0.9 b	0.8 b	1.8 a	0.6 c	1.0 a	1.0 B						
KS 5	--	1.1 ab	0.6 c	1.5 b	0.6 a	1.0 B						
SC 118-15E	--	0.8 b	1.5 ab	2.0 b	1.3 a	1.4 AB						
Redlan	1.9 a	0.9 b	1.9 a	0.6 c	1.0 a	0.9 B						
Martin	0.4 b	1.2 ab	0.9 bc	0.8 c	0.6 a	0.9 B						
Fe level means	1.1 A	1.1 A	1.3 A	1.4 A	0.9 A							

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 42. Total Fe content in the upper, lower leaves and roots of selected sorghum genotypes grown with varied levels of Fe.

Genotype	Fe level (μM)											
	0	5	11	16	22	Genotype means	0	5	11	16	22	Genotype means
				UL						LL		
SC 33-9-8-E4	--	19.8 c†	14.2 d	31.4 c	53.5 b	29.7 B	--	7.8 d	20.2 b	14.0 c	41.8 b	21.0 B
NP	11.9 a	28.5 b	23.7 b	45.9 a	24.1 d	30.6 B	12.2 b	34.4 a	12.6 c	30.9 b	22.5 d	25.0 B
KS 5	--	24 c	28.9 b	47.6 a	61.1 a	40.4 A	--	16.4 c	24.8 b	19.2 c	32.2 c	23.2 B
SC 118-15E	--	59.2 a	19.3 c	33.9 bc	7.2 e	29.9 B	--	14.4 c	12.4 c	11.8 c	13.7 e	13.1 C
Redlan	14.6 a	25.3 b	24.2 b	32.8 c	35.0 c	29.3 B	6.0 b	20.9 b	16.7 c	49.2 a	22.7 d	27.4 B
Martin	7.5 b	20.4 c	77.5 a	37.9 b	50.7 b	46.6 A	39.3 a	20.9 b	54.5 a	35.6 b	52.8 a	41.0 A
Fe level means	11.3 C	29.5 B	31.3 B	38.3 A	38.6 A		19.2 B	19.1 B	23.5 AB	26.8 AB	31.0 A	
				R								
SC 33-9-8-E4	--	7.8 bc	4.6 d	22.5 a	12.2 b	11.8 B						
NP	0.6 b	9.0 b	17.2 b	8.7 d	13.5 b	12.1 B						
KS 5	--	5.8 c	3.5 d	13.6 c	7.5 c	7.6 B						
SC 118-15E	--	5.0 cd	9.9 c	12.2 cd	8.1 c	8.8 B						
Redlan	1.6 b	3.8 d	13.1 c	4.3 e	7.8 c	7.3 B						
Martin	4.8 a	15.7 a	23.2 a	17.5 b	17.2 a	18.4 A						
Fe level means	2.3 C	7.9 B	11.9 AB	13.1 A	11.1 AB							

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

i. Dry-matter production per unit Fe taken up

Average dry-matter production per unit Fe taken up was higher when plants were grown without added Fe than when plants were grown with added Fe (Table 43). However, differences amongst Fe levels were significant only for the upper leaves dry-matter production. The genotypes also differed. SC 118-15E and Redlan produced the highest upper leaf dry-matter per unit Fe and KS 5 and Redlan produced the highest root dry-matter per unit of Fe.

2. Genotype Responses in Experiment to Study 'Reductant' Produced

a. Growth of plants

The genotypes SC 33-9-8-E4, NP, SC 118-15E, and Martin were grown in nutrient solutions with 18, 36, and 54 μM Fe. No Fe deficiency appeared in the plants, and they grew well during the experiment. When the experiment was terminated, NP showed slight P deficiencies. Dry-matter yields of genotypes are shown in Table 44. Martin had the highest dry-matter yields and SC 118-15E had the lowest.

b. Plant height and top/root ratios

No differences in plant height were observed due to Fe treatments (Table 44). Genotypes, however, differed. Of the genotypes used, SC 33-9-8-E4 was the tallest and SC 118-15E was the shortest. Genotype x Fe level interactions were not significant. SC 33-9-8-E4 had higher top/root ratios than the other genotypes (Table 44).

c. 'Reductant' released by roots into nutrient solution

The relative amounts of 'reductant' released into the nutrient solution by the four genotypes grown at various levels of Fe with plant

Table 43. Dry-matter production per unit of Fe taken up by selected sorghum genotypes grown with varied levels of Fe.

Genotype	Fe level (μM) 0	5	11	16	22	Genotype means	0	5	11	16	22	Genotype means
	mg dry wt./μg Fe						mg dry wt./μg Fe					
				UL						LL		
SC 33-9-8-E4	--	11.2 bc†	2.1 c	13.0 b	14.7 b	10.3 C	--	9.0 a	15.1 a	13.7 a	8.5 b	11.6 A
NP	25.5 b	27.0 a	13.2 ab	15.1 b	20.0 b	18.8 AB	15.4 a	11.0 a	14.7 a	11.4 a	12.2 a	12.3 A
KS 5	--	17.0 a	22.7 a	13.0 b	14.7 b	16.9 B	--	11.2 a	12.2 ab	15.1 a	10.5 b	12.3 A
SC 118-15E	--	5.5 c	16.7 a	11.9 b	66.8 a	25.2 A	--	13.9 a	14.0 a	14.7 a	20.0 a	15.7 A
Redlan	13.5 c	29.0 a	14.9 ab	28.5 a	15.9 b	22.1 A	15.8 a	13.3 a	12.7 a	9.4 a	13.0 b	12.1 A
Martin	71.1 a	19.3 ab	8.9 bc	20.8 ab	20.4 b	17.4 B	8.4 b	13.3 a	7.4 b	13.1 a	10.0 b	11.0 A
Fe level means	36.7 A	18.2 BC	13.1 C	17.1 C	25.4 B		13.2 A	12.0 A	12.7 A	11.2 A	12.4 A	
				R								
SC 33-9-8-E4	--	9.1 b	15.5 b	4.7 c	7.7 c	9.3 B						
NP	22.5 a	14.7 ab	8.2 b	19.6 ab	11.7 bc	13.6 AB						
KS 5	--	9.9 b	20.8 a	10.2 c	18.4 a	14.8 A						
SC 118-15E	--	17.2 a	9.3 b	7.5 c	15.0 ab	12.3 AB						
Redlan	8.3 b	15.1 a	6.5 b	23.0 a	13.0 b	14.4 A						
Martin	22.4 a	11.4 ab	8.3 b	16.3 b	16.0 ab	13.0 AB						
Fe level means	17.7 A	12.9 A	11.4 A	13.6 A	13.6 A							

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 44. Dry-matter yields of selected sorghum genotypes grown in nutrient solutions with three levels of Fe.

Fe level	Genotypes				
	SC 33-9-8-E4	NP	SC 118-15E	Martin	Treatment means
(µM)	----------mg/plant----------				
	Top yield				
18	529 a†	580 a	415 a	584 b	527 A
36	455 b	574 a	396 a	627 a	513 A
54	476 b	569 a	392 a	540 c	494 A
Genotype means	486 B	574 A	401 C	584 A	
	Root yield				
18	298 a	318 a	264 a	399 a	320 A
36	256 b	335 a	243 ab	423 a	314 A
54	234 c	320 a	229 b	339 b	280 A
Genotype means	263 C	324 B	245 C	387 A	
	Total yield				
18	827 a	899 a	679 a	983 b	847 A
36	711 b	909 a	639 b	1050 a	827 A
54	710 b	722 b	621 b	878 c	733 A
Genotype means	749 C	843 B	646 C	970 A	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 45. Plant height and top/root dry-matter ratios of selected sorghum genotypes grown in nutrient solutions with three levels of Fe.

Fe level	Genotypes				
	SC 33-9-8-E4	NP	SC -18-15E	Martin	Treatment means
(μM)			Plant height (cm)		
18	32 a†	28 a	14 a	26 a	25 A
36	29 a	28 a	15 a	27 a	25 A
54	29 a	25 a	15 a	23 a	25 A
Genotype means	30 A	27 AB	15 C	25 B	
			Top/root ratio		
18	1.8 b	1.9 a	1.6 a	1.5 a	1.7 A
36	1.8 b	1.7 a	1.7 a	1.5 a	1.7 A
54	2.3 a	1.6 a	1.7 a	1.6 a	1.8 A
Genotype means	2.0 A	1.7 B	1.7 B	1.5 B	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

age are given in Table 46. The genotypes did not show any differences in the amounts of 'reductant' released by their roots during the first two sampling days. The amounts of 'reductant' released due to Fe treatments were markedly different, the amounts increasing as Fe level increased. From the third sampling until the experiment was terminated, the genotypes showed differences in the relative amounts of 'reductant' they released. SC 33-9-8-E4 released more 'reductant' than the other genotypes.

The amount of 'reductant' released increased with plant age after day 10 until day 16. After day 18 (6th sample) the release of 'reductant' declined gradually until the experiment was terminated. The decline in 'reductant' corresponded with rises in solution pH.

Differences among genotypes were significant only after day 10, most likely because seedlings initially had different and sufficient amounts of Fe available from the seed and the release of 'reductant' into the nutrient solution was not crucial. In addition, the mechanism for 'reductant' synthesis may require activation and the time lag was necessary for this. Over all sampling dates, the amount of 'reductant' released was affected much more by Fe level than by genotype (Table 46). Plants released about 2.5 times more 'reductant' at 36 μM Fe than at 16 μM Fe and over two times more at 56 μM Fe than at 36 μM Fe. The amount of 'reductant' released by the plants followed nearly a linear increase with increased Fe level.

d. Genotype effects on nutrient solution pH

The pH of the nutrient solutions increased slightly for the first 2 days after the treatments had been added and then decreased gradually for 8 days before increasing again. The decreases in pH appeared to be independent of the Fe in solution. The pH decreases were smaller for

Table 46. 'Reductant' released into nutrient solutions by the roots of selected sorghum genotypes grown in nutrient solutions with three levels of Fe.

Plant age	Fe level	Genotypes				
		SC 33-9-8-E4	NP	SC 118-15E	Martin	Treatment mean
(days)	(μM)	μg reductant/ml nutrient solution				
8	18	0.08 a†	0.10 a	0.15 a	0.10 a	0.11 C
	36	0.42 b	0.38 b	0.52 b	0.46 b	0.44 B
	54	1.08 c	1.10 c	1.11 c	1.31 c	1.15 A
	Genotype means	0.53 A	0.53 A	0.60 A	0.62 A	
10	18	0.17 a	0.11 a	0.14 a	0.16 a	0.15 C
	36	0.45 b	0.37 b	0.39 b	0.37 b	0.39 B
	54	1.02 c	0.86 c	1.02 c	1.04 c	0.98 A
	Genotype means	0.55 A	0.45 A	0.52 A	0.52 A	
12	18	0.26 a	0.15 a	0.16 a	0.21 a	0.19 C
	36	0.67 b	0.42 b	0.45 b	0.45 b	0.50 B
	54	1.35 c	0.97 c	1.06 c	1.16 c	1.13 A
	Genotype means	0.76 A	0.52 C	0.56 C	0.61 B	

Table 46. (Continued)

Plant age	Fe level	Genotypes				
		SC 33-9-8-E4	NP	SC 118-15E	Martin	Treatment mean
(days)	(μM)	μg reductant/ml nutrient solution				
14	18	0.34 a	0.23 a	0.22 a	0.23 a	0.25 C
	36	0.85 b	0.56 b	0.56 b	0.56 b	0.64 B
	54	1.67 c	1.21 c	1.34 c	1.39 c	1.40 A
	Genotype means	0.95 A	0.66 B	0.71 B	0.73 B	
16	18	0.44 a	0.27 a	0.28 a	0.26 a	0.31 C
	36	0.88 b	0.72 b	0.59 b	0.54 b	0.68 B
	54	1.77 c	1.20 c	1.55 c	1.51 c	1.51 A
	Genotype means	1.03 A	0.81 B	0.77 B	0.73 B	
18	18	0.33 a	0.31 a	0.20 a	0.13 a	0.26 C
	36	0.84 b	0.56 b	0.59 b	0.54 b	0.63 B
	54	1.68 c	1.29 c	1.20 c	1.56 c	1.43 A
	Genotype means	0.95 A	0.74 B	0.68 C	0.74 C	

Table 46. (Continued)

Plant age	Fe level	Genotypes				
		SC 33-9-8-E4	NP	SC 118-15E	Martin	Treatment mean
(days)	(μM)	μg reductant/ml nutrient solution				
20	18	0.26 a	0.20 a	0.18 a	0.13 a	0.19 C
	36	0.72 b	0.48 b	0.46 b	0.38 b	0.51 B
	54	1.42 c	0.99 c	1.20 c	1.11 c	1.18 A
	Genotype means	0.80 A	0.56 C	0.61 B	0.54 C	
22	18	0.24 a	0.17 a	0.17 a	0.15 a	0.18 C
	36	0.60 b	0.44 b	0.44 b	0.41 b	0.47 B
	54	0.92 c	0.95 c	1.06 c	1.14 c	1.10 A
	Genotype means	0.70 A	0.53 B	0.56 B	0.56 B	

† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

SC 118-15E than for the other genotypes (Fig. 10) and were larger for SC 33-9-8-B4.

