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To the Graduate Council:

I am submitting herewith a thesis written by Marlon W. Yankee entitled "Response of soybeans to acid soils and to aluminum and manganese on nutrient solution." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant, Soil and Environmental Sciences.

Russell J. Lewis, Major Professor

We have read this thesis and recommend its acceptance:

W. L. Parks, G. M. Lessman

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by Marlon W. Yankee entitled "Response of Soybeans to Acid Soils and to Aluminum and Manganese in Nutrient Solution." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant and Soil Science.

Russell J. Lewis

Russell J. Lewis, Major Professor

We have read this thesis and recommend its acceptance:

W L Parks

Gary M. Lessman

Accepted for the Council:

Hilton A. Smith

Vice Chancellor
Graduate Studies and Research

RESPONSE OF SOYBEANS TO ACID SOILS AND TO ALUMINUM AND MANGANESE IN NUTRIENT SOLUTION

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee

Marlon W. Yankee

December 1974

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ABSTRACT

Three greenhouse pot experiments were conducted to study the effects of soil pH, Al and Mn on the growth of Forrest and Lee 68 varieties of soybeans (Glycine max L.). The effect of Al and Mn in soils and in nutrient solution on nutrient concentrations in soybeans was also studied.

The first study consisted of altering the pH values of three Tennessee soils (Huntington-Bewleyville silt loam, Jefferson loam, Leadvale loam) with additions of HCl or 3/4 $Ca(OH)_2 \cdot 1/4$ MgO. Different amounts of acid or lime were added to change the pH of each soil to that of the other two soils. Levels of exchangeable Al and various extractable fractions of Mn in the soil were measured and correlated with the concentrations of Al, Mn, K, Ca, Mg, P, Mo and B in the leaves of the soybeans. In the second study soybeans were grown in one-fifth strength Hoagland's Number Two nutrient solution in perlite. The nutrient solutions received added levels of 0.0, 4.0 and 8.0 ppm Al as $Al_2(SO_4)_3 \cdot 18\ H_2O$ and 0.5, 2.5 and 5.0 ppm Mn as $MnCl_2$. Concentrations of Al, Mn, K, Ca, Mg and P in the leaves were measured and correlated with the added levels of Al and Mn. The third study was conducted as the second but with 4.0, 12.0 and 20.0 ppm Al and 0.5, 1.5 and 3.0 ppm Mn in nutrient solution.

Exchangeable Al and Mn in the soil decreased with increasing pH in each soil. The H_2O soluble and exchangeable fractions of soil Mn gave the highest correlation coefficients with the Mn concentration in the plant. At higher pH values soybean growth was greater on the Jefferson and Huntington-Bewleyville soils. At lower pH values these soils contained high levels of exchangeable Mn, which resulted in Mn toxicity. The effect of Al in the soils was apparently masked by an acid-induced increase in P solubility in the soil. Manganese toxicity symptoms were associated with pH values of less than 4.7 and Mn leaf concentrations of greater than approximately 300 ppm. The concentrations of K, Ca and Mo in the plants grown on soils were variable. The Mg concentration in the plant generally increased with increasing pH while the B concentration tended to decrease with increasing pH.

Perlite was a poor growth medium for the study of Al in nutrient solutions due to an apparent ability to sorb and/or release Al in solutions. A decrease in top weights of soybeans was the best indication of Al toxicity in the nutrient solution studies. Percent Ca, Mg and P in the plant decreased as the Al added to nutrient solution increased. Potassium concentrations varied directly with the Al levels in the first study while they were variable in the second study.

Forrest variety was more susceptible to Mn toxicity than Lee 68 variety. Manganese toxicity symptoms were associated with a Mn leaf concentration of greater than 125 ppm. Increasing Mn in nutrient solution tended to decrease the percent Ca in the plant while percent K and Mg were unaffected. The effect of Mn on the percent P in the plant differed between varieties.

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LITERATURE REVIEW

I. ALUMINUM

Acid conditions within soils have long been known to be detrimental to the growth of most plants (8,9,10,29,40,41). Much of this poor growth at lower soil pH values has been attributed to the presence of toxic levels of aluminum and manganese (8,10,13,24,26,27,29,30,31,34,42,47).

Magistad (29) showed that Al uptake was governed by its solubility, which in turn is controlled by the pH. Pierre, Pohlmann and McIlvaine (41) found that Al was present in the soil solution in sufficient quantities to be toxic to plants. Soil solution levels of Al varied from a high of 27.25 ppm to 3.91 ppm, at pH values of 4.75 and 4.95, respectively. These soils differed considerably in Al content even at the same pH. Ragland and Coleman (44) concluded that only a few parts per million Al in soil solution is very toxic to plant growth.

Liming the soil increases the pH and reduces the Al available to the plant (8,9,10,15,18,29,44). Conversely, adding various acidifying materials lowers the pH and results in an increase in available Al (9,18,43,44).

