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The Influence of Cation Exchange Capacity and Depth of Incorporation on Ammonia Volatilization from Ammonium Compounds Applied to Calcareous Soils[1]

L. B. FENN AND D. E. KISSEL[2]

ABSTRACT

The objective of this study was to determine the influence of soil cation exchange capacity (CEC) and depth of incorporation on NH_3-N volatilization from NH_4^+-N compounds applied to calcareous soil. This study was conducted in the laboratory on soils with a wide range of CEC. An increasing CEC resulted in decreasing NH_3 losses. Ammonium sulfate produced higher soil pH values and NH_3 losses than did NH_4NO_3. The pH of the soil decreased with increasing NH_4NO_3 application rates. With NH_4NO_3, percent NH_3-N losses decreased with increasing application rate; however, with $(NH_4)_2SO_4$, percent NH_3-N losses increased as the application rates increased.

Incorporation of the NH_4^+-compounds into the soil reduced NH_3 losses. Increasing depths of NH_4^+-incorporation resulted in reduced NH_3 loss. Losses decreased as the CEC of soil increased. The effectiveness of soil depth in reducing NH_3 loss was associated with soil water content. Decreasing the soil water increased the effectiveness of soil incorporation for reducing NH_3 losses.

Two regression equations were developed to describe NH_3 losses with respect to CEC, soil pH, time, NH_4^+-N application rate and temperature. Correlation coefficients were 0.86 and 0.81 for $(NH_4)_2SO_4$ and NH_4NO_3 systems, respectively.

Additional Index Words: $(NH_4)_2CO_3$ formation, N fertilization, soil $CaCO_3$, NH_3-N loss model.

MOST RESEARCH concerning the effect of cation exchange capacity (CEC) on NH_3 retention has been associated with the use of anhydrous ammonia (7, 8, 10, 11, 13, 14, 15). Working with anhydrous ammonia, Stanley and Smith (13) found that NH_3-N losses to a depth of 23 cm

were greatest in sandy soil, intermediate in silt loam and least in clay soil. McDowell and Smith (11) reported similar results, and concluded that NH_3-N loss was inversely related to CEC. Wahhab et. al. (15) applying $(NH_4)_2SO_4$ to a sand and a sandy loam, found that the sand lost greater percentages of NH_3.

Soil water content has also been noted to affect ammonia retention. Stanley and Smith (13) noted that with air-dry soil, near maximum NH_3-N losses occurred following anhydrous ammonia applications. They also found that NH_3-N losses decreased as the soil water content increased to an intermediate level, with a rapid increase in NH_3-N loss occurring as field capacity was reached. In several cases greater losses of applied NH_3-N were recorded for soil at field capacity than for air dry soils. They stated that evaporating water probably helped transport this NH_3 to the surface and hence increased NH_3-N loss. McDowell and Smith (11) and Jackson and Chang (8), however, noted the opposite effect. They found that greater soil water content reduced NH_3-N losses. Jenny et al. (9), and Brown and Bartholomew (1), noted that dilute NH_3 solutions were competitive with water. Increasing the water contents tended to replace adsorbed NH_3. They stated that even in

Table 1—Selected physical and chemical properties of the experimental soils.

Soil mixture	Soil CaCO$_3$ content	Added CaCO$_3$	Soil	Field water capacity	Cation exchange capacity	Working water content
	%	%	pH	%	meq/100 g	%
Houston Black clay (HBc)	29	0	7.6	55	58	30
50% HBc + 50% Sand		5		37	29	23
25% HBc + 75% Sand		10		26	18	19
15% HBc + 85% Sand		10		23	9	17
10% HBc + 90% Sand		10		20	6	14
100% Sand		10		17	0	10
Harkey silty clay loam (Ha sicl)	6	10	7.6		22	22

clay suspensions, NH$_3$ was not strongly adsorbed. Many of the apparently different conclusions might be explained by the physical design used in the research.

The objective of this research was to examine the effect of cation exchange capacity on NH$_3$-N volatilization from NH$_4^+$-N compounds applied to the surface of calcareous soils and to determine the effect of shallow soil incorporation in reducing these losses.