3. Genotype Differences in Leaf Properties

Twenty-two sorghum genotypes were grown on two low Fe and one Fe-sufficient soils in a greenhouse to determine the effects of differential Fe deficiency on plant height, leaf areas, chlorophyll concentrations, and dry-matter yields of genotypes. Plants for these determinations were the same as those grown on the low Fe and Fe-sufficient soils described on pages 82 and 85. Plants were grown in two groups at different times.

a. Plant growth and Fe deficiency symptoms

These have been discussed under Section B, pages 85-86.

b. Plant height

Plant heights were measured for each genotype from the soil surface to the tip of the youngest fully expanded leaf. The soil effects on plant height were different for the genotypes (Tables 47 and 48). Plants grown on Bridget soil at the later date were taller than plants grown in the greenhouse during the months of May and June, so greenhouse conditions were not that different in day length but appeared to be different in temperature.

In both groups, plants grown on the Bridgeport soil were taller than plants grown on the Bridget soil and plants grown on the Sharpsburg soil were considerably taller than plants grown on the low Fe soils. NP and SC 500-6-1 were the tallest genotypes in the first and second groups, respectively. Plainsman and SC 369-3-1JB were the shortest genotypes in

Fig. 10. Changes in pH of nutrient solution for sorghum genotypes grown with three levels of Fe (mean average for 3 levels of Fe).

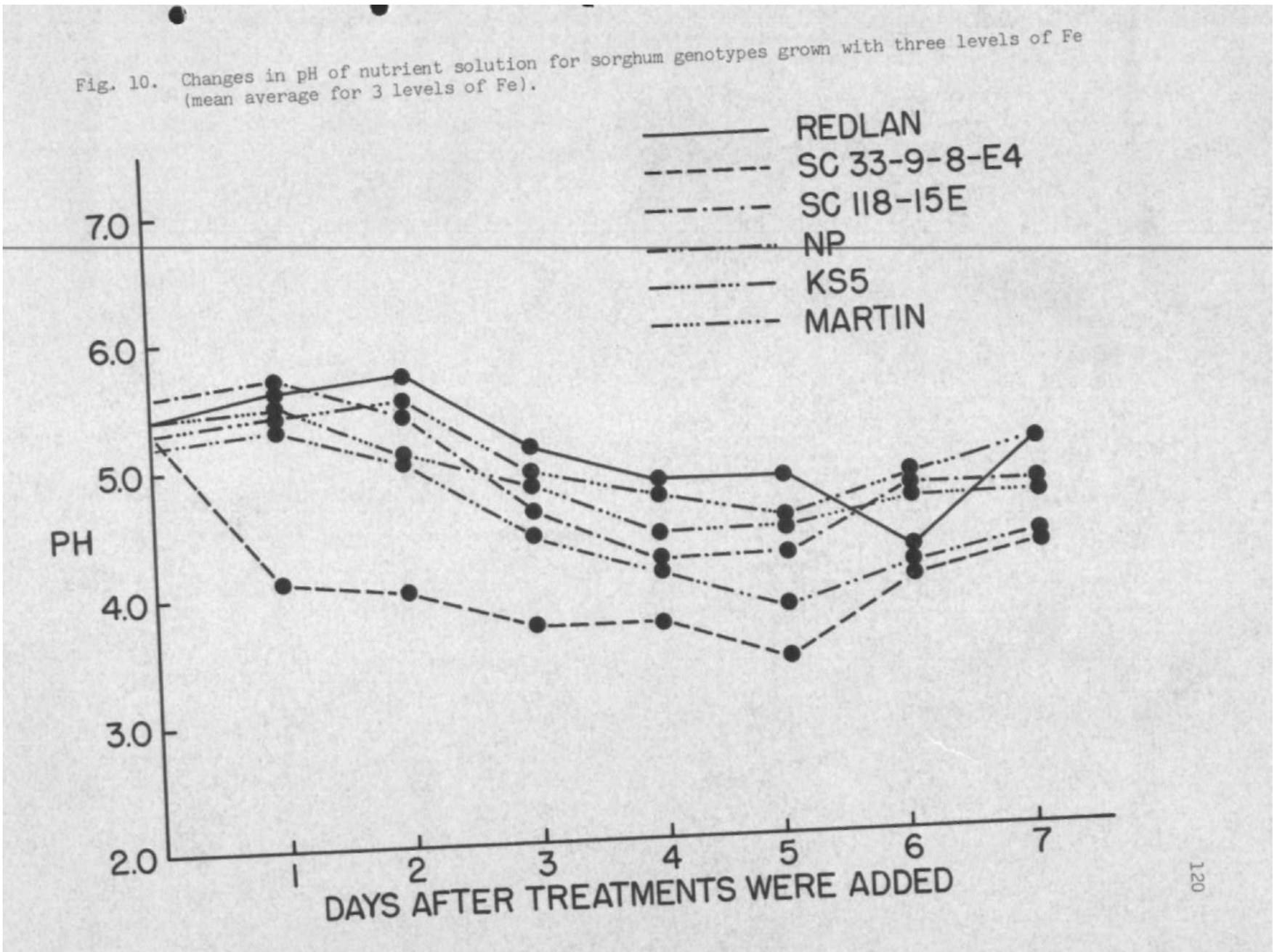


Table 47. Plant heights and leaf surface areas of sorghum genotypes grown on low Fe and Fe-sufficient soils in the greenhouse (Group 1).

Genotype	Soil							
	Bridget+	Bridgeport+	Sharpsburg	Genotype means‡	Bridget+	Bridgeport+	Sharpsburg	Genotype means‡
	cm				cm^2			
	Plant height				Leaf area			
SC 118-15E	9.5 bc†	12.0 bc	14.5 ab	11.0 BC	24.7 b	46.2 a	63.5 b	35.4 A
SC 134	10.7 ab	11.6 cd	15.1 a	11.3 AB	21.9 cd	30.9 d	50.3 de	26.4 BC
SC 500-6-1	11.3 a	12.0 bc	14.4 ab	11.7 AB	30.0 a	42.5 b	46.4 e	36.3 A
Wheatland	10.3 ab	12.5 bc	14.9 ab	11.4 AB	28.6 ab	44.4 b	54.3 cd	36.5 A
TAM 428	10.6 ab	10.2 d	13.6 bc	10.4 B	25.2 bc	28.9 d	55.3 cd	27.1 B
Redbine 60	11.0 a	11.2 cd	13.6 bc	11.1 BC	25.0 bc	33.4 c	44.0 ef	29.2 B
Redlan	9.8 bc	12.7 b	14.8 ab	11.3 AB	24.3 bc	37.5 c	52.3 d	30.9 B
Plainsman	9.0 c	11.7 cd	13.4 bc	10.4 B	19.4 de	31.1 d	43.9 ef	25.3 BC
SC 109-9	8.9 c	9.3 e	14.9 ab	9.1 C	16.3 e	24.9 e	71.1 a	20.6 D
CK 60	10.2 ab	10.7 de	12.7 c	10.5 B	17.8 e	30.1 d	41.0 f	24.0 CD
KS 5	11.4 a	13.3 ab	13.9 bc	12.4 A	23.9 b	49.9 a	58.1 c	36.9 A
Martin	11.1 a	13.4 ab	14.2 ab	12.3 A	21.5 cde	33.4 c	40.3 e	27.5 BC
NP	10.9 ab	14.5 a	15.9 a	12.7 A	18.1 e	43.0 b	44.6 ef	30.6 B
SC 33-9-8-E4	11.3 a	11.9 cd	13.8 bc	11.6 AB	22.2 cd	33.2 c	51.7 d	27.7 BC
Soil means	10.4 C	11.9 B	14.3 A		22.8 C	36.4 B	51.2 A	

+ Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 48. Plant heights and leaf surface areas of sorghum genotypes grown on low Fe and Fe-sufficient soils in the greenhouse (Group 2).

Genotype	Soil							
	Bridget†	Bridgeport†	Sharpsburg	Genotype means‡	Bridget†	Bridgeport†	Sharpsburg	Genotype means‡
	cm				cm^2			
	Plant height				Leaf area			
SC 369-3-1JB	9.8 b†	14.0	15.4 cd	11.9 C	5.1 d	18.3 c	22.6 de	11.7 C
TX 7078	14.1 a	17.8 b	19.2 a	16.0 A	13.6 b	20.3 c	26.5 b	17.0 B
TX 414	11.5 b	17.5 b	19.6 a	14.5 B	11.6 b	21.4 bc	29.2 ab	16.5 BC
SD 106	15.8 a	16.8 bc	17.0 bc	16.3 A	15.9 a	30.1 a	24.1 cd	23.0 A
KS 56	10.5 b	14.1 d	15.4 cd	12.3 C	9.8 c	24.7 b	22.3 cd	17.3 B
Norghum	11.4 b	15.1 cd	18.3 ab	13.3 B	11.3 b	20.8 c	18.7 e	16.0 BC
TX 412	9.8 b	14.6 d	16.2 bcd	12.2 C	8.9 c	25.9 b	29.8 ab	17.4 B
TX 07	11.2 b	13.2 d	17.3 bc	12.2 C	7.4 cd	14.6 d	23.8 cd	11.0 C
TAM 428	11.1 b	13.8 d	18.2 ab	12.5 C	12.2 b	14.3 d	26.2 b	13.3 C
SC 500-6-1	14.4 a	21.8 a	19.8 a	15.1 B	17.5 a	29.7 a	31.1 a	23.6 A
SC 118-15E	14.1 a	19.9 a	18.5 ab	17.0 A	12.5 b	30.3 a	27.6 ab	21.4 A
SC 33-9-8-E4	11.3 b	15.1 c	15.3 d	13.2 B	11.2 b	18.9 c	25.2 b	15.0 BC
Soil means	12.2 C	16.1 B	17.5 A		11.4 C	22.4 B	25.6 A	

† Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

the first and second groups, respectively. The genotype x soil interactions were not significant.

c. Leaf surface area

For both groups of genotypes, the leaf surface area varied among genotypes in the three soils (Tables 47 and 48). Plants grown in the first group had about twice the amount of leaf surface as the genotypes grown in the first group. With each group of genotypes, leaf surface areas of plants grown in the soils followed the sequence of Sharpsburg > Bridgeport > Bridget. Plants grown on the Sharpsburg soil had over two times more leaf area than plants grown on the Bridget soil but had only 25% more leaf area than plants grown on the Bridgeport soil. The genotype x soil interactions for both groups were significant.

d. Chlorophyll content in Fe deficient and green leaves

Leaves from SC 118-15E, Martin, SC 33-9-8-E4 (severely Fe deficient), SC 500-6-1, TAM 428, and NP (slightly Fe deficient) from the first group and KS 56, Norghum (severely Fe deficient), TX 7078, and SD 106 (slightly Fe deficient) from the second group were selected for chlorophyll determinations.

Tables 49 and 50 show fresh and dry weights, specific leaf weights, and leaf areas of the two top leaves taken for chlorophyll determinations. The genotypes differed in leaf surface area in fresh and dry weights in concentrations of chlorophyll a and b, in total chlorophyll concentration, and in Fe deficiency symptoms. In the first group, SC 118-15E, SC 500-6-1, and SC 33-9-8-E4 had comparable leaf surface areas and were higher than the other genotypes. TX 7078 had the highest

Table 49. Fresh and dry weights of the two top leaves from selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse.