Using H_2SO_4 and $CaCO_3$ to adjust the pH, Helyar and Anderson (18) reported soil solution concentrations of Mg, K and Na decreased as the pH increased but the soil solution plus exchangeable fractions of these elements did not vary. Increasing pH decreased the Al and Mn in soil solution. The dominant effect of liming in this experiment was the reduction of Al toxicity and inducement of P deficiency. Changing the pH of Mardin silt loam with $CaCO_3$ in greenhouse pot experiments, Schnechl, Peech and Bradfield (47) reported Al and Mn were reduced by liming. Armiger, Foy, Fleming and Caldwell (5) grew 15 varieties of soybeans in the greenhouse for 43 days on acid Bladen surface soil (pH 4.4) which originally contained 5.56 meq/100 g KCl extractable Al, 1.52 meq/100 g Ca, 0.12 meq/100 g Mg, 0.10 meq/100 g K and 0.003 meq/100 g Mn. The soil was limed at five different rates of $CaCO_3$ (0, 750, 1500, 3000, 6000 ppm). Liming increased top yields up to rates of 1500 and 3000 ppm where yields tended to equalize. Liming with 3000 ppm to pH 5.5 gave the highest yields. However, liming to higher pH values resulted in nutrient deficiencies and poorer growth.

Nelson and Barker (35) stated that the optimum pH range for soybeans is 6.2 to 6.5. This is in the range of lowest Al solubility in soils as reported by Magistad (29) and Blair and Prince (9).

Plant species differ in their tolerance to Al (3,4,5,16,28,30,31). McLean and Gilbert (30,31) found that Al stimulated the growth of six different species but at different levels in nutrient solution. Rye grew best at 3.4 ppm Al while oats, alfalfa and buckwheat had higher yields at 6.8 ppm and onions and red top at 13.6 ppm. Macleod and Jackson (28) found that alfalfa and clover dry matter yields (tops and roots) increased at 0.2 and 0.5 ppm Al in nutrient solution but decreased at 1.0 and 2.0 ppm. Later, Andrew, Johnson and Sandland (3) and Andrew and vanden Berg (4) classified various pasture legumes as being either Al sensitive or tolerant. Tolerant species increased in dry matter yield with addition of 0.5 ppm Al in nutrient solution. In one of these studies (3) the researchers postulated that lower levels of Al may enhance growth of some species. Whether Al is an essential nutrient or whether it creates a better balance of nutrients was not determined. Foy and Brown (16), working with buckwheat, barley, bushbeans and soybeans, found that these species also differed in their susceptibility to Al.

In a separate experiment by Armiger et al. (5) 48 soybean varieties were grown in greenhouse pot experiments using acid Bladen subsoil. Aluminum was known to be the primary growth limiting factor in this soil (15). The varieties differed widely in growth on the soil, ranging in dry matter yield from a low of 1.58 g/pot to 6.58 g/pot. Rios and Pearson (46) found that Jackson soybean root growth was increased by increasing surface soil pH. Furthermore, increasing only the subsoil pH resulted in increased root growth. Foy, Fleming and Armiger (14) classified Chief soybeans as Al tolerant and Perry soybeans as Al sensitive. Increasing Al in nutrient solution decreased top weight of both varieties, with Perry decreasing more than Chief. Chief root weight increased to the 4.0 ppm level of Al but decreased at higher aluminum levels. Aluminum concentration of the tops was quite variable, ranging from 0.8 to 3.1 meq/100 g dry weight. In this same study liming Bladen soil increased the top and root weights and decreased the Al content of the leaves and stems of both varieties. Jones (23) reported that Al is in excess when its concentration in the upper fully mature trifoliate leaves of soybeans is greater than 400 ppm.

Various levels of Al have resulted in decreased root weights of different plants in both soils (15,44) and nutrient solutions (14,26, 28,29). On the other hand, increased Al has also resulted in increased root weights of some species (14,28). McLean and Gilbert (30,31) stated that injury of sensitive crops to Al was localized in roots, and the first symptoms of Al toxicity was dwarfing and injury to the roots. Ligon and Pierre (26) also concluded that injury from Al toxicity is first noted in the roots, and injury to the roots is greater than to the tops. Rios (46) stated that in cotton the Al effect is apparently on the roots and indirectly on the tops.

Aluminum tolerance has been closely related to the ability of the plant to absorb and utilize P in the presence of excess Al (16). Pratt (43) reported that acidification of two soils with $(NH_4)_2SO_4$ from near neutral to 3.5 resulted in a high P solubility which in turn precipitated Al as aluminum phosphate. The NH_4F extracts of aluminum phosphate increased as pH decreased while H_2SO_4 extracts of calcium phosphate decreased as the pH decreased. Bartlett and Reigo (7) postulated that Al might still be soluble and toxic even as the soil pH reaches neutrality as long as positively charged Al was present in excess of equivalent negatively charged phosphate. These workers also found that at higher pH values there was difficulty in distinguishing between Al toxicity and P deficiency. Pierre and Stuart (40) found that adding superphosphate to the soil reduced Al in the soil solution and increased yields of barley and alfalfa. Conclusions were that since considerable amounts of Al were still in the soil solution at high P application and high pH values, P must also act within the plant to relieve Al toxicity.