MATERIALS AND METHODS

The experimental apparatus used has been described in an earlier publication (3). All research was conducted in the laboratory with Houston Black clay (HBc), Harkey silty clay loam (Ha sicl), and sand + CaCO$_3$. Various values of CEC were produced by mixing HBc and sand. Calcium carbonate was added, at the rate of 5% by weight of the 50–50% HBc-sand mixture and 10% by weight to all other HBc-sand mixtures, sand and to Ha sicl. The mixtures with their characteristic CEC, CaCO$_3$ contents, gravimetric water content at field capacity and experimental soil water contents are given in Table 1. The 75% sand + 25% HBc, 85% sand–15% HBc, 90% sand–10% HBc, and 100% sand were wetted and then dried at 105°C for 24 hours. The soil mixtures were then pulverized and rewetted. The HBc-sand mixtures were placed 5 to 10 cm deep on saturated sand (23% water by weight). Unsieved Ha sicl tended to form large spheres and puddle in wetting, therefore, it could not be used. The Ha sicl therefore, was sieved and only 4.8- to 19.0-mm sized aggregates were used due to better physical condition in the wetting process.

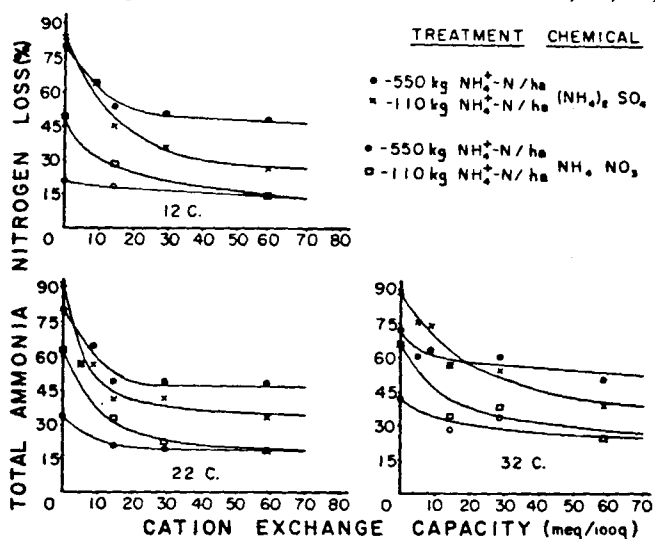The NH$_3$ volatilization studies were conducted at 12, 22, 30,

Fig. 1—Influence of cation exchange capacity, temperature, NH$_4^+$-salt and NH$_4^+$-N application rate on total NH$_3$-N losses from HBc and sand mixtures.

and 32°C for 100 hours with surface-applied NH$_4^+$-compounds. When the NH$_4^+$-compounds were incorporated into the soil, NH$_3$ collection times approached 300 to 400 hours. Ammonia collection with soil-incorporated NH$_4^+$-compounds was terminated when <1% of the applied NH$_4^+$-N was collected as NH$_3$N in 24 hours. Ammonium-nitrogen as (NH$_4$)$_2$SO$_4$ or NH$_4$NO$_3$ was applied to the soil at rates of 110 and 550 kg/ha. The NH$_4^+$-N was applied as a dry salt in the following manner; (i) to the soil surface at 110 and 550 kg/ha, (ii) placed 2.5, 5.0 or 7.5 cm deep at rates of 550 kg/ha, (iii) or uniformly incorporated into the top 2.5, 5.0, or 7.5 cm of soil simulating field incorporation by disking.

A study was conducted with different aggregate sizes of HBc as a soil cover for reduction of NH$_3$ losses. Ammonium sulfate was used as the N source. Sieved air-dry soil (8% H$_2$O by weight) of either 2.5- to 4.5-mm or 0- to 4.5-mm aggregates was placed 1.3 or 2.5 cm deep on HBc at 25% H$_2$O. A similar study was conducted with air-dry Ha sicl (3% H$_2$O by weight), with 0- to 4.8-mm or 4.8- to 19.0-mm soil aggregates at 2.5- and 5.0-cm depths. The underlying sand was added at either 6% or 23% moisture. Treatments used are given in Table 3.