Group	Genotype	Soil: Bridget+	Bridgeport+	Sharpsburg	Genotype means‡
		mg/plant			
		Fresh weights			
1	SC 118-15E	183 b†	479 a	573 b	331 A
	Martin	202 b	360 c	288 e	281 B
	SC 33-9-8-E4	225 ab	413 b	676 a	319 A
	SC 500-6-1	241 a	417 b	446 c	329 A
	TAM 428	226 a	278 d	499 c	252 B
	NP	190 b	468 a	396 d	329 A
	Soil means	212 C	402 B	480 A	
2	TX 7078	117 a	244 a	392 a	181 A
	SD 106	126 a	219 ab	259 b	173 A
	KS 56	84 c	141 c	270 b	113 C
	Norghum	94 b	202 b	153 c	148 B
	Soil means	105 C	202 B	268 A	

Table 49. (Continued)

Group	Genotype	Soil: Bridget+	Bridgeport+	Sharpsburg	Genotype means‡
		mg/plant			
		Dry weights			
1	SC 118-15E	33 b	53 c	113 ab	43 B
	Martin	29 b	51 c	59 d	40 B
	SC 33-9-8-E4	28 b	61 b	128 a	45 B
	SC 500-6-1	34 b	62 b	94 bc	48 B
	TAM 428	53 a	65 b	82 c	59 A
	NP	32 b	77 a	73 cd	55 A
	Soil means	35 C	61 B	91 A	
2	TX 7078	17 b	36 a	59 a	27 A
	SD 106	26 a	30 a	39 b	28 A
	KS 56	11 c	17 c	39 b	14 C
	Norghum	13 c	29 b	26 c	21 B
	Soil means	16 C	28 B	41 A	

+ Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 50. Specific leaf weights and leaf surface areas of two top leaves from selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse.

Group	Genotype	Soil			
		Bridget+	Bridgeport+	Sharpsburg	Genotype means‡
		Specific leaf wt. (mg dry wt./(cm^2) leaf surface area)			
1	SC 118-15E	2.5 ab†	1.7 c	3.0 ab	2.1 B
	Martin	2.0 bc	2.1 bc	3.0 ab	2.1 B
	SC 33-9-8-E4	1.9 c	2.3 b	3.4 a	2.1 B
	SC 500-6-1	1.9 c	2.2 b	2.7 b	2.1 B
	TAM 428	2.9 a	3.2 a	2.7 b	3.1 A
	NP	2.3 b	2.4 b	2.8 ab	2.4 B
	Soil means	2.2 B	2.3 B	2.9 A	
2	TX 7078	1.8 b	2.2 a	2.7 a	2.0 A
	SD 106	2.5 a	1.8 b	2.1 b	2.2 A
	KS 56	2.0 b	1.6 b	2.1 b	1.8 A
	Norghum	2.0 b	1.9 b	2.1 b	2.0 A
	Soil means	2.1 AB	1.9 B	2.3 A	

Table 50. (Continued)

Group	Genotype	Soil			
		Bridget[+]	Bridgeport[+]	Sharpsburg	Genotype means[‡]
		Leaf surface area (cm^2/plant)			
1	SC 118-15E	12.9 c	33.7 a	37.2 a	23.3 A
	Martin	14.7 bc	24.8 bc	19.6 d	19.8 B
	SC 33-9-8-E4	15.6 b	26.3 b	36.9 ab	21.0 B
	SC 500-6-1	18.4 a	28.9 ab	35.9 ab	23.6 A
	TAM 428	18.2 a	20.3 c	32.1 b	19.3 B
	NP	13.5 c	32.6 a	25.9 c	23.1 A
	Soil means	15.5 B	27.8 A	31.2 A	
2	TX 7078	8.9 a	16.3 a	22.4 a	12.6 A
	SD 106	9.7 a	16.1 a	18.2 b	12.9 A
	KS 56	5.6 b	11.0 b	18.5 b	8.3 C
	Norghum	6.3 b	15.1 a	11.5 c	10.7 B
	Soil means	7.6 C	14.6 B	17.6 A	

[+] Low Fe soils.
[‡] Average of the low Fe soils.
[†] Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

leaf areas as well as the highest fresh and dry weights of the genotypes in the second group. Fresh leaf weights were higher for SC 33-9-8-E4 compared to the other genotypes in the first group and dry weights were higher for TAM 428, SC 33-9-8-E4, and SC 118-15E. Higher specific leaf weights were noted for TAM 428, but no differences among genotypes were noted in the second group. Thus, TAM 428 most likely had thicker leaves than the other genotypes.

SC 118-15E had the lowest chlorophyll a concentration of the genotypes in the first group. SC 33-9-8-E4 and TAM 428 contained the highest amounts of chlorophyll b. TAM 428 had the highest total chlorophyll and SC 118-15E contained the lowest. The genotypes in the first group did not differ in chlorophyll a/b ratios. In the second group, genotypes did not differ in chlorophyll a and b or in total chlorophyll even though Fe deficiency ratings were different. Norghum had the highest chlorophyll a/b ratio.

Fresh and dry weights of the two top leaves from plants grown on the Sharpsburg soil were higher than for plants grown on the Bridget and Bridgeport soils (Table 49). Even though specific leaf weights were higher for plants grown on the Sharpsburg soil, they were not that much higher than for plants grown on the low Fe soils. Total chlorophyll and chlorophyll a and b concentrations were higher in plants grown on the Sharpsburg soil than in plants grown on the low Fe soils. Plants grown on the Bridgeport soil also had higher chlorophyll than plants grown on the Bridget soil. The chlorophyll a/b ratios were higher in plants grown on the Sharpsburg soil, although they were not statistically different from ratios of plants grown on the Bridgeport soil.

Table 51. *Chlorophyll concentrations in the two top leaves from selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse.*

Group	Genotype	Soil			
		Bridget[+]	Bridgeport[+]	Sharpsburg	Genotype means[‡]
		mg/gm dry wt.			
		Chlorophyll a			
1	SC 118-15E	1.0 b[†]	1.8 c	3.9 b	1.4 C
	Martin	1.3 b	2.4 bc	5.3 a	1.9 BC
	SC 33-9-8-E4	1.7 b	3.8 a	4.1 b	2.9 AB
	SC 500-6-1	1.6 b	3.1 ab	3.7 b	2.4 B
	TAM 428	2.8 a	3.7 a	3.9 b	3.3 A
	NP	1.5 b	2.2 bc	5.1 a	1.9 BC
	Soil means	1.6 C	2.8 B	4.3 A	
2	TX 7078	1.6 a	3.4 a	5.1 a	2.5 A
	SD 106	2.3 a	2.8 a	3.9 a	2.6 A
	KS 56	1.9 a	2.4 a	4.8 a	2.2 A
	Norghum	1.4 a	3.3 a	4.1 a	2.4 A
	Soil means	1.8 C	3.0 B	4.5 A	
		Chlorophyll b			
1	SC 118-15E	0.6 b	0.9 c	2.1 ab	0.8 B
	Martin	0.7 b	0.9 c	1.8 b	0.8 B
	SC 33-9-8-E4	0.8 b	1.9 a	2.5 a	1.4 A
	SC 500-6-1	1.0 b	1.6 ab	1.1 c	1.3 A
	TAM 428	1.6 a	1.4 abc	2.0 ab	1.5 A
	NP	0.9 b	1.3 bc	2.2 ab	
	Soil means	0.9 C	1.3 B	1.9 A	
2	TX 7078	1.0 ab	1.4 a	1.5 b	1.2 A
	SD 106	1.2 ab	1.3 a	1.6 ab	1.3 A
	KS 56	1.4 a	1.2 a	2.0 a	1.3 A
	Norghum	0.8 b	1.4 a	1.6 ab	1.1 A
	Soil means	1.1 C	1.3 B	1.7 A	

Table 51. (Continued)

Group	Genotype	Soil			
		Bridget+	Bridgeport+	Sharpsburg	Genotype means‡
		mg/gm dry wt.			
		Total chlorophyll			
1	SC 118-15E	1.6 b	2.7 c	5.9 bc	2.2 C
	Martin	2.0 b	3.3 c	7.1 ab	2.7 C
	SC 33-9-8-E4	2.5 b	5.6 a	6.6 ab	4.1 AB
	SC 500-6-1	2.6 b	4.6 ab	4.8 c	3.6 B
	TAM 428	4.4 a	5.1 a	5.8 bc	4.8 A
	NP	2.4 b	3.4 bc	7.3 a	2.9 C
	Soil means	2.6 C	4.1 B	6.3 A	
2	TX 7078	2.6 a	4.8 a	6.6 a	3.7 A
	SD 106	3.5 a	4.1 a	5.5 a	3.8 A
	KS 56	3.3 a	3.6 a	6.8 a	3.5 A
	Norghum	2.2 a	4.7 a	5.7 a	3.5 A
	Soil means	2.9 C	4.3 B	6.2 A	

+ Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 52. Degree of Fe deficiency and chlorophyll a/b ratio for the two top leaves of selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse.

Group	Genotype	Soil			
		Bridget[+]	Bridgeport[+]	Sharpsburg	Genotype means[‡]
		Degree of Fe deficiency			
1	SC 118-15E	2.8 a[†]	1.6 a	0.0 a	2.2 A
	Martin	2.1 ab	1.0 a	0.0 a	1.6 AB
	SC 33-9-8-E4	2.8 a	1.3 a	0.0 a	2.1 A
	SC 500-6-1	0.4 c	0.1 b	0.0 a	0.3 C
	TAM 428	0.9 c	0.0 b	0.0 a	0.5 C
	NP	1.8 b	0.3 b	0.0 a	1.1 C
	Soil means	1.8 A	0.7 B	0.0 C	
2	TX 7078	3.8 a	0.8 b	0.0 a	2.3 B
	SD 106	2.4 b	0.4 b	0.0 a	1.4 C
	KS 56	3.4 a	2.5 a	0.0 a	3.0 A
	Norghum	3.8 a	2.4 a	0.0 a	3.1 A
	Soil means	3.3 A	1.5 B	0.0 C	

Table 52. (Continued)

Group	Genotype	Soil			
		Bridget+	Bridgeport+	Sharpsburg	Genotype means‡
		Chlorophyll a/b ratio			
1	SC 118-15E	1.9 a	2.1 b	2.1 bc	2.0 AB
	Martin	1.8 a	2.4 ab	3.2 a	2.1 AB
	SC 33-9-8-E4	2.2 a	1.9 b	1.7 c	2.1 AB
	SC 500-6-1	1.5 b	2.1 b	3.3 a	1.8 B
	TAM 428	1.9 a	2.8 a	2.0 bc	2.4 A
	NP	2.0 a	1.8 b	2.3 b	1.9 B
	Soil means	1.9 B	2.2 AB	2.4 A	
2	TX 7078	1.0 c	2.3 a	3.4 b	1.7 B
	SD 106	2.0 a	2.2 a	2.5 c	2.1 A
	KS 56	1.4 bc	2.0 a	2.5 c	1.7 B
	Norghum	1.7 ab	2.4 a	4.3 a	2.1 A
	Soil means	1.7 C	2.2 B	3.2 A	

+ Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

e. Nutrient element concentrations

Only data for Fe, Mn, Cu, Zn, and P are reported here. Tables 53, 54, 55, 56, and 57 show the concentrations of these nutrient elements in both the upper and lower leaves of genotypes in the first group.

The amounts of Fe, Mn, and Cu accumulated by plants on the three soils were different. Plants grown on Sharpsburg soil had higher Fe concentrations in the upper leaves than plants grown on Bridget and Bridgeport soils. Plants grown on Bridgeport soil had higher Mn and Cu concentrations than plants grown on either Bridget or Sharpsburg soil. However, plants had similar concentrations of P and Zn in the upper leaves on all soils. In the lower leaves, plants grown on Bridget soil had higher concentrations of Mn than plants grown on the other two soils while plants grown on Sharpsburg soil had higher Fe concentrations than plants grown on the low Fe soils. Concentrations of Cu, Zn, and P were similar in the lower leaves for plants grown on the three soils.