Adding P to a nutrient solution, Foy and Brown (15) reported that increasing P was associated with decreasing Al in solution, which resulted in higher yields of cotton. In a separate experiment these researchers found that cotton yield and uptake of ^{32}P decreased as the amount of Al added to nutrient solution increased. Andrew, Johnson and Sandland (3) and Andrew and vanden Berg (4) reported that Al "sensitive" pasture legumes showed both decreased yield and P concentration in the tops with increasing Al in nutrient solution. "Tolerant" species showed an increase in P concentration and dry matter yield to the 0.5 and 1.0 ppm levels of Al. However, at the 2.0 ppm level of Al, yield and P concentration in the tops decreased. In contrast, P sorption by roots increased in all species. In other work with pasture legumes (28) percent P in the tops and top yield increased as Al in nutrient solution increased. However, in a similar experiment by these same workers higher levels of Al decreased the P concentration and yield of alfalfa tops. They surmised that low levels of Al increase P uptake while higher levels decrease the P concentration in plants. This study tends to support the theory put forth by Andrew et al. (3) that low levels of Al may stimulate plant growth by creating a better nutrient balance. Foy (14) added Al as $Al_2(SO_4)_3 \cdot 18H_2O$ to nutrient solution at levels of 0, 4, 6, 8, 10 and 12 ppm to study the effect on P concentration in two soybean varieties. Phosphorus concentration in the tops of Perry soybeans decreased up to the 10 ppm Al level and then increased at the 12 ppm level. Phosphorus concentration of Chief soybeans decreased up to the 6 ppm level of Al and then increased to the 12.0 ppm level.

Aluminum also affects the uptake of other nutrients by the plant (3,12,14,15,18,25,28). Increasing Al levels in nutrient solution decreased the absorption of Ca, K, B and Mn in cotton (15). Both K and Ca concentration in pasture legumes increased as Al in nutrient solution increased (28). However, other researchers (3) found that Al reduced the Ca concentration in the tops of pasture legumes while the K concentration increased or was not affected. The Mg concentrations were unchanged. Other work (25) indicated that liming soils had little effect on the B concentration of soybean leaves although there was a tendency for B in the leaves to decrease with liming. Helyar and Anderson (18) showed that lowering the pH of soil with H_2SO_4 reduced the Na, K, Mg, Ca and P in the plant tops of Harding grass and reduced K, Ca and P in alfalfa tops. Cheng and Ouellette (12) concluded that Mo uptake by pastures and vegetables was increased by liming soils. Calcium concentrations in the leaves of soybeans, as reported by Foy et al. (14), steadily decreased in Chief variety as increasing amounts of Al were added to nutrient solution. The Ca concentration of Chief soybeans increased up to the 6 ppm Al level and then decreased to the 12 ppm level.

II. MANGANESE

Similar to Al, the various fractions of extractable Mn in soils are lowered with increasing pH (2,18,20,32,36,42,47,53) and, unlike Al, may even become deficient at very high pH values (24). As Anderson postulated (2), plants tend to absorb Mn in proportion to the amount available, and thus at lower soil reactions toxicities may develop (27,36,39,42).

Piper (42) used the Mn concentration in oat plants as an indicator of availability to determine the effect of pH on Mn. In a Glen Osmond soil which had been treated two years earlier with HCl and $CaCO_3$ to alter pH there was a steady decrease in the Mn concentration of oats as the pH progressed from 5.7 to 7.0 and only a slight decrease at pH values above 7.0. Further experimentation in this study showed that soils at the same pH and with about the same total Mn content had remarkably different amounts of available Mn.

Altering the pH of four soils with additions of $CaCO_3$ and H_2SO_4, Truong, Andrew and Wilson (53) found that increasing the pH decreased Mn availability in the soil and absorption by white clover. In a similar experiment using Samford (pH 3.90) and Charleville (pH 4.50) soils, these same researchers (54) reported that additions of $CaCO_3$ lowered the exchangeable fraction (extracted with neutral normal NH_4OAc) sharply and increased the easily reducible (extracted in neutral normal NH_4OAc plus 2 percent hydroquinone) but affected the total Mn very little. In contrast, high $Ca(H_2PO_4)_2$ application to these soils increased the exchangeable fraction at the expense of the easily reducible. This work indicated that, possibly due to the accompanying anion, $CaCO_3$ and $Ca(OH)_2$ are among the few compounds that can reduce exchangeable Mn in the soil. This is consistent with a report by Schmehl et al. (47) who found that addition of gypsum increased the amount of Mn in the soil solution. Helyar and Anderson (18) also altered the soil pH with additions of $CaCO_3$ and H_2SO_4 and found that extractable Mn decreased with increasing pH.