Statistical analysis of the NH$_3$ losses from surface-applied NH$_4^+$- salts was run using a multiple linear regression program. Additional detail can be found in an earlier publication (4).

RESULTS AND DISCUSSION

Influences of Cation Exchange Capacity on NH$_3$ Losses

The effect of CEC on NH$_3$ volatilization from surface-applied (NH$_4$)$_2$SO$_4$ and NH$_4$NO$_3$ is shown in Fig. 1. Losses of NH$_3$ varied from 14% to 91% of the NH$_4^+$-N applied. In general NH$_3$-N loss decreased as the CEC was increased. The reduction in percentage of NH$_3$ loss as the CEC increased was greatest at 110 and least at 550 kg NH$_4^+$-N/ha.

The water content of the soil-sand mixtures also increased as the CEC's increased. Because of this problem, there was some question if the decrease in NH$_4^+$-N loss was due entirely to the increase in CEC. In other unpublished work, we have found NH$_4^+$-N volatilization from HBc to be nearly constant over a range of water contents from 0.15 to 0.30 g/g. Because of this, it was felt that CEC exerted the major influence (as opposed to changes in water content) on the results shown in Fig. 1.

Volatilization losses of NH$_3$ were greater from (NH$_4$)$_2$SO$_4$ than from NH$_4$NO$_3$, which agreed with previously reported data (3,4). The difference in NH$_3$-N losses between these two chemicals was greatest at 12°C (Fig. 1). The percentage of NH$_3$-N losses from NH$_4$NO$_3$ were consistently higher at 110 than at 550 kg NH$_4^+$-N/ha except for pure HBc where losses were identical. Losses of NH$_3$ from (NH$_4$)$_2$SO$_4$ were generally highest at the highest NH$_4^+$-N application rates and lowest at the lowest application rates as reported earlier for HBc (3,4). At 110 kg N/ha and a CEC of 0, (NH$_4$)$_2$SO$_4$ lost 35, 28, and 23% more of applied NH$_4^+$-N than NH$_4$NO$_3$ at 12, 22, and 32°C, respectively. Differences in NH$_3$ volatilization at 550 kg NH$_4^+$-N/ha and a CEC of 0 were 60, 47, and 30% of applied NH$_4^+$-N at 12, 22, and 32°C, respectively. At the same CEC and temperature, two possible differences existed between (NH$_4$)$_2$SO$_4$ and NH$_4$NO$_3$: (i) the type of chemical reaction each undergoes with CaCO$_3$, and (ii) differences in soil pH because of the particular soil chemical reaction. Sauchelli (12) states that an equivalent quantity of (NH$_4$)$_2$SO$_4$ is more acidic than NH$_4$NO$_3$. However, when placed in a calcareous soil, lower pH values were observed with NH$_4$NO$_3$ in this experiment

Table 2— Soil pH as influenced by cation exchange capacity, ammonium chemical, ammonium-N application rate, and amount of ammonia volatilization.

Soil mixture,† % sand + % HBr	CEC	Ammonium chemical	NH4+-N application rate	Initial‡ pH	Final§ pH
	meq/100 g		kg/ha		
100-0	0	$(NH_4)_2SO_4$	110	7.6	8.1
	0		550	7.4	8.0
90-10	5.8	$(NH_4)_2SO_4$	110	7.4	7.8
	5.8		550	7.4	7.9
85-15	8.7	$(NH_4)_2SO_4$	110	7.5	7.8
	8.7		550	7.4	7.8
75-25	14.5	$(NH_4)_2SO_4$	110	7.4	7.6
	14.5		550	7.4	7.6
0-100	58.0	$(NH_4)_2SO_4$	110	7.4	-
	58.0		550	7.4	7.6
100-0	0	NH_4NO_3	110	7.4	7.6
	0		550	7.1	7.1
75-25	14.5	NH_4NO_3	110	7.1	7.5
	14.5		550	6.8	7.2
50-50	29.0	NH_4NO_3	110	7.0	7.5
	29.0		550	6.8	7.1
0-100	58.0	NH_4NO_3	110	7.1	-
	58.0		550	6.8	7.0

† All soil mixtures had at least 10% CaCO by weight.
‡ pH measured immediately after NH_4^+-compound addition.
§ pH measured after approximately 120 hours of NH_3-N losses.