Nutrient element concentration data for genotypes in the second group were available only for the upper leaves (Tables 56, 57, and 58). The genotypes in this group accumulated similar amounts of P on all soils (Table 54). Plants grown on Bridgeport soil had higher Cu and Zn concentrations than plants grown on Bridget and Sharpsburg soils. Fe concentrations were higher in plants grown on Bridget soil than in plants grown on Sharpsburg soil. Plants grown on Sharpsburg soil had higher Mn concentrations than plants grown on the low Fe soils.

Within each soil, genotypes differed. Martin and TAM 428 had higher P concentrations in the upper leaves than the other genotypes. Martin also accumulated more Mn, Cu, and Zn on the low Fe soils than the

Table 53. Nutrient element concentrations in the upper leaves of selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse.

Genotype	Soil							
	Bridget†	Bridgeport†	Sharpsburg	Genotype means‡	Bridget†	Bridgeport†	Sharpsburg	Genotype means‡
	µg/g				µg/g			
	Mn				Fe			
SC 118-15E	66.7 c†	83.7 d	57.1 bc	75.0 D	46.0 a	45.3 b	117.7 bc	45.6 A
Martin	134.6 a	190.3 a	44.9 c	162.5 A	46.0 a	55.2 b	120.9 b	50.6 A
SC 33-9-8-E4	94.8 b	115.0 c	97.0 a	104.9 C	32.9 b	41.6 b	85.5 d	37.3 B
SC 500-6-1	87.0 bc	177.0 a	62.6 b	132.0 B	36.0 b	67.0 a	127.3 b	51.5 A
TAM 428	82.5 bc	155.2 b	55.2 bc	118.9 BC	33.1 b	62.4 a	143.3 a	47.8 A
NP	112.7 b	126.7 c	55.2 bc	119.7 BC	43.3 a	45.7 b	105.6 c	44.5 A
Soil means	96.4 B	141.3 A	62.0 C		39.6 C	54.5 B	116.7 A	
	Cu				Zn			
SC 118-15E	7.0 b	11.1 c	14.9 a	9.1 B	42.5 c	39.6 c	54.0 a	41.1 D
Martin	10.4 a	19.3 a	10.1 bc	14.9 A	57.3 a	50.6 ab	43.6 b	54.0 A
SC 33-9-8-E4	10.8 a	11.4 c	12.0 abc	11.1 B	51.4 b	41.3 c	45.9 b	46.4 C
SC 500-6-1	9.6 a	15.3 b	12.4 ab	12.5 AB	48.4 b	55.1 a	54.0 a	51.8 AB
TAM 428	7.6 b	15.7 b	12.7 ab	11.7 B	44.9 c	47.4 b	56.6 a	46.2 C
NP	9.5 a	9.3 c	8.7 c	9.4 B	54.5 a	40.5 c	38.0 c	47.5 BC
Soil means	9.2 C	13.7 A	11.8 B		49.8 A	45.8 A	48.7 A	

† Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 54. Nutrient element concentrations in the lower leaves of selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse.

Genotype	Soil							
	Bridget†	Bridgeport†	Sharpsburg	Genotype means‡	Bridget†	Bridgeport†	Sharpsburg	Genotype means‡
	µg/g				µg/g			
	Mn				Fe			
SC 118-15E	291.4 d†	234.6 d	90.0 a	263.0 D	122.9 a	93.0 b	141.3 c	108.0 B
Martin	--	374.0 b	93.1 a	--	--	115.5 ab	187.6 b	--
SC 33-9-8-E4	334.5 cd	336.8 c	39.2 b	335.7 C	91.7 b	115.9 ab	82.0 d	103.8 B
SC 500-6-1	478.2 b	330.9 c	123.0 a	404.6 B	122.4 a	126.6 a	214.0 a	124.5 A
TAM 428	369.6 c	326.1 c	99.8 a	347.9 C	101.9 b	127.8 a	140.2 c	114.9 B
NP	690.5 a	481.4 a	106.7 a	586.0 A	104.9 b	121.2 a	165.2 b	113.1 B
Soil means	432.8 A	347.3 B	92.0 C		108.8 B	116.7 B	155.1 A	
	Cu				Zn			
SC 118-15E	9.7 c	13.0 b	11.9 b	11.4 B	53.1 a	33.9 c	69.0 a	43.5 B
Martin	--	19.2 a	13.3 ab	--	--	45.1 b	56.3 b	--
SC 33-9-8-E4	10.6 bc	12.4 b	8.5 c	11.5 B	53.2 a	29.4	47.4 c	41.3 B
SC 500-6-1	18.6 a	14.4 b	15.9 a	16.5 A	43.6 b	45.9 b	69.9 a	44.8 B
TAM 428	16.1 a	17.7 a	12.0 b	16.9 A	55.1 a	51.4 a	40.4 c	53.3 A
NP	14.4 ab	18.0 a	12.2 b	16.2 A	46.6 b	37.9 c	58.2 b	41.3 B
Soil means	13.9 A	15.8 A	12.3 A		50.3 A	40.6 B	56.9 A	

† Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 55. Phosphorus concentration in the upper and lower leaves of selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse.

Genotype	Soil			
	Bridget+	Bridgeport+	Sharpsburg	Genotype means‡
	----------% P----------			
		UL		
SC 118-15E	0.96 b†	1.04 b	0.86 b	1.00 B
Martin	1.06 b	1.49 a	0.77 b	1.28 A
SC 33-9-8-E4	0.91 c	0.90 b	0.59 b	0.90 BC
SC 500-6-1	1.07 b	1.09 b	1.29 a	1.08 B
TAM 428	1.21 a	1.39 a	1.18 a	1.30 A
NP	0.60 d	0.90 b	0.83 b	0.75 C
Soil means	0.97 A	1.14 A	0.92 A	
		LL		
SC 118-15E	0.58 c	1.02 b	0.88 b	0.80 BC
Martin	--	1.00 b	0.61 c	--
SC 33-9-8-E4	1.05 a	0.85 b	0.77 bc	0.95 B
SC 500-6-1	0.88 b	1.00 b	1.34 a	0.94 B
TAM 428	1.17 a	1.46 a	1.24 a	1.32 A
NP	0.68 c	0.65 c	0.59 c	0.67 C
Soil means	0.87 A	1.00 A	0.91 A	

+ Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 56. Nutrient element concentration in the upper leaves of selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse.

Genotype	Soil							
	Bridget[+]	Bridgeport[+]	Sharpsburg	Genotype means[‡]	Bridget[+]	Bridgeport[+]	Sharpsburg	Genotype means[‡]
	µg/g				µg/g			
	Mn				Fe			
TX 7078	157.2 a[†]	132.2 b	194.5 a	144.7 B	26.4 b	32.6 b	23.1 b	29.6 C
SD 106	100.4 c	104.8 c	74.1 b	102.6 D	64.6 a	54.9 a	24.3 b	59.8 A
KS 56	153.3 a	187.0 a	177.0 a	170.2 A	55.9 a	62.2 a	66.9 a	59.1 A
Norghum	138.8 b	128.4 b	171.5 a	133.6 C	58.9 a	40.9 b	60.8 a	49.9 B
Soil means	137.4 B	138.1 B	154.3 A		51.5 A	47.7 AB	43.8 B	
	Cu				Zn			
TX 7078	7.4 c	11.3 b	9.2 b	9.4 B	50.4 b	97.5 a	62.5 a	74.0 A
SD 106	9.7 bc	12.7 b	7.9 b	11.2 B	71.1 a	79.0 b	44.9 b	75.0 A
KS 56	16.0 a	19.5 a	14.5 a	17.8 A	55.0 b	65.4 b	64.3 a	60.2 B
Norghum	12.7 ab	13.3 b	17.3 a	13.0 B	46.3 b	36.9 c	48.9 b	42.6 C
Soil means	11.5 B	14.2 A	12.2 B		55.7 B	69.7 A	55.2 B	

[+] Low Fe soils.
[‡] Average of the low Fe soils.
[†] Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 57. Phosphorus concentrations in the upper leaves of selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse.

Genotype	Soil			
	Bridget+	Bridgeport+	Sharpsburg	Genotype means‡
	% P			
TX 7078	1.04 a†	1.10 ab	0.90 a	1.07 A
SD 106	0.65 b	0.88 b	0.80 a	0.77 B
KS 56	1.02 a	1.33 a	1.08 a	1.17 A
Norghum	0.95 a	0.90 b	1.10 a	0.93 AB
Soil means	0.92 A	1.10 A	0.97 A	

+ Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 58. Total Fe content in the upper leaves and dry-matter produced per unit of Fe taken up by selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse.

Genotype	Soil							
	Bridget+	Bridgeport+	Sharpsburg	Genotype means‡	Bridget+	Bridgeport+	Sharpsburg	Genotype means‡
	----------µg Fe----------				----------mg dry wt./µg Fe----------			
TX 7078	3.5 c†	3.4 d	5.1 d	3.5 B	38.4 a	31.4 a	31.0 a	32.9 A
SD 106	4.8 c	8.6 c	14.4 c	6.7 B	32.1 b	18.6 c	15.5 b	20.4 B
KS 56	19.0 a	27.1 a	34.2 a	23.0 A	23.1 c	17.2 c	16.0 b	20.2 B
Norghum	14.9 b	21.0 b	25.4 b	18.0 A	43.5 a	23.5 b	17.6 b	33.5 A
Soil means	10.6 C	15.0 B	19.8 A		32.5 A	23.4 B	20.0 B	

+ Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

other genotypes. In the lower leaves, differences were also noted amongst genotypes in the concentrations of all nutrient elements.

f. Nutrient element ratios

The P:Fe and Mn:Fe ratios in both upper and lower leaves of genotypes in the first group were higher in plants grown on Bridget and Bridgeport soils than in plants grown on Sharpsburg soil (Tables 59 and 60). The Fe:Cu and Fe:Zn ratios were much higher in plants grown on Sharpsburg soil both in the upper and lower leaves.

Table 61 shows the ratios for genotypes in the second group. Both P:Fe and Mn:Fe ratios were much higher for plants grown on Bridget and Bridgeport soils. The Fe:Cu ratios were higher in plants grown on the Bridget soil. However, the Fe:Zn ratios were similar for plants grown on the three soils.

In both groups, genotypes differed within each soil. However, in the first group, the Fe:Zn ratios in the upper leaves and Mn:Fe ratios in the lower leaves were similar for plants grown on Sharpsburg soil. In the second group, the P:Fe, Mn:Fe, and Fe:Zn ratios were much higher in TX 7078 on the low Fe soils than in other genotypes. SD 106 had the lowest P:Fe, Mn:Fe, and Fe:Zn ratios amongst the genotypes.

g. Total Fe content

In both upper and lower leaves, total Fe content was higher in plants grown on Sharpsburg soil than in plants grown on Bridget and Bridgeport soils (Table 62). The difference between Bridgeport and Bridget soils was also significant. In the second group, plants grown on Sharpsburg soil contained twice as much Fe as plants grown on Bridget

Table 59. Nutrient element ratios in the upper leaves of selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse.

Genotype	Soil							
	Bridget†	Bridgeport†	Sharpsburg	Genotype means‡	Bridget†	Bridgeport†	Sharpsburg	Genotype means‡
	P:Fe				Mn:Fe			
SC 118-15E	220.6 cd	239.8 a	78.2 a	230.2 C	1.5 b	2.0 c	0.5 b	1.8 C
Martin	235.5 c	230.9 a	71.5 a	233.2 C	2.9 a	3.5 a	0.4 b	3.2 A
SC 33-9-8-E4	314.5 b	215.9 a	69.9 a	265.2 B	3.0 a	2.8 ab	1.2 a	2.9 A
SC 500-6-1	237.7 c	176.7 b	85.6 a	207.2 CD	1.8 b	2.5 bc	0.5 b	2.2 BC
TAM 428	373.1 a	228.4 a	83.4 a	300.8 A	2.5 a	2.4 bc	0.4 b	2.5 B
NP	205.9 d	198.2 b	89.5 a	202.1 D	2.6 a	2.8 ab	0.5 b	2.7 AB
Soil means	264.6 A	215.0 B	79.7 C		2.4 A	2.6 A	0.6 B	
	Fe:Cu				Fe:Zn			
SC 118-15E	8.2 a	4.3 a	13.3 a	6.3 A	1.1 a	1.2 a	2.5 a	1.2 A
Martin	4.8 b	2.9 b	10.8 b	3.9 B	0.9 a	1.1 a	2.5 a	1.0 A
SC 33-9-8-E4	3.2 c	3.9 a	8.0 c	3.6 B	0.7 a	1.0 a	2.2 a	0.9 A
SC 500-6-1	3.9 bc	4.4 a	10.4 b	4.2 B	0.8 a	1.3 a	2.5 a	1.1 A
TAM 428	4.5 b	4.0 a	11.8 ab	4.3 B	0.8 a	1.4 a	2.7 a	1.1 A
NP	4.7 b	3.9 a	13.1 a	4.3 B	0.8 a	1.1 a	2.1 a	1.0 A
Soil means	4.9 B	3.9 B	11.2 A		0.9 B	1.2 B	2.4 A	

† Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 60. Nutrient element concentration ratios in the lower leaves of selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse.