Messing (32), using the same extraction procedures as Truong, Wilson and Andrew (54), reported that both water soluble and exchangeable Mn decreased with increasing lime application and a subsequent rise in the soil pH. However, easily reducible Mn increased, with the most marked change in the three Mn fractions occurring from pH 5.3 to 5.9. Increasing lime application decreased the Mn concentration of lettuce leaves. The water soluble and exchangeable Mn fractions gave the best measure of availability to the plant. Similarly, Page (36) and Page, Schofield-Palmer and McGregor (37) found that water soluble Mn decreased with increasing pH and corresponded well with Mn uptake by oats. Anderson (2) stated that the pH of soils affects the water soluble and exchangeable Mn fractions the most, and the source of Mn for the plant comes only from these two fractions. However, Parker (39) reported that exchangeable Mn did not vary with soil pH. In this experiment Mn toxicity of soybeans (crinkle leaf) was associated with high levels of leaf Mn and water soluble soil Mn, with the water soluble soil Mn closely associated with pH.

Hoff and Mederski (21) attempted to find a soil extraction method for Mn which would correlate well with the Mn concentration in the uppermost mature leaf of soybeans. Extractions with $NH_4H_2PO_4$, alcoholic hydroquinone and H_3PO_4 yielded the highest correlation coefficients, ranging from 0.856 to 0.899. These had the smallest variances and were statistically different from extractions with NH_4OAc and NaOAc. Extracting with NH_4OAc and NH_4OAc plus 0.05 percent hydroquinone gave correlation coefficients of 0.686 and 0.771, respectively.

Plants differ in their ability to withstand high levels of Mn either in soil or nutrient solution (27,33,39,45,46,53,54). These differences may be partially due to a disturbance in the nutrient balance of the plant (34,45,53,54).

Lohnis (27) reported that beans (Phaseolus vulgaris) grown in a soil that was limed at different levels exhibited Mn toxicity symptoms when the Mn concentration of the foliage rose above approximately 1200 ppm. When these beans were grown in nutrient solution, a Mn concentration in the foliage of 1100 ppm proved toxic. A Mn level of 2.5 ppm in a von der Crone nutrient solution resulted in toxicity to lucerne. The Mn concentration in the foliage of injured lucerne plants varied from 500 to 1100 ppm while red clover showed no signs of toxicity until concentrations in the foliage reached 1300 ppm. Conclusions were that susceptibility to Mn toxicity appears to be a strong absorption or a weak tolerance within the plant. Growing spinach and barley in water and sand cultures, Rees and Sidrak (45) found that increasing Mn in solution (0.5, 25, 50, 100 ppm) resulted in increased Mn absorption and decreased yields of both species. Manganese had no effect on the N, P, K, Ca or Mg concentrations in either species. Truong et al. (53) and Truong et al. (54) reported that increasing Mn in nutrient solution (0.5, 5.0, 15.0, 30.0 ppm) decreased yield and increased Mn concentration in the shoots of white clover. Increasing Mn also increased percent Ca, Mg, K and decreased percent P. Morris and Pierre (33) found that a Mn concentration of 5.0 ppm in nutrient solution was toxic to lespedeza. In a similar study with cotton (46) increasing Mn concentration in nutrient solution did not severely affect the roots; however, top yields steadily decreased.

Soybeans have a high Mn requirement for growth (49,51), therefore, relative to other species, higher concentrations in soybeans may not be toxic. Manganese toxicity of Scott soybeans grown on Tifton (pH 5.1) and Hiwassee (pH 4.6) soils was associated with 2.5 ppm water soluble Mn and a leaf concentration of 495 ppm. In another study toxicity reduced the size of pods and the number of seeds per pod (39). Somers and Shive (51), growing soybeans in nutrient solution with added Mn levels of 0.00, 0.002, 0.01, 0.25, 2.0 and 5.0 ppm, reported that at iron levels of 0.005, 0.5 and 3.0 ppm both green weight and dry weight increased to 0.002, 0.25 and 2.0 ppm Mn, respectively. Above these levels yields decreased. In a similar study (34) Richland soybeans began showing Mn toxicity symptoms when the Mn level in nutrient solution was 2.5 ppm, and the Mn concentration in the tops was 529 ppm. Calcium concentration of the tops was quite variable. Singh, Kambal and Singh (49) reported that soybeans increased in plant height and weight up to a level of

0.10 ppm Mn in nutrient solution. Jones (23) reported that a Mn concentration of greater than 250 ppm in the upper fully mature trifoliate leaves of soybeans is in excess of that required by the plant.