Table 3—Ammonia-nitrogen losses from applied $(NH_4)_2SO_4$ placement depth, surface and subsurface moisture content, and soil aggregate size. Nitrogen applied at 550 kg/ha.

Experimental soil	Covering soil depth	Temperature	Surface moisture	Subsurface soil moisture	Soil aggregate size	Applied nitrogen loss
	cm	°C	%	%	mm	%
Houston Black clay	0	32	30	25	0-4.5	50
	2.5	32	30	25		18
	2.5	32	8	25	2.5-4.5	33
	2.5	32	8	25	0-4.5	1
Harkey silty clay loam	0	30	20	23	4.8-19.0	66
	2.5	30	20	23		52
	2.5†	30	20	23		60
	5.0	30	20	23		35
	5.0†	30	20	23		45
	7.5	30	20	23		26
	7.5†	30	20	23		29
	0	30	3	23		65
	2.5	30	3	23	0-4.8	52
	2.5	30	3	6		32
	5.0	30	3	6		0

† Uniformly mixed.

(Table 2). The higher rate of NH_4NO_3 application resulted in the lowest soil pH values and consequently the lowest percentage NH_3-N losses. Ammonium nitrate, from a practical standpoint, has one-half of its N in the NO_3^- form; therefore, NH_3 losses are much less than from $(NH_4)_2SO_4$ on an equivalent N basis.

The percentage of NH_3-N losses decreased more rapidly at 110 kg NH_4^+-N/has than at 550 kg/ha as the CEC increased. The more rapid decrease in NH_3 losses at the lower NH_4^+-N application rates was probably due to a greater percentage of NH_4^+ being absorbed on the cation exchange sites. Precipitation of $CaSO_4$ would probably occur more quickly at CEC=0 than at higher CEC's. At the higher CEC's the rate of $(NH_4)_2CO_3$ production would likely be reduced because a greater percentage of the NH_4^+ would be adsorbed, resulting in a lower soil solution pH. This explanation is consistent with the final pH values for $(NH_4)_2SO_4$, where the highest pH occurs at the lowest CEC (Table 2).

The percent losses of applied N at 110 kg NH_4^+-N/ha with $(NH_4)_2SO_4$ exceeded the N losses from the 550 kg NH_4^+-N/ha treatment at CEC values of 0 to 4, 6, and 17 meq/100 g soil at 12, 22, and 32°C, respectively. This resulted in the 110 kg NH^+-N/ha treatment losing 4, 10, and 18% more NH_3-N than the 550 kg NH^+-N/ha treatment at 12, 22, and 32°C, respectively, at zero CEC. It seems reasonable that the lowest NH_4^+-N application rate would have the least loss of N at the highest CEC and losses close to, or equal to losses with the 550 kg/ha treatment at the lowest CEC. The fact that the percentage NH_3-N losses were less at 550 kg NH^+-N/ha with sand, suggested a slower reaction of $(NH_4)_2SO_4$ with $CaCO_3$ within the 100 hour NH_3-N collection time. The percent loss of applied NH_4^+-N (110 kg/ha) from a sand as NH_3-N was 91, 90, and 89% at 12, 22, and 32°C, respectively. Percent NH_3-N losses at 550 kg N/ha were 87, 80, 71% of applied NH^+-N, respectively, at 12,

22, and 32°C. Previous work (6) indicated that 10% $CaCO_3$ by weight was necessary for maximum NH_3 loss. The prior research, however, was done on a soil with a CEC of 26 meq/100g. Previous losses of NH_3 were approximately 50% of applied NH_3^+-N as compared to the present maximum 91% loss recorded on sand. Since NH_3-N losses with low CEC soils were so high, greater $CaCO_3$ contents would have decreased the necessary reaction time at high $(NH_4)_2SO_4$ application rates. Collection of the evolved NH_3 for 200 hours at the high N application rate, however, resulted in NH_3 loss values approximately equal to that collected in 100 hours at 110kgN/ha. The 200-hour NH_3 losses were approximately 89, 89, and 72% of applied NH^+-N at 12, 22, and 32°C, respectively.