Genotype	Soil							
	Bridget+	Bridgeport+	Sharpsburg	Genotype means‡	Bridget+	Bridgeport+	Sharpsburg	Genotype means‡
	P:Fe				Mn:Fe			
SC 118-15E	49.2 b†	123.0 a	62.2 b	86.1 B	2.4 c	2.6 b	0.7 a	2.5 B
Martin	--	86.6 b	40.0 c	--	--	3.2 b	0.6 a	--
SC 33-9-8-E4	122.4 a	82.1 b	94.8 a	103.2 A	3.7 b	2.9 b	0.5 a	3.3 B
SC 500-6-1	68.2 b	89.3 b	69.1 b	78.8 B	3.9 b	2.7 b	0.7 a	3.3 B
TAM 428	128.0 a	114.8 a	91.0 a	121.4 A	3.6 b	2.5 b	0.7 a	3.1 B
NP	64.8 b	68.8 b	40.3 c	66.8 B	6.6 a	4.3 a	0.7 a	5.5 A
Soil means	86.5 A	94.1 A	66.2 B		4.0 A	3.0 B	0.7 C	
	Fe:Cu				Fe:Zn			
SC 118-15E	14.0 a	7.4 b	12.5 b	10.7 A	2.3 a	2.7 b	2.2 c	2.5 B
Martin	--	6.2 b	14.8 a	--	--	2.7 b	4.7 a	--
SC 33-9-8-E4	8.5 b	9.3 a	10.1 b	8.9 A	1.8 a	3.8 a	1.8 c	2.8 AB
SC 500-6-1	6.6 b	8.6 a	14.0 a	7.6 B	2.9 a	3.7 a	3.1 b	3.3 A
TAM 428	6.5 b	7.3 b	11.7 b	6.9 B	2.0 a	2.8 b	3.8 ab	2.4 B
NP	7.3 b	6.6 b	13.5 ab	7.0 B	2.3 a	3.1 ab	3.2 b	2.7 B
Soil means	8.6 B	7.6 B	12.8 A		2.3 B	3.3 A	3.1 A	

+ Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 61. Nutrient element concentration ratios in the upper leaves of selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse.

Genotype	Soil							
	Bridget+	Bridgeport+	Sharpsburg	Genotype means‡	Bridget+	Bridgeport+	Sharpsburg	Genotype means‡
	P:Fe				Mn:Fe			
TX 7078	398.2 a†	360.2 a	372.2 a	379.2 A	6.2 a	4.0 a	8.4 a	5.1 A
SD 106	99.9 c	162.0 c	364.2 a	131.0 C	1.5 b	1.9 b	3.2 b	1.7 B
KS 56	186.7 b	223.1 b	166.3 b	204.9 B	2.8 b	3.1 a	2.7 b	3.0 B
Norghum	170.6 b	220.7 b	199.5 b	195.7 B	2.5 b	3.2 a	2.9 b	3.0 B
Soil means	213.9 C	241.5 B	275.6 A		3.3 B	3.0 B	4.3 A	
	Fe:Cu				Fe:Zn			
TX 7078	3.8 b	2.9 b	2.5 b	3.4 B	1.5 a	1.4 a	2.7 a	1.5 A
SD 106	8.8 a	4.5 a	3.1 b	6.7 A	1.0 a	0.7 b	0.5 c	0.9 B
KS 56	3.5 b	3.6 ab	4.7 a	3.6 B	1.0 a	0.9 ab	1.0 b	1.0 AB
Norghum	4.7 b	3.1 b	3.5 b	3.9 B	1.3 a	1.1 ab	1.4 b	1.2 AB
Soil means	5.2 A	3.5 B	3.5 B		1.2 A	1.0 A	1.4 A	

+ Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

Table 62. Total Fe content and the UL/LL Fe ratios of selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse.

Genotype	Soil							
	Bridget+	Bridgeport+	Sharpsburg	Genotype means‡	Bridget+	Bridgeport+	Sharpsburg	Genotype means‡
	µg Fe				µg Fe			
	UL				LL			
SC 118-15E	4.8 a†	10.9 b	46.4 a	7.9 B	7.8 a	11.2 b	23.9 a	9.5 B
Martin	4.3 a	12.7 b	31.5 b	8.5 B	--	10.9 b	18.7 b	--
SC 33-9-8-E4	4.1 a	8.5 b	38.0 b	6.3 B	5.8 a	12.4 b	10.8 c	9.1 B
SC 500-6-1	5.0 a	20.7 a	46.2 a	12.9 A	8.2 a	16.1 a	24.9 a	12.1 A
TAM 428	4.0 a	8.9 b	45.3 a	6.5 B	8.3 a	9.8 b	13.3 c	9.0 B
NP	4.3 a	10.5 b	32.7 b	7.4 B	6.2 a	11.1 b	16.7 bc	8.7 B
Soil means	4.4 C	12.1 B	40.0 A		7.3 C	11.9 B	18.1 A	
	Total (UL+LL)				UL/LL			
SC 118-15E	12.6 a	21.8 b	70.3 a	17.2 B	0.61 a	0.98 b	1.68 b	0.80 B
Martin	--	24.7 b	50.1 bc	--	--	1.26 b	1.96 b	--
SC 33-9-8-E4	9.6 b	20.9 b	51.3 bc	15.3 B	0.54 a	0.42 c	0.76 c	0.48 C
SC 500-6-1	14.1 a	37.9 a	71.0 a	26.0 A	0.74 a	2.34 a	2.36 b	1.54 A
TAM 428	12.1 a	20.4 b	58.7 b	16.3 B	0.47 a	1.21 b	3.62 a	0.84 B
NP	9.0 b	21.2 b	49.3 c	15.1 B	0.45 a	1.05 b	1.80 b	0.75 B
Soil means	11.5 C	24.5 B	58.5 A		0.56 C	1.21 B	2.03 A	

+ Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

soil. Plants grown on Bridgeport soil also had higher Fe content than plants grown on Bridget soil.

The genotypes showed differences in Fe content also. On the Bridget soil, however, Fe contents among genotypes in both upper and lower leaves were similar. On the Bridgeport soil, SC 500-6-1 contained higher Fe in both upper and lower leaves than the other genotypes. Differences amongst genotypes in Fe content were smaller on the Sharpsburg soil. In the second group, KS 56 had the highest Fe content amongst the genotypes grown on all soils.

For genotypes in the first group, the ratio of the Fe content in the upper leaves to that in the lower leaves was much higher in plants grown on Sharpsburg soil. The ratio was twice as high in plants grown on Bridgeport soil as in plants grown on Bridget soil. The genotypes had similar ratios on the Bridget soil but differed on both Bridgeport and Sharpsburg soils.

h. Dry matter produced per unit Fe

Plants grown on Bridget and Bridgeport soils produced more dry matter per unit of Fe taken up in both upper and lower leaves than plants grown on Sharpsburg soil (Table 63). The genotypes differed in the amount of dry matter produced per unit of Fe. SC 33-9-8-E4 produced the highest upper leaf dry matter per unit of Fe taken up and TAM 428 produced the lowest. Dry-matter production in the lower leaves was similar amongst the genotypes on the three soils.

In the second group of genotypes, plants grown on Bridget soil had the highest dry-matter production per unit of Fe taken up (Table

Table 63. Dry-matter produced per unit of Fe taken up by selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse.

Soils	Genotypes						
	SC 118-15E	Martin	SC 33-9-8-E4	SC 500-6-1	TAM 428	NP	Soil means
	mg dry wt./µg Fe						
				UL			
Bridget+	23.1 c†	22.4 c	34.3 a	28.8 b	30.1 ab	20.2 c	21.7 A
Bridgeport+	23.1 a	18.8 b	23.7 a	16.7 b	16.7 b	21.9 a	20.1 A
Sharpsburg	9.0 b	9.3 b	11.8 a	8.7 b	7.2 b	11.5 a	9.6 B
Genotype means‡	23.1 B	20.6 BC	29.0 A	22.8 B	18.4 C	21.0 BC	
				LL			
Bridget+	8.3 c	--	11.2 b	14.4 a	11.7 b	9.5 c	11.0 A
Bridgeport+	11.9 a	8.7 bc	9.6 b	8.8 bc	7.9 c	10.5 ab	9.6 A
Sharpsburg	7.1 b	6.3 bc	12.2 a	5.2 c	7.6 b	7.1 b	7.6 B
Genotype means‡	10.1 A	--	10.4 A	11.6 A	9.8 A	10.0 A	

+ Low Fe soils.
‡ Average of the low Fe soils.
† Numbers followed by the same letter in each column are not significant at P=0.05 according to Duncan's Multiple Range Test.

58). The productivity of plants grown on Bridgeport and Sharpsburg soils was similar. The genotypes also differed on each soil. TX 7078 had the highest dry-matter production per unit of Fe on Bridgeport and Sharpsburg soils. Norghum had the highest dry-matter production per unit of Fe on Bridget soil. On the low Fe soils, TX 7078 and Norghum had the higher dry-matter production per unit of Fe.

4. Discussion

Even though a particular sorghum genotype may have been classified as 'Fe-efficient' or 'Fe-inefficient,' nearly every plant grown at very low Fe levels will develop Fe deficiency symptoms. How early these symptoms appear and how severe they become will depend upon the initial Fe reserve in the seed. The genotypes identified as 'Fe-efficient' in nutrient solution screening studies became more Fe deficient than genotypes identified as 'Fe-inefficient' (Table 31). Except for Martin, as Fe increased in solution, genotypes identified as 'Fe-inefficient' became more Fe deficient than those identified as 'Fe-efficient.' These differences could be either due to differences in the rate of Fe uptake or due to differences in the amount of Fe required for growth and metabolism. The differences in responses among genotypes could not be explained because of pH changes in the growth medium. In this experiment (varied Fe levels) Martin (an 'Fe-inefficient' genotype) behaved similar to SC 33-9-8-E4 (an 'Fe-efficient' genotype). The response of Martin might be explained in two ways. Firstly, Martin was classified as 'Fe-inefficient' in nutrient solutions where the genotypes were grown together in the same container. Martin would have to compete against the other genotypes for the Fe in solution. If the competitive ability

of Martin was not sufficiently high, it would become Fe deficient while the others would remain green. Secondly, Martin was one of the most vigorous genotypes and its Fe requirements may be higher than those of the other genotypes.

In a study with barley plants, Agarwala et al. (1964) reported an increase in the dry-matter yields with increasing Fe supplies. Miller et al. (1961) reported similar results for field beans. Twyman (1959) reported that total dry weight of tomato plants decreased with low Fe. Root yields of carrots increased with added Fe (Gupta and Chipman, 1976). Iron deficiency symptoms on carrot leaves and reduced yields of carrot plants were associated with 39 to 82 μg/g Fe in the growth medium. Agarwala et al. (1955) obtained optimal yields of maize and radish at 0.5 and 0.1 mM Fe, respectively. In both plant species, characteristic Fe deficiency effects were produced at lower levels of Fe. The dry-matter yield and the genotype responses to varied levels of Fe are in agreement with the observations reported by other workers. The addition of only 5 μM Fe (the lowest level of Fe used) yielded 190% more dry matter in the tops than that of the no Fe treatment. Higher rates of Fe brought about further yield increases, but the magnitude of the increases diminished as the level of Fe increased. For six genotypes, the optimum level of Fe for root dry-matter production was 16 μM Fe (Table 32).

Top/root dry-matter ratios were higher for plants grown in solution with no added Fe. The lack of Fe restricted both top and root growth, but the restriction appeared to affect roots more than tops (Table 33).

Both the concentration and total Fe content were found to increase as the level of Fe in the growth medium increased. These results agree with DeKock et al. (1960) who reported higher Fe concentrations in mustard leaves as the Fe supply increased.