Various researchers (34,38,39,49,51) are in close agreement as to the visual symptoms of Mn toxicity in soybeans, and these symptoms differ little from those evident in other species (27,46). The plants are stunted, and roots become tan and later turn a browner color. The uppermost, younger leaves curl (crinkle), and a yellowing of the interveinal tissue begins at the tip and progresses toward the base of the leaf. As toxicity is prolonged, necrotic areas develop on the upper leaves and further curling occurs.

Little work has been conducted concerning any interaction which might exist between Al and Mn in plants. Foy and Brown (15) showed that increasing the Al in nutrient solution decreased the Mn concentration in cotton. Working with spinach and barley, Rees and Sidrak (45) concluded that high Al does significantly lower leaf Mn in most plants. These workers postulated that this effect may be due to Al effects on roots.

CHAPTER II

METHODS AND MATERIALS

I. SOILS STUDY

General

To ascertain suspected differences between two soybean varieties in their tolerance of acid soil conditions, Forrest and Lee 68 varieties were grown for 85 days (July 18 to October 10, 1973) in a greenhouse pot experiment. The experimental design was a randomized complete block with a 3 x 3 x 2 factorial (three soils x three pH values of each soil x two varieties) treatment arrangement with three replications.

Eight kilograms of either acidified, limed or untreated air dry soil was added to eight liter, glazed earthenware pots equipped with holes for drainage. An equivalent amount of 100 kg/ha of K as KCl and 50 kg/ha of P as $CaH_4(PO_4)\cdot H_2O$ was added to each pot of Leadvale and Jefferson soil. None was added to the Huntington-Bewleyville soil.

Twelve seeds which had been inoculated with "molynoctin" were pregerminated between moist paper towels in an incubator and planted in each pot. Planting directly into the soil failed to obtain adequate emergence; thus 12 additional seeds were planted in approximately one and one-half inches of silica sand on top of the soil. After emergence plants were thinned to four per pot, and the pots were randomized on tables in the greenhouse. Plants were watered as needed with distilled water.

Bamboo poles were used to support the plants when, possibly due to the excessive heat in the greenhouse, the plants grew tall and spindly.

Harvesting occurred earlier than planned primarily because the plants growing on Leadvale soil (regardless of pH) were maturing much earlier than on the other two soils, and the leaves were beginning to fall. Plants were measured prior to harvest with a meter stick from the top of the sand to the tip of the tallest leaf. Harvesting consisted of cutting the plants at the base of the stem.

Samples of the soil in each pot were taken both before planting and after harvest. Only exchangeable Al and Mn were determined on the soils after harvest. Analysis of the soils is described later in this chapter.

Soils

The samples collected for the experiment were taken from the top three to four inches in the surface layer of three soils. A Huntington-Bewleyville silt loam (2 percent to 5 percent slope) at Springfield, Tennessee, was selected because some problems had developed with Forrest variety of soybeans grown on this soil in field crop performance trials in 1971 and 1972 (17). The other two soils, Jefferson loam (5 percent to 12 percent slopes) and Leadvale silt loam (2 percent to 5 percent slopes, eroded) from Hawkins County, Tennessee, were selected in order to have a wide range in pH across the three soils.

pH Change of Soils

Samples of the soils were titrated with 0.01 N H_2SO_4 and 0.01 N NaOH to determine the amount of acid or base needed to alter the pH of each soil to that of the other two soils. Amounts and kind of acid and base added to each eight kilograms of air dry soil and the subsequent change in pH (H_2O) are presented in Table 1. Soils were moistened to a saturated paste and pH (H_2O) measured. A small amount of KCl salt was added to the saturated paste and pH (KCl) was measured.

Table 1. Amounts of Acid and Base Added to Soils in Altering pH

Soil	pH (H_2O)[a]	meq HCl	meq 3/4 $Ca(OH)_2$ and 1/4 MgO	Total Added/ 8 kg Soil
Leadvale	4.72[b]	---	---	---
	5.20	---	168	5.51 g
	5.71	---	264	8.66 g
Jefferson	4.51	192	---	640 ml (0.3 N)
	5.51[b]	---	---	---
	6.12	---	144	4.62 g
Huntington-Bewleyville	4.68	320	---	640 ml (0.5 N)
	5.36	176	---	587 ml (0.3 N)
	6.72[b]	---	---	---

[a]Mean of six replications.

[b]Original pH.

Lime was added to the soil and then mixed thoroughly in a twin shell blender. Acid was applied in eight equal portions with a pipette and was mixed by hand after each application. Each pot which had been treated with acid was allowed to dry for six days. Limed soils were saturated with distilled water and allowed to stand for four days. Later, all pots were saturated with water a second time and allowed to stand for ten additional days before planting.