Influence of Depth of Placement on NH_3-N Loss

The depth from which significant NH_3-N can be lost from applied N fertilizers is important in determining remedial cultural practices. The water content of this soil cover could also be managed to some extent if it saved N for the plant environment. Since a soil cover is the most practical means of reducing NH_3-N losses, additional knowledge in this area is needed.
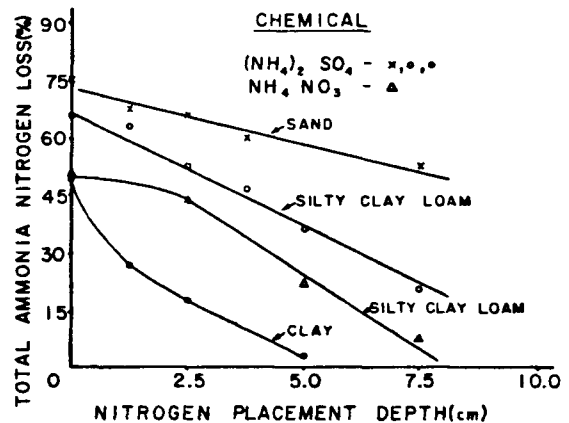

Fig. 2—Influence of soil type and fertilizer placement depth on NH_3-N losses. Ammonium sulfate and ammonium nitrate were applied at 550 kg NH_4^+N/ha at 30°C.

MOIST SOIL COVER

The influence of soil CEC on NH_3-N retention with respect to depth of placement of the NH_4^+-compound is shown in Fig. 2 and Table 3. Placement of $(NH_4)_2SO_4$ in sand at a depth of 7.5 cm resulted in an NH_3-loss reduction from 75 to 60% of applied NH_4^+-N. In Ha sicl at the same depth NH_3-N losses were reduced from 69 to 25% with $(NH_4)_2SO_4$ and from 51 to 10% of applied NH_4^+-N with NH_4NO_3. A 10 to 20% lower NH_3-N loss value was observed for NH_4NO_3 than for $(NH_4)_2SO_4$ at all placement depths (Fig. 2). Even though the volatile NH_3 from the $(NH_4)_2SO_4$ and NH_4NO_3 treatments moved through 7.5 cm of soil, NH_3 losses from $(NH_4)_2SO_4$ remained greater than from NH_4NO_3.

Houston Black clay with the same pH as Ha sicl lost less of the applied NH_4^+-N with increasing depth of placement. Less than 2% NH_3-N was lost when $(NH_4)_2SO_4$ was placed at 5.0 cm and none at 7.5 cm in HBc. Cation exchange capacity effects on NH_3 loss were more effective when the NH_4^+-compounds were incorporated into the soil (Fig. 2, Table 3). Houston Black clay has a CEC of 58 meq/100 g and Harkey sicl has a CEC of 22 meq/100 g. If the NH_3 has to diffuse through the soil, it is more likely to be adsorbed in a high CEC soil. If the soil has a low CEC, the NH_3-N losses can be large with compounds such as NH_4NO_3, and even greater with compounds like $(NH_4)_2SO_4$.

The uniform mixing of $(NH_4)_2SO_4$ into Ha sicl simulating field incorporation by disking, increased NH_3-N losses (Table 3). A fertilizer placement depth of 2.5, 5.0, and 7.5 cm resulted in NH_3-N losses of 52, 35, and 26%, respectively, whereas N losses from mixing the fertilizer into the 2.5, 5.0, and 7.5 cm of soil were 60, 45, and 29%, respectively. The NH_3-N losses are 3 to 10% greater from mixing the fertilizer into the soil than from the placement of all fertilizer at 2.5, 5.0, and 7.5 cm depth.