The results also indicated the existence of antigonism between Fe and Mn, Zn, and P. In all plant parts, the concentration of Mn was noted to decrease with increased Fe level. This agrees with the findings of Tanaka and Navasero (1966) who reported a decrease in Mn content of rice plants with increasing Fe levels. Zinc concentrations in the upper leaves and the roots decreased as the level of Fe increased. This is in agreement with the findings of Bassiri et al. (1979) who observed decreases in Zn concentration in Mung beans with increasing Fe levels in the soil. Brown et al. (1963) reported that Zn reduced the uptake and transport of Fe by 15% when present in the nutrient solution at levels as low as 5×10^{-6} M.

The Fe nutrition of plants is also highly associated with their P nutrition. Phosphate generally accentuates Fe deficiency in plants. DeKock (1955) emphasized P:Fe ratio in plants as a useful index of their Fe status. Biddulph and Woodbridge (1952) found that at pH 7, Fe was precipitated on the surface and within the roots of soybean plants grown with KH_2PO_4 at 10^{-3} M. The soluble Fe in a nutrient solution as acid at pH 4 may be severely decreased by an increase in soluble P (Holmes, 1960). Wallace et al. (1978) reported that at high pH, increasing solution P decreased Fe in roots but not in leaves and stems of soybeans. In contrast, at low pH, increasing the P resulted in less Fe in leaves, stems, and roots. Iron concentrations declined in both millet and

sorghum as P levels increased and high P concentration in the growth medium inhibited ^{55}Fe absorption and translocation in both crops (Ajakaiye, 1979)

In this study (varied Fe levels) the P concentrations in the upper leaves of plants grown without added Fe were twice as high as those in the upper leaves of plants grown with Fe. However, there were no differences in P concentrations in the leaves and roots of plants grown with added Fe. The genotypes did not differ in P concentrations in all plant parts. These findings deviate from those of Mikesell et al. (1973) who reported that under Fe deficient conditions, 'Fe-inefficient' genotypes tended to accumulate high P than 'Fe-efficient' genotypes.

The P:Fe and Mn:Fe ratios were found to be much higher in plants grown without added Fe. The results agree with the findings of previous workers (DeKock et al., 1960) who reported decreases in P:Fe ratios with increasing Fe level in the growth medium. However, the Mn:Fe and Zn:Fe ratios in the upper leaves and roots decreased as the Fe level increased.

The most Fe deficient genotype SC 118-15E had higher P:Fe and Mn:Fe ratios in both upper and lower leaves as well as higher Mn:Fe ratios in the roots and Zn:Fe ratios in the upper and lower leaves when plants were grown with added Fe. Plants grown without added Fe had higher dry matter per unit Fe than plants grown with added Fe. The most Fe deficient genotype produced the highest upper leaf and root dry matter per unit of Fe taken up.

Several years ago, Brown et al. (1961) reported the release of fluorescing materials from the roots of Hawkeye (HA) and PI-54619-5-1

(PI) soybeans. More fluorescent materials were released from the HA ('Fe-efficient') than from PI ('Fe-inefficient') soybeans. The release of the fluorescent materials was considered incidental to the greater reduction of Fe^{3+} to Fe^{2+} by the root of Fe deficient HA than by the Fe deficient PI soybeans. Subsequent studies indicated that in addition to reduction of Fe^{3+} by the root, nutrient solutions that had HA soybeans grown in them reduced more Fe^{3+} than nutrient solutions in which PI soybeans had grown. Ambler et al. (1970) also showed that Zn suppressed the formation of 'reductant' in the roots of HA soybeans.

The release of some type of 'reductant' by tomato [Lycopersicon esculentum (L.) Mill] roots into nutrient solution has also been established (Ambler, 1971). Even though the nature of the 'reductant' has not been determined, Raju and Marschner (1972) observed a release of riboflavin from the roots of sunflower plants growing in culture solution under Fe-stress conditions following the precipitation of Fe^{3+}-phosphate in the solution. This release was accompanied by a decrease in pH in culture medium brought about by an excess cation uptake over anion uptake. The decreased pH and the reducing effect of the riboflavin mobilized precipitated Fe by reducing it to Fe^{2+}. Iron availability was thus improved and regreening occurred in the plants.

The 'reductant' can reduce inorganic Fe^{3+} and chelated Fe^{3+} (Brown et al., 1973) if present in sufficient quantities. These workers were of the opinion that the 'reductant' contains phenolic compounds which react to keep iron as Fe^{2+}. Their belief was further strengthened by Himes et al. (1963) who found that phenolic compounds contained in the water extract oak leaves solubilized Fe from freshly precipitated ferric

hydroxide. Olson et al. (1980) noted that p-coumaric acid (phenolic compound) was effective in reducing Fe^{3+} to Fe^{2+} in tomato.

Roots exudates are not uncommon, but the 'reductant' released from Fe-deficient HA soybeans was believed to be adaptive. That is, it is controlled by the Fe supply. The 'reductant's' major role in the root may be its ability to keep Fe^{2+} in the reduced state, thereby increasing its mobility and availability for transport (Brown et al., 1961).

Even though 'Fe-efficient' and 'Fe-inefficient' sorghum genotypes were grown under sufficient levels of Fe, 'reductant' released by the roots was detected. The release of 'reductants' could have been induced since Fe was supplied as a chelate (Fe-HEDTA). Since chelates compete with plant roots for Fe in the growth media (Brown et al., 1960), this competition could induce the release of 'reductant' by the roots. The higher the level of Fe added, the more the 'reductant' released by the roots to compete with the chelate (Table 46).

Brown et al. (1973) proposed that the presence of 'reductants' in the external solution may be indicative of a leaky root resulting from a lowering of the pH of the nutrient solution. Of more importance, however, may be the adaptive production of 'reductants' inside the root as a result of Fe deficiency to keep Fe in the more available Fe^{2+} form.

The sorghum genotypes used in this experiment showed no significant differences in 'reductant' released until after day 12 (6 days after treatments were added). After that time, one 'Fe-efficient' genotype (SC 33-9-8-E4) released more 'reductant' than the other genotypes (Table 46). The responses of the other genotypes one considered to be 'Fe-efficient' (NP) and two considered to be 'Fe-inefficient' (SC 118-15E and Martin) showed no particular trend in the amounts of 'reductant'

released. Top, root, and total dry-matter yields did not differ among the varied Fe rates (Table 45). In fact, the yields decreased gradually as the supply of Fe increased above 18 mM indicating that at the higher rates, Fe may have had interacting or toxic effects. Toxic effects of Fe have been reported to be above 3000 µg/g Fe for rice (Tanaka and Navasero, 1966). Iron levels causing toxic effects in sorghum have not been reported. The effects of the higher Fe rates on decreased dry matter appeared to be more damaging to roots than to tops. The levels of Fe in the soil greatly influenced plant height and leaf surface areas (Tables 47 and 48). Genotypes also differed in these parameters.

Of the genotypes selected for chlorophyll determinations, differences in chlorophyll concentrations were noted only for the genotypes in the first group. SC 118-15E had the lowest chlorophyll a concentration (Table 51). Both SC 118-15E and Martin had the lowest concentrations of chlorophyll b and total chlorophyll. In both groups, genotypes differed in fresh and dry weights and leaf areas. TAM 428 also had a higher specific leaf weight than the other genotypes in the first group.

The level of Fe supply greatly influenced the chlorophyll concentrations in plants (Table 51). Plants grown on the Fe sufficient soil generally contained 2.1 and 1.4 times more total chlorophyll than plants grown on the Bridget and Bridgeport soils, respectively. These results agree with Sideris and Young (1956) who reported that the total chlorophyll concentrations in pineapple leaves were 2.2 times greater in plants grown with ample Fe as in Fe deficient plants. Shetty and Miller (1966) reported that chlorophyll a and b in tobacco chloroplasts isolated from chlorotic tissue was lower than that of normal tissue. They noted

a 45% decrease in chlorophyll labelling in deficient tissue compared to normal tissue. A marked correlation between Fe supply and chlorophyll content in Timothy and Yorkshire grasses has also been reported (O'Sullivan, 1969). Agarwala et al. (1965) observed a linear correlation between chlorophyll concentration and Fe supply in maize and radish up to a concentration of about 0.5 μM Fe. Marsh et al. (1963) reported that Fe deficiency in cowpea resulted in the limited formation of a-amino leavulinic acid which is a rate-limiting step in chlorophyll synthesis.

The limited Fe supply seemed to impose a greater limitation on the synthesis of chlorophyll a than on chlorophyll b. This is pointed out by the amounts of chlorophyll a noted in plants grown on the Bridget and Bridgeport soils. Plants grown on Bridget and Bridgeport soils had only 40% and 67%, respectively, chlorophyll a concentration in plants grown on the Sharpsburg soil, whereas the chlorophyll b concentrations in plants grown on the Bridget and Bridgeport soils were 64% and 80%, respectively, of that found in plants grown on the Sharpsburg soil. Chlorophyll a/b ratios were higher for plants grown on the Sharpsburg soil.

In the first group of genotypes, plants grown on the Fe sufficient Sharpsburg soil had higher Fe concentrations in the upper leaves than plants grown on the low Fe soils, but genotypes in the second group had higher Fe concentrations in the upper leaves when grown on Bridget soil. Both of these findings agree with the findings of other workers. DeKock et al. (1960) reported higher Fe concentrations in Fe deficient mustard leaves than in green leaves. On the other hand, Sideris and Young

(1956) reported higher Fe concentrations in green leaves of pineapple plants than in the Fe deficient leaves.

In both groups of genotypes, plants grown on Bridget and Bridgeport soils had higher Mn and Cu concentrations in the upper leaves than plants grown on Sharpsburg soil. This was not surprising since the high Fe supply in the Sharpsburg soil would depress the uptake and translocation of Mn, Cu, and Zn (Tanaka and Navasero, 1966; Dokiya et al., 1968). The P and Zn concentrations in the upper leaves of plants were similar on all soils.

The nutrient element ratios are in total agreement with Biddulph et al. (1952) who reported lower P:Fe ratios in bean plants as the supply of Fe in the growth medium increased. In both groups of genotypes, P:Fe and Mn:Fe ratios were higher for plants grown on the low Fe soils than in plants grown on the Fe sufficient soil. The reverse was the case for Fe:Cu ratios. Of the genotypes in the second group, the P:Fe and Mn:Fe ratios were higher in TX 7078 which had only slight Fe deficiency symptoms. This did not agree with the findings of Mikesell et al. (1973) who observed that under low Fe conditions, 'Fe-inefficient' genotypes tended to have higher P:Fe ratios than the 'Fe-efficient' sorghum genotypes.

Total Fe content in both groups of genotypes was higher for plants grown on Sharpsburg soil. But, dry-matter production per unit of Fe taken up was much higher for plants grown on the low Fe soils than for plants grown on the Fe sufficient soil. The genotypes also differed. Two genotypes SC 500-6-1 (slightly Fe deficient) and KS 56 (severely Fe deficient) generally had higher Fe contents than the other

genotypes. However, some of the genotypes, TX 7078 (slightly Fe deficient), SC 33-9-8-E4 and Norghum (severely Fe deficient) had the highest dry-matter production per unit of Fe taken up on the low Fe soils.

SUMMARY AND CONCLUSIONS

Sorghum [Sorghum bicolor (L.) Moench] genotypes were screened for differential Fe use by inducing Fe deficiency through the addition of P, $CaCO_3$, and using NO_3^- as the source of N in nutrient solutions. Some genotypes were also screened in low Fe and Fe-sufficient soils in a greenhouse to correlate the nutrient solution responses with those in the soil.

Some physiological properties of selected genotypes evaluated were (1) genotype responses to varied levels of Fe, (2) 'reductant' released by the roots into nutrient solution, (3) differential changes in solution pH, (4) plant height and leaf surface area, (5) chlorophyll concentrations, (6) mineral element concentrations and ratios, and (7) dry matter produced per unit Fe taken up.