Soil Analysis

Data from the soil analysis are presented in Table 2. Air dry samples of soil were ground with a mortar and pestle and passed through a 1 mm sieve. Manganese was extracted by a combination of methods proposed by Sherman, McHargue and Hodkins (48) and Adams (1). Water soluble Mn was extracted by adding 200 ml of ion-free water to 25 g of soil in a 500 ml Erlenmeyer flask, shaking 30 minutes and then filtering through Whatman's Number 42 filter paper in a Buchner funnel. Four additional 10 ml increments of water were filtered through the soil, and the total volume was brought to 250 ml. The soil was then transferred to another flask and 200 ml of neutral normal NH_4OAc were added. The flask was shaken, allowed to stand overnight, filtered and brought to volume as before. Easily reducible Mn was extracted by transferring the same soil from the NH_4OAc extraction to another flask and adding 200 ml of a 2 percent hydroquinone in neutral normal NH_4OAc solution. This was shaken intermittently for six hours and then treated as in the other extractions.

Exchangeable Mn as well as exchangeable K, Ca and Mg was considered the sum of that extracted by water and NH_4OAc. The exchangeable plus

Table 2. Selected Extractable Cations of Soils at Original and Altered pH Values (meq/100 g)

pH (KCl)	pH (H_2O)	Exch.[a] K	Exch. Ca	Exch. Mg	Exch. Al	H_2O Mn	NH_4OAc Mn	Red. Mn	Exch. Mn	Total Mn	Titra. Acidity	CEC
					Leadvale							
3.71[b]	4.72	0.178	1.608	0.226	1.034	0.011	0.116	0.340	0.127	0.467	5.917	7.929
4.14	5.20	0.417	2.568	0.828	0.188	0.008	0.093	0.364	0.102	0.466	3.096	6.909
4.74	5.71	0.385	3.169	0.919	0.030	0.000	0.062	0.371	0.062	0.433	2.329	6.802
					Jefferson							
4.10	4.51	0.918	6.304	0.978	0.139	0.140	0.256	0.813	0.396	1.209	6.165	14.365
4.70[b]	5.51	0.798	7.954	0.844	0.015	0.012	0.143	1.019	0.155	1.174	4.316	13.912
5.30	6.12	0.598	8.510	0.578	0.000[c]	0.010	0.170	0.898	0.180	1.078	3.425	13.111
					Huntington-Bewleyville							
4.38	4.68	0.844	6.107	2.387	0.043	0.242	0.258	0.750	0.500	1.250	3.452	12.790
4.96	5.36	0.801	5.828	3.352	0.006	0.091	0.210	0.922	0.301	1.223	1.986	11.967
6.03[b]	6.72	0.720	4.114	3.550	0.000	0.000	0.042	0.467	0.042	0.509	0.891	9.275

[a]All values are means of six replications except titratable acidity which is a mean of two replications.

[b]Original pH of soil.

[c]A value of 0.000 indicates none measurable.

easily reducible Mn was considered the total Mn in the soil. Concentrations of Mn, K, Ca and Mg in the extracts were determined by a Perkin-Elmer, Model 303 atomic absorption spectrophotometer. Procedures suggested by the United States Department of Agriculture (50) were used in the extraction of Al from soils. Amounts of Al present in extracts were determined colorimetrically by a modification of the aluminon method (55) on a Beckman, Model B spectrophotometer. The titratable acidity was determined by titration with $Ba(OH)_2$ to pH 7.0, and the cation exchange capacity (CEC) was calculated by adding the exchangeable K, Ca, Mg and titratable acidity. Changes in the nutrient content of the soils upon altering the pH will be discussed in a later chapter.

Plant Analysis

Plant samples were oven dried at approximately 105°C and weighed with pods attached. Seeds and pods were separated, and the seeds were weighed. All mineral analysis was conducted on the leaves of the plant. The leaves were ground in a Wiley Mill to pass through a 2 mm screen. One gram of each sample was dry ashed in a muffle furnace at 550°C and dissolved in 1.0 N HCl. Aluminum and Mn concentrations of these extracts were determined as in the soils analysis. Another 1 g sample was dry ashed and dissolved in 0.1 N HCl. Potassium and Ca in these samples were determined by flame emission photometry, Mg by the Magnesium Blue Method and P by the ammonium vanadate colorimetric procedure on a Technicon, Model III autoanalyzer. Molybdenum was extracted from solution by a thiocyanate procedure outlined by Chapman and Pratt (11) and determined colorimetrically on a Beckman, Model B spectrophotometer. One-half gram of dry ashed sample was dissolved in 0.1 N HCl for the determination of B. Concentrations of B were determined colorimetrically by the curcumin procedure (22), using the above mentioned spectrophotometer.

Statistical Analysis

Analysis of variance and F tests were executed by an IBM System/360 model 65 computer using a Statistical Analysis System developed by Barr and Goodnight (7). Treatment means were compared by Duncan's New Multiple Range test.