DRY SOIL COVER

A dry soil cover was more effective in reducing NH_3-N losses than a moist soil cover (Table 3). Ammonia-nitrogen losses with a cover of 2.5 cm (0- to 4.5-mm aggregates) of HBc reduced the NH_3-N loss by 49% of applied NH^+-N. A coarser HBc soil aggregate (2.5- to 4.5-mm) placed 2.5 cm deep over $(NH_4)_2SO_4$ resulted in a 17% reduction in NH_3 loss when compared to surface-applied $(NH_4)_2SO_4$. Placement of $(NH_4)_2SO_4$ under a dry soil cover of Ha sicl with a water-saturated sand subsoil, however, resulted in large NH_3-N losses. The NH_3-N losses with 2.5 cm air dry Ha sicl over $(NH_4)_2SO_4$ on a water-saturated sand subsoil was 52% of applied N, identical to the loss with a wet soil cover (Table 3). Ammonium-nitrogen applied at the same depth, but with a drier subsurface sand (6% water by weight), lost only 32% of the applied NH_4^+-N. An increased placement depth of 5.0 cm of air dry Ha sicl over the same drier subsoil completely eliminated NH_3-N loss. McDowell and Smith (11) and Jackson and Chang (8) also noted that drier soils lost less NH_3-N. If evaporation of water from the soil was largely stopped, as was probably the case with a dry soil cover in this experiment, adsorption of NH_3 and water by the dry soil could explain our observations.

Physical movement of NH_3 to the soil surface through capillary water movement may be a major factor causing NH_3 losses from subsurface applied NH_4^+-salts. Without capillary water movement, large quantities of NH_3-NH_{4+} may never reach the soil surface.

A REGRESSION EQUATION MODEL FOR PREDICTING NH_3-N LOSSES

Two regression equations predicting NH_3-N loss from surface-applied NH_4^+-compounds were derived using the following variables: time (t), temperature (T), ammonium-nitrogen application rate (U), cation exchange capacity (CEC), average soil pH for 0 and 120 hours after fertilizer addition (pH), NH_3-N loss as a percent of added NH_4^+-N (X). Separate and highly significant regression equations were derived for $(NH_4)_2SO_4$ and NH_4NO_3. The regression equation for $(NH_4)_2SO_4$ is as follows:

$$X = 786.995 - 0.132U + 0.585\ T + 0.541\ CEC + 1.923t + 103.087\ pH + 2.112 \times 10^{-4}U^2 - 8.838 \times 10^{-3}\ CEC^2 - 0.0295t^2 + 2.145 \times 10^{-4}t^3 - 5.694 \times 10^{-7}t^4.\ R^2 = 0.86$$

The corresponding regression equation for NH_4NO_3 is as follows:

$$X = -192.800 - 0.0264U + 0.659T - 0.658\ CEC + 0.582t + 26.430\ pH + 4.613 \times 10^{-5}U^2 + 8.027 \times 10^{-3}\ CEC^2 - 5.48 \times 10^{-3}t^2 + 2.906 \times 10^{-5}t^3 - 5.363 \times 10^{-8}t^4.\ R^2 = 0.81.$$

The program used for multiple linear regression analysis (4), in this study did not permit forcing of the curves through zero. Consequently, the equation will not predict NH_3 losses for the first 6 hours after solubilization of the NH_4^+-compound. The regression equation tends to overpredict many values at 6 to 10 hours and underpredict the 90- to 100-hour NH_3 loss values. The errors in predicted NH_3 loss values at 6 to 10 hours varied from 25% to 40%; beyond 90 hours it varied from 10 to 12% from measured NH loss values.

The poorer performance of the regression equation for NH_3 volatilization from NH_4NO_3 probably resulted from a poor approximation of the effect of added acidity. Some other means for determining the effect of acidity might improve the final equation. The principal limitation of these equations are (i) an air flow in excess of 0.16 km/hour (0.1 mph) near the soil surface, (ii) all experimental soils have been of montmorillonitic mineralogy, (iii) lack of NH_3-N loss predictability during the first 6 hours, and (iv) the fact that these are laboratory data which have not been tested under field conditions.