Genotypes differed in their response to induced Fe deficiency. In nutrient solution studies, SC 33-9-8-E4, NP, Plainsman, KS 5, SD 102, SC 149, TX 412, and Norghum (U.S. genotypes), RZ 1, L 181, and KANO L.1 Nigerian genotypes were considered to be more 'Fe-efficient' and SC 118-15E, Redlan, Martin, SC 109-9, KS 56, SC 369-3-1JB, TX 7078, CK 60 (U.S. genotypes), FFB-L, SK 5912, L 187, and C 7.4 (Nigerian genotypes) were considered to be 'Fe-inefficient' based on the degree of Fe deficiencies. In the low Fe soils, SC 500-6-1, NP, TAM 428, and SD 106 were considered to be 'Fe-efficient' and SC 118-15E, SC 369-3-1JB, SC 109-9, KS 56, Norghum, Wheatland, and SC 33-9-8-E4 were considered to be 'Fe-inefficient.'

On the basis of the degree of Fe deficiency symptoms, the nutrient solution results did not correlate closely with the soil results. When P and NO_3^- treatments were added to 7-, 10-, and 14-day-old seedlings, the younger seedlings became Fe deficient first. However, at the time experiments were terminated, the older plants were more Fe deficient than the younger plants. The two treatment effects were similar only on 10-day-old seedlings. The 7-day-old seedlings developed more severe Fe deficiency symptoms in the NO_3^- treatment, and 14-day-old plants developed more severe Fe deficiency symptoms in the added P treatments.

Regardless of the age at which the two treatments were added to plants, the genotypes differed in the degree of Fe deficiency symptoms. The various genotypes also differed in dry-matter yields. The most effective treatments were 0.39 mM P and NO_3^- added at 1.4 mM N/plant.

When plants were supplied with NO_3^- as the source of N, the pH of the growth media decreased initially and then increased for the duration of the experiments. When plants were induced into Fe deficiency by the addition of P or supplying N as NH_4^+, the pH of the nutrient solutions decreased throughout the duration of the experiments. When $CaCO_3$ was added in the growth medium, the pH decreased and after 4 days increased.

Dry-matter reductions due to Fe deficiencies induced in nutrient solutions were small because of the short duration of the stresses imposed (7 days). However, in the low Fe soils the reductions in dry-matter yields caused by the low Fe were large.

From these experiments, the following conclusions were drawn: (1) Fe deficiency can be induced by withholding Fe, by the addition of

excess P and $CaCO_3$ or by using NO_3^- or NH_4^+ alone as a source of N.

(2) Plants that developed moderate Fe deficiency symptoms had only small reductions in dry matter.

(3) Rate of Fe deficiency development depended upon the age of the plants used.

(4) Added NO_3^- induced Fe deficiency in young seedlings but not in older seedlings. Added P induced Fe deficiency at all seedling ages.

(5) Sorghum can be screened for 'Fe-efficiency' in nutrient solutions. The optimum or best conditions to screen for 'Fe-efficiency' were:

(a) Four-day-old seedlings grown in 0.3 strength nutrient solution for 3 days without added Fe.

(b) At 7 days of age, uniform seedlings were transferred to a full strength nutrient solution with 2.3 µMole Fe and either 0.39 mM P or 0.15 mM $CaCO_3$. Plants were grown in these treatment solutions for 7 days.

(c) Alternatively, 7-day-old or older plants could be supplied with 2.3 µMole Fe and NO_3^- only as the N source at 1.4 mM N/plant or the same Fe level and 0.39 mM P and plants should remain in treatment solutions for 5-7 days. As many as 125 plants/7.0 l container could be used.

The four genotypes grown with three levels of Fe did not differ in the amount of 'reductant' released by the roots for the first two sampling dates. After 6 days in treatment, SC 33-9-8-E4 released more 'reductant' than the other genotypes. The higher the level of Fe in the growth medium the more 'reductant' released by plant roots. 'Reductant' released by plants grown with 54 µM Fe was 5 to 6 times higher than

'reductant' released by plants grown with 18 μM Fe. Decreased pH of the growth medium increased 'reductant' and subsequent increase in pH decreased 'reductant.' Sorghum genotypes will release 'reductant' from their root even when supplied with adequate levels of Fe.

The low Fe in the Bridget and Bridgeport soils caused marked reductions in plant heights, leaf surface areas, chlorophyll a and b, and total chlorophyll concentrations. Plants grown on the Fe-sufficient soil had higher specific leaf weights than those grown on the low Fe soils. More severe Fe deficiencies were noted on plants grown on the Bridget soil than on plants grown on the Bridgeport soil even though both soils had similar amounts of available Fe. These differences could have been due to the higher Zn in the Bridget soil which may have interacted with Fe. The Bridgeport soil gave better differential Fe deficiencies than the Bridget soil. The Fe deficiencies on plants grown on Bridget were too severe to give good differential responses among genotypes screened for 'Fe-efficiency.'

In nutrient solutions, Fe concentrations in the upper leaves and roots increased with increasing Fe level in the growth medium. Manganese concentrations decreased in all plant parts as the level of Fe increased. Similarly, Zn concentrations in the upper leaves and roots decreased. Phosphorus concentrations in all plant parts were similar irrespective of the level of added Fe. However, plants grown without added Fe had higher P concentrations than plants grown with added Fe. Total Fe content was higher in the upper leaves (Fe-deficient) of plants than in the lower leaves and roots. Plants grown without added Fe produced more dry matter per unit of Fe taken up. Genotypes differed in these variables at each Fe level.

When plants were grown on low Fe and Fe-sufficient soils, plants in the first group had higher Fe concentrations in the upper leaves when grown on the Fe-sufficient soil than plants grown on the low Fe soils. Genotypes grown on the Fe-sufficient soil also had higher total Fe content. Plants grown on Bridgeport (low Fe) soil had higher Mn and Cu concentrations than plants grown on Sharpsburg (Fe-sufficient) soil. Genotypes had similar P and Zn concentrations in both upper and lower leaves on all soils. Plants grown on the low Fe soils produced more dry matter per unit of Fe taken up. The genotypes also differed on each soil for dry matter produced per unit Fe taken up and Fe, Mn, Cu, and Zn concentrations.

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Table A1. Mean squares for top, root, total dry-matter yields, top/root dry-matter ratios, and degree of Fe deficiency symptoms of sorghum genotypes grown with added P and $CaCO_3$ (Expt. 1).

Source of variation	df	Tops	Roots	Total	Top/Root	Degree of Fe deficiency
Model	59	1860.25**	615.64**	4525.78**	0.16	1.07**
Treatments (A)	3	1049.63	1356.90	5386.62	0.86**	2.03
Error (a)	14	2728.82	747.66	6382.97	0.14	2.71
Genotypes (B)	13	6503.93**	1708.60**	15320.74**	0.15	2.89**
A x B	39	285.62	180.75	670.77	0.10	0.22
Error (b)	52	168.73	129.95	389.85	0.07	0.31
Total	111	1067.82	388.11	2588.23	0.12	0.71
C.V. %		16.82	26.89	16.64	13.76	23.83

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A2. Mean squares for top, root, total dry-matter yields, top/root dry-matter ratios, and degree of Fe deficiency symptoms of sorghum genotypes grown with added P and $CaCO_3$ (Expt. 2).

Source of Variation	df	Tops	Roots	Total	Top/Root	Degree of Fe Deficiency
Model	51	5226.07**	2622.37	13705.86**	0.20**	1.12**
Treatments (A)	3	6715.70**	949.39	7416.74	1.56**	8.37**
Error (a)	4	2245.03	998.69	6784.84	0.15	0.52
Genotypes (B)	11	18472.43**	9853.78**	50114.70**	0.28**	1.39**
A x B	33	1036.53	560.80	2980.23	0.06	0.44*
Error (b)	44	636.46	381.35	2078.98	0.04	0.10
Total	95	3100.35	1584.42	8320.78	0.12	0.65
C.V. %		21.04	26.10	23.57	11.34	35.20

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A3. Mean squares for top, root, total dry-matter yields, top/root dry-matter ratios, and degree of Fe deficiency symptoms of sorghum genotypes grown with different sources of N (Expt. 3).

Source of Variation	df	Tops	Roots	Total	Top/Root	Degree of Fe deficiency
N sources	2	25543.36**	12316.45**	67063.74**	0.90**	9.52**
Error (a)	3	488.67	1816.93	3679.06	0.60	1.23
Model	44	7755.05**	1921.96**	16243.72**	0.22	1.26**
Genotypes (B)	13	18632.11**	3236.58**	37049.46**	0.22**	2.27**
A x B	26	1744.32**	477.20*	3381.39	0.13*	0.12
Error b	39	506.61	165.42	1065.42	0.05	0.12
Total	83	4349.16	1096.60	9111.75	0.14	0.72
C.V. %		12.86	14.82	12.52	11.08	15.60

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A4. Mean squares for top, root, total dry-matter yields, top/root dry-matter ratios, and degree of Fe deficiency symptoms of sorghum genotypes grown with different sources of N (Expt. 4).

Source of Variation	df	Tops	Roots	Total	Top/Root	Degree of Fe deficiency
N sources (A)	2	8453.17**	599.50	7893.22	0.10	5.01**
Error (a)	6	2723.42	1061.65	9098.80	0.18	0.83
Model	32	9460.57**	2256.40**	20250.59**	0.20*	0.94**
Genotypes (B)	8	21467.30**	3845.30**	41020.76**	0.34*	1.22**
A x B	16	6109.57**	2117.09**	15592.09**	0.15	0.33**
Error (b)	48	1620.25	324.28	3932.52	0.09	0.15
Total	80	4756.38	1097.13	10459.75	0.13	
C.V. %		15.16	15.78	16.83	12.58	17.45

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A5. Mean squares for top, root, total dry-matter yields, top/root dry-matter ratios, and degree of Fe deficiency symptoms of sorghum genotypes grown with different sources of N (Expt. 5).

Source of Variation	df	Tops	Roots	Total	Top/Root	Degree of Fe deficiency
N sources (A)	2	1082.64	712.93	360.79	0.50**	15.25**
Error (a)	6	4221.23	993.13	7502.38	0.15	0.16
Model	32	5881.74**	1336.41*	11208.56**	0.18**	1.65**
Genotypes (B)	8	16461.25**	3675.77**	30694.40**	0.39**	1.56**
A x B	16	1814.55	373.59	4211.41	0.04	0.56**
Error (b)	48	1656.42	527.41	3702.55	0.07	0.19
Total	80	3346.54	851.01	6704.95	0.11	0.77
C.V.		19.35	21.04	19.19	13.23	21.27

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A6. Mean squares for top, root, total dry-matter yields, top/root dry-matter ratios, and degree of Fe deficiency symptoms for sorghum genotypes grown with P and NO_3^- added when seedlings were 7 days old.

Source of Variation	df	Tops	Roots	Total	Top/Root	Degree of Fe Deficiency
Treatments (A)	1	735.15**	7.21	609.18**	7.91**	17.72**
Error (a)	2	7.45	23.04	35.11	1.49	1.16
Model	29	239.22**	50.76**	457.71**	1.93	1.73**
Genotypes (B)	13	446.20**	99.00**	933.71	1.70	1.84**
A x B	13	29.75	10.12	35.08	1.76	0.48
Error (b)	26	24.18	11.80	41.81	1.52	0.17
Total	55	137.57	32.34	261.10	1.73	0.99
C.V. %		14.11	19.05	12.15	19.71	29.83

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A7. Mean squares for top, root, total dry-matter yields, top/root dry-matter ratios, and degree of Fe deficiency symptoms of sorghum genotypes grown with P and NO_3 added when plants were 10 days old.

Source of Variation	df	Tops	Roots	Total	Top/Root	Degree of Fe deficiency
Treatments (A)	1	323.04**	1034.58**	1737.17*	2.14*	2.28
Error (a)	2	20.21	38.07	100.95	0.73	3.39
Model	29	1437.47**	306.35**	2990.53**	0.83	1.32**
Genotypes (B)	13	2681.02**	439.75**	5734.43**	0.87	1.98**
A x B	13	497.69	158.20	787.59	0.70	0.26
Error (b)	26	343.19	81.22	600.44	0.55	0.23
Total	55	920.18	199.92	1860.67	0.70	0.80
C.V. %		21.22	23.09	19.24	31.15	26.50

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A8. Mean squares for top, root, total dry-matter yields, top/root dry-matter ratios, and degree of Fe deficiency symptoms of sorghum genotypes grown with P and NO_3 added when plants were 14 days old.