II. FIRST NUTRIENT SOLUTION STUDY

General

To study further the effects of two often toxic elements in acid soils, the same soybean varieties used in the soil study were grown in one-fifth strength Hoagland's Number Two nutrient solution at different levels of added Al and Mn. Iron EDTA was prepared by procedures outlined by Steiner and van Winden (52) and added in the amounts suggested by Hoagland and Arnon (19). The experiment was conducted in the greenhouse in a randomized complete block design with a split, split block arrangement of treatments and three replications. Plants were grown for 29 days, from July 25 to August 22, 1973.

Aluminum was added to solution as $Al_2(SO_4)_3 \cdot 18\ H_2O$ in the amounts of 0.0, 4.0 and 8.0 ppm. Manganese was supplied as $MnCl_2$ in concentrations of 0.5 (normal Hoagland's), 2.5 and 5.0 ppm. Originally, five liters of nutrient solution were added to 780 g of perlite in nine liter polyethylene pots. This put the nutrient solution approximately one inch from the top of the perlite and the perlite about two inches from the top of the pots, except eight pots which were larger than the others (approximately 12 liters).

A rough experiment was conducted after this study in an attempt to determine the effect of perlite on the amounts of added Al in nutrient solution. Indications were that Al is given up to the solution by perlite when none or small amounts of Al are added. Furthermore, perlite may sorb Al when added amounts in solution are higher, possibly establishing an equilibrium. There was no indication that any other elements were affected in this manner by perlite. However, it should be noted that any further reference to amounts of elements in the nutrient solution refers only to amounts added and not to the amounts actually in solution.

Each pot was equipped with curved glass tubing that hung over the rim of the pot and extended to approximately one and one-half inches from the bottom. The end of the tubing that was placed in the perlite was covered with cheesecloth to prevent clogging. This tubing was used when changing solutions and facilitated siphoning with a vacuum pump.

Inadvertently lower concentrations of Al and Mn were originally added to the perlite than was intended. Since the weight of the perlite and the weight of the pots were known, the amount of original solution left after siphoning could be calculated. Another solution was added to the remaining solution in the pot to obtain the desired concentrations. This solution was poured down the side of the pots so that it would mix first with that solution remaining in the bottom.

Twelve seeds, pregerminated as in the soils study but not inoculated, were planted in each pot. After emergence these were thinned to six. Solutions were changed once each week for the first two weeks and then twice each week thereafter. These plants also required support. Each pot contained four wooden plot markers connected by string around the plants.

Procedures for plant height measurements and harvesting of tops were the same as in the soils study. Roots were removed from the pots and cleaned of adhering perlite by hand. The roots were oven dried at approximately 105^{o}C and weighed.

Plant Analysis and Statistical Analysis

Both plant analysis and statistical analysis were conducted as described under the soils experiment.

III. SECOND NUTRIENT SOLUTION STUDY

Added Al concentrations in nutrient solution of this study were 4.0, 12.0 and 20.0 ppm. Manganese levels were 0.5, 1.5 and 3.0 ppm. Soybeans were grown from October 6 to November 9, 1973 for a total of 35 days. The larger pots used in the first nutrient solution study were trimmed to the approximate height of the other pots. All other aspects of the experiment were the same as the first nutrient solution study.

CHAPTER III

RESULTS AND DISCUSSION

I. SOILS STUDY

Effect of Changing pH on the Soil Al and Mn Content

The levels of cations present in the soil were presented earlier in Table 2, page 16. The levels of Ca, K and Mg were quite variable among soils and across pH values of each soil. One should note, however, that the Huntington-Bewleyville soil effervesced upon addition of HCl to lower the pH, indicating the presence of $CaCO_3$. This could explain the decrease in exchangeable Ca with increasing pH in this soil. Further discussion will be limited to the changes that occurred in the Al and Mn content of the soils.

The effect of pH on the exchangeable Al content of the soils is presented in Figure 1. This figure is strikingly similar to one obtained in a similar study by Helyar and Anderson (18). The soils differed considerably in exchangeable Al content at respective pH values. Soils increased in exchangeable Al in the order of Leadvale < Jefferson < Huntington-Bewleyville. All soils decreased in Al content as the pH increased. The curves indicate that the higher the Al content at low pH values the greater the pH must be increased to reach a nondetectable level of Al in the soil. These results suggest that different amounts of lime would be required to alleviate toxic levels of Al in different soils having identical pH values.