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A Technique to Determine Iron Efficiency in Plants[1]

J. C. BROWN AND W. E. JONES[2]

ABSTRACT

Soil tests should predict crop response to fertilization. In the case of Fe, plant factors seem to affect the use of Fe by the plant; thus, soil tests may not be reliable. Use of soil Fe by plants is genetically controlled by an adaptive mechanism which is activated in Fe-efficient plants in response to Fe-stress, but remains inactive if Fe is sufficient. Fe-inefficient plants develop less Fe-stress response than Fe-efficient plants. Using this range of Fe-stress response in plants as a basis, we developed a technique to screen plants for Fe efficiency.

A limited supply of Fe and some control of pH in the growth medium were required in this technique. The pH was controlled by using nutrient solutions, N only as NO_3, and N as NH_4 and NO_3, and by varying the $CaCO_3$ and P concentrations in the solutions. The optimum supply of Fe (0.2 mg Fe/liter) was determined by growing the plants at different Fe concentrations.

Four Fe-inefficient and four Fe-efficient plant varieties, representing four plant species, were used as test plants. The plants were screened in mixed cultures and were rated in order of greatest Fe efficiency as follows:

T3238FER tomato (*Lycopersicon esculentum* Mill.) ≥ Hawkeye soybean (*Glycine max* (L.) Merr.) > W59 Corn (*Zea mays* L.) > Pioneer 846 sorghum (*Sorghum bicolor* (L.) Moench) > PI-54619-5-1 soybean > Wheatland sorghum > ys_1/ys_1 corn > T3238fer tomato.

Green plants contained more and chlorotic plants contained < 43 μg Fe/g, but the degree of Fe-chlorosis was the best index of Fe-efficiency. A suggested sequence for screening plants for Fe-efficiency is presented.

Additional Index Words: Fe-stress response, Fe-inefficient plants, Fe-efficient plants, Fe-stress.

T HE ROLE of a soil test is to predict crop response to fertilization (11). Cox and Kamprath (11) discussed several soil tests for Fe that use ammonium acetate (15, 1), EDDHA [ethylenediamine di (*o*-hydroxyphenylacetic acid)] (I), and DTPA (diethylenetriaminepentaacetic acid) as soil extractants. The DTPA procedure was used by Lindsay and Norvell.[3] Cox and Kamprath (11) concluded that the availability of Fe seems to depend on many factors aside from an extractable amount of Fe in the soil. They indicated that some of these factors may be inherent in the plant and that until these plant factors are understood, soil tests for Fe may not be reliable.

We attempted to develop a soil test for available Fe in soils (3, 6, 4) and also learned that available Fe in a soil depends on the crop grown. For example, when Millville, Tripp, and Quinlan soils (3) were extracted with DTPA (3, 6) and EDDHA (4), the available Fe in Quinlan < Tripp < Millville. When Wheatland sorghum (*Sorghum bicolor* (L.) Moench) was used as a test plant, the degree of Fe deficiency was related to the amount of chelate-extractable Fe in the soil. But when PI-54619-5-1 (PI) and Hawkeye (HA) soybeans (*Glycine max* (L.) Merr.) were used as test plants, PI-soybeans developed Fe chlorosis and HA-soybeans were green, respectively, on all three soils. These observations showed that the plant varieties were affecting the uptake of Fe from the soil (8).

The total quantity of Fe in a soil is usually sufficient for plant growth, but the use of this Fe by plants is genetically controlled by an adaptive mechanism (8) which is activated in Fe-efficient plants in response to Fe stress, but which remains inactive if Fe is sufficient.

Iron-efficient plants release H ions and "reductants" from their roots when they are under Fe stress. The pH at their root zone is lowered which favors Fe^{3+} solubility and reduction of Fe^{3+} to Fe^{2+}. This Fe is reduced externally by the root because it can be prevented from entering the plant