Source of Variation	df	Tops	Roots	Total	Top/Root	Degree of Fe deficiency
Treatments (A)	1	1212.72	6681.73**	11442.86	4.78**	66.45**
Error (a)	2	2951.12	1015.89	11892.16	0.71	0.36
Model	29	7086.63**	2365.18**	17293.09**	0.43*	2.80**
Genotypes (B)	13	14478.05**	4152.94**	31936.33	0.30	0.59**
A x B	13	783.29	452.96	3930.79**	0.19	0.49**
Error (b)	26	622.14	502.78	4450.74	0.22	0.10
Total	55	4030.69	1484.77	11222.16	0.33	1.52
C.V. %		14.14	25.55	25.00	21.76	27.23

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A9. Mean squares for top dry-matter yields, plant height, leaf surface area, and degree of Fe deficiency symptoms of sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse (Group 1).

Source of Variation	df	Tops	Height	Leaf Area	Degree of Fe Deficiency
Model	44	17800.73**	13.53**	700.54**	3.44**
Genotypes (A)	13	8704.32**	7.05**	257.37**	2.12**
Soils (B)	2	303958.47**	210.88**	11318.37**	53.07**
A x B	26	2169.46**	2.96**	174.01**	0.67**
Error	123	1040.71	1.18	40.06	0.18
Total	167	5456.52	4.43	214.08	1.04
C.V. %		22.26	8.89	17.21	23.59

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A10. Mean squares for top dry-matter yields, plant height, leaf surface area, and degree of Fe deficiency symptoms of sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse (Group 2).

Source of Variation	df	Tops	Height	Leaf Area	Degree of Fe Deficiency
Model	38	15557.28**	36.04**	207.06**	76.56**
Genotypes (A)	11	4553.75**	41.16**	137.27**	2.52**
Soils (B)	2	253800.95**	382.33**	2664.01**	118.51**
A x B	22	1412.34	6.77*	44.57*	0.98**
Error	105	701.62	2.76	11.11	0.18
Total	143	4649.28	11.60	63.19	2.14
C.V. %		20.77	10.89	16.84	27.39

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A11. Mean squares for top, root, total dry-matter yields, top/root dry-matter ratios, and degree of Fe deficiency symptoms of selected sorghum genotypes grown with varied Fe levels.

Source of Variation	df	Tops	Roots	Total	Top/Root	Degree of Fe Deficiency
Model	36	783772.72**	46092.25**	531346.75**	0.37	2.30**
Genotypes (A)	5	532142.89**	97677.71**	1013031.41**	0.62	2.72**
Fe levels (B)	5	907336.59**	106861.70**	1644344.22**	0.18	6.48**
A x B	25	109270.28**	22699.37*	210455.62*	0.35	1.45**
Error	35	25843.45	4873.90	78674.91	0.25	0.12
Total	71	156993.93	25832.38	308847.50	0.31	1.23
C.V. %		21.39	26.39	28.35	16.40	36.18

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A12. Mean squares for Fe, Mn, Cu, Zn, and P concentrations in the upper leaves of selected sorghum genotypes grown with varied Fe levels.

Source of Variation	df	Fe	Mn	Cu	Zn	P
Model	30	218254.84	485543.79**	2851.61*	61017.82**	1.65**
Genotypes (A)	5	112448.02	4035354.53**	1340.88	27791.93	3.46**
Fe levels (B)	4	111025.41	1325958.81**	3613.40*	103856.80**	0.07
A x B	20	271609.88	377059.46*	3358.27**	67394.72**	1.41**
Error	29	162247.82	101766.65	1140.82	11391.40	0.34
Total	59	190847.15	297737.96	2014.42	36732.55	1.01
C.V. %		36.27	19.98	12.60	10.44	9.17

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A13. Mean squares for Fe, Mn, Cu, Zn, and P concentrations in the lower leaves of selected sorghum genotypes grown with varied Fe levels.

Source of Variation	df	Fe	Mn	Cu	Zn	P
Model	30	68020.68	1340937.80**	281003.70**	38029.09	0.16
Genotypes (A)	5	80547.89*	2180952.05**	284822.46**	48760.54	0.15
Fe levels (B)	4	39985.58	1305803.65**	250860.86**	60635.27*	0.19
A x B	20	74013.68*	1058461.91**	306094.90**	32002.08	0.16
Error	29	30601.61	278939.38	2578.94	22866.82	0.20
Total	59	49726.91	821738.57	144884.93	30616.43	0.18
C.V. %		21.32	20.51	12.04	11.73	29.32

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A14. Mean squares for Fe, Mn, Cu, Zn, and P concentrations in the roots of selected *sorghum genotypes* grown with varied Fe levels.

Source of Variation	df	Fe	Mn	Cu	Zn	P
Model	30	33213.24**	1461310.87**	457588.32*	111410.35**	1.91
Genotypes (A)	5	244546.77	3482581.24**	443884.83*	210592.00**	2.65
Fe levels (B)	4	280657.21	4571158.10**	795600.41**	348714.83**	0.91
A x B	20	372273.77**	117937.91	422271.54*	32198.36	1.93
Error	29	110115.50	230811.33	193685.77	27595.11	1.22
Total	59	223632.11	859733.32	328569.30	70434.01	1.57
C.V. %		37.09	34.38	25.28	17.72	23.07

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A15. Mean squares for 'reductant' released by the roots of selected sorghum genotypes grown with three levels of Fe.

Source of Variation	df	Days After Treatments Were Added							
		0	2	4	6	8	10	12	14
Genotypes (A)	3	0.02	0.02	0.10**	0.15**	0.16**	0.13*	0.13*	0.11*
Fe rates (B)	2	3.41**	2.23**	2.76**	4.11**	4.50**	4.32**	3.06**	2.84
A x B	6	0.02	0.01	0.01	0.02	0.05	0.05	0.02	0.02
Model	11	0.63**	0.41**	0.54**	0.80**	0.89**	0.85**	0.60**	0.45**
Error	22	0.01	0.01	0.01	0.01	0.02	0.03	0.02	0.02
Total	35	0.21	0.14	0.17	0.26	0.29	0.29	0.20	0.25
C.V. %		13.25	14.00	12.80	11.47	10.98	11.40	12.60	11.95

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A16. Mean squares for top, root, total dry-matter yields, and top/root dry-matter ratios for selected sorghum genotypes grown with three levels of Fe.

Source of Variation	df	Top	Root	Total	Top/Root
Model	13	21573.89**	12606.78**	70608.98**	0.13*
Genotypes (A)	3	66245.93**	37184.52**	171523.07**	0.31**
Fe levels (B)	2	3278.12	5508.03	4460.14*	0.14*
A x B	6	2441.40	1493.97	9024.69	0.06
Error	22	4738.22	2356.23	14643.13	0.04
Total	35	10991.47	6163.39	35430.45	0.07
C.V. %		13.46	15.92	15.08	11.77

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A17. Mean squares for leaf area (LA), fresh weights (FW), dry weights (DW), specific leaf weights (SLW), chlorophyll contents, chlorophyll a/b ratios, and degree of Fe deficiency of sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse (Group 1).

Source of Variation	df	LA	FW	DW	SLW	Chloro. a	Chloro. b	Total Chloro.	a/b	Degree of Fe deficiency
Model	20	255.18**	73764.65**	2789.42**	0.90*	5.99**	1.15**	11.52**	0.84*	3.33**
Genotypes (A)	5	117.12**	36688.30**	927.70	0.63	1.99**	0.85**	4.74**	0.53	3.47**
Soils (B)	2	1633.70**	458469.56**	19172.29**	3.82**	43.59**	6.15**	82.19**	1.79**	19.07**
A x B	10	104.29*	30750.66**	11643.21*	0.61	2.04	0.62	3.86**	1.04*	1.09*
Error	51	37.65	10429.19	466.36	0.32	0.49	0.16	0.78	0.40	0.18
Total	71	98.93	28270.17	1120.74	0.48	2.04	0.44	3.80	0.53	1.06
C.V. %		24.70	78.04	34.54	22.76	23.91	28.82	20.44	29.27	51.02

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

able A18. Mean squares for Fe, Mn, Cu, Zn, and P concentrations, P:Fe, Mn:Fe, Fe:Cu, and Fe:Zn ratios, Fe content, and dry matter produced per unit Fe by selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse (Group 1).

ource of ariation	df	Fe	Mn	Cu	Zn	P	P:Fe	Mn:Fe	Fe:Cu	Fe:Zn	Fe Cont.	mg dry wt/ mg Fe
odel	20	172951.14**	199323.11*	1009.10*	6063.77*	0.081**	15492.61**	1.09*	2.76**	0.88*	657.26**	2166.50**
enotypes (A)	5	332649.00*	564795.17**	16111.26**	6303.89**	0.076	38902.83*	2.90**	5.36**	0.49*	444.41**	2033.57**
oils (B)	2	408873.40**	130166.45**	453465.10**	2043.40	0.003	24756.48**	2.40**	6.22**	1.91**	1494.71**	2625.20**
x B	10	766394.02	264137.62	328.30	8589.67**	0.029**	10190.96	0.57	1.97**	0.74*	256.28**	2644.84**
rror	51	105060.40	16300.44	456.63	1948.38	0.004	5113.10	0.45	0.38	0.13	125.88	1731.42
otal	71	1219818.15	678316.29	597.09	2994.67	0.019	8513.28	0.66	1.16	0.35	299.96	1873.95
.V. %		37.58	29.15	37.97	26.26	32.54	23.89	29.20	14.59	6.56	18.24	37.45

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A19. Mean squares for leaf area (LA), fresh weights (FW), dry weights (DW), specific leaf weight (SLW), chlorophyll contents, chlorophyll a/b ratios, and degree of Fe deficiency of selected sorghum genotypes grown on low Fe and Fe-sufficient soils (Group 2).

Source of Variation	df	LA	FW	DW	SLW	Chloro. a	Chloro. b	Total Chloro.	a/b	Degree of Fe Deficiency
Model	14	92.49**	27065.17**	604.79**	0.39*	4.88**	0.32	7.45**	1.98**	7.79**
Genotypes (A)	3	66.64**	24531.25**	604.61**	0.19	0.36	0.14	0.41	1.44**	3.20**
Soils (B)	2	422.77**	107685.90**	2404.25**	0.80**	28.70**	1.38**	43.35**	9.00**	44.02**
A x B	6	28.17	11635.40**	270.16	0.30	1.25	0.14	1.94	0.92	1.63**
Error	33	14.94	4455.08	98.19	0.13	0.70	0.09	1.24	0.27	0.21
Total	47	38.04	11189.99	249.09	0.21	1.93	0.16	3.10	0.78	2.47
C.V. %		29.07	34.82	35.00	16.96	26.75	22.52	25.14	21.86	28.67

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.

Table A20. Mean squares for Fe, Mn, Cu, Zn, and P concentrations, P:Fe, Mn:Fe, Fe:Cu, and Fe:Zn ratios, Fe content, and dry matter produced per unit Fe by selected sorghum genotypes grown on low Fe and Fe-sufficient soils in a greenhouse (Group 2).

Source of Variation	df	Fe	Mn	Cu	Zn	P	P:Fe	Mn:Fe	Fe:Cu	Fe:Zn	Fe Cont.	mg dry wt/ mg Fe
Model	14	292491.33**	318013.55**	1583.03**	30851.08**	0.33**	1680.40**	0.86**	9.58**	3.36**	1.65*	3.42**
Genotypes (A)	3	1432210.00**	312161.50**	1875.44**	11901.73**	0.25**	2180.40**	2.90**	6.10**	4.70**	3.46**	6.48**
Soils (B)	2	2075765.23**	945518.05**	7972.20**	181539.20**	1.79**	3346.40**	1.76**	57.02**	17.75**	5.46**	10.18**
A x B	6	209623.80*	38297.23	132.11	5438.40	0.10	298.4	0.58	1.07*	0.31	1.40*	0.12
Error	33	93834.71	20223.46	284.03	9872.69	0.03	154.60	0.21	0.20	0.15	0.34	0.71
Total	47	181493.11	120426.29	771.12	19088.60	0.11	845.60	0.74	3.24	1.21	2.87	3.37
C.V. %		33.49	23.87	31.02	38.60	12.58	21.40	13.47	8.82	12.89	9.17	10.41

* Denotes significance at P=0.05.

** Denotes significance at P=0.01.