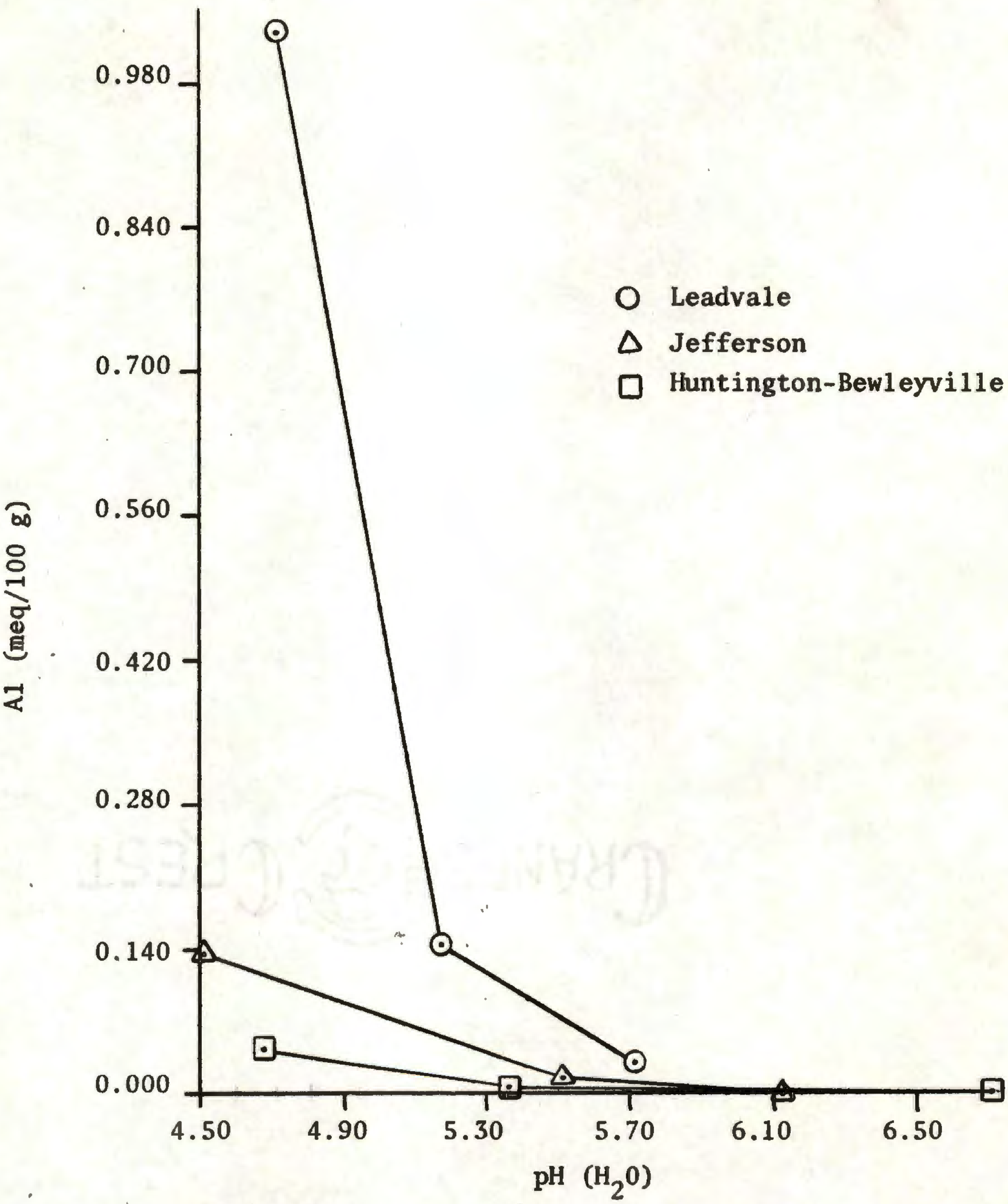

Figure 1. Effect of varying pH on the content of exchangeable aluminum in soils.

Proportions of the various fractions of extractable Mn contained in each soil differed across pH values and among soils. Figures 2, 3 and 4 show the effect of pH on these fractions. Both water soluble and total Mn decreased as the pH increased in all soils. Only the Jefferson soil showed an increase in the NH_4OAc extractable and exchangeable fractions as the pH increased. The Leadvale soil contained the lowest amounts of all fractions of extractable Mn.

These fractions of soil Mn were correlated with pH, plant weight, seed weight and the Mn concentration in soybean leaves in an attempt to establish any relationships between them. Correlation coefficients are presented in Table 3. The pH of the soils gave the highest correlation coefficients with the water soluble, NH_4OAc extractable and exchangeable fractions of soil Mn. Of the extractable Mn fractions the water soluble and exchangeable Mn gave the best indication of the Mn concentration in soybean leaves. Yield gave the highest correlation coefficient with water soluble Mn. These findings are consistent with those reported by Messing (32).

Effect of Soil pH and Soil Al and Mn Content on Growth and Yield of Soybeans

Soil pH, exchangeable Al and exchangeable Mn did not correlate well with plant height. Heights of plants are presented in Table 4. The greatest differences between varieties were evident at the lower pH values of each soil. Forrest plant height was significantly (P .05) greater than Lee 68 when grown on the Leadvale soil at pH 4.7. However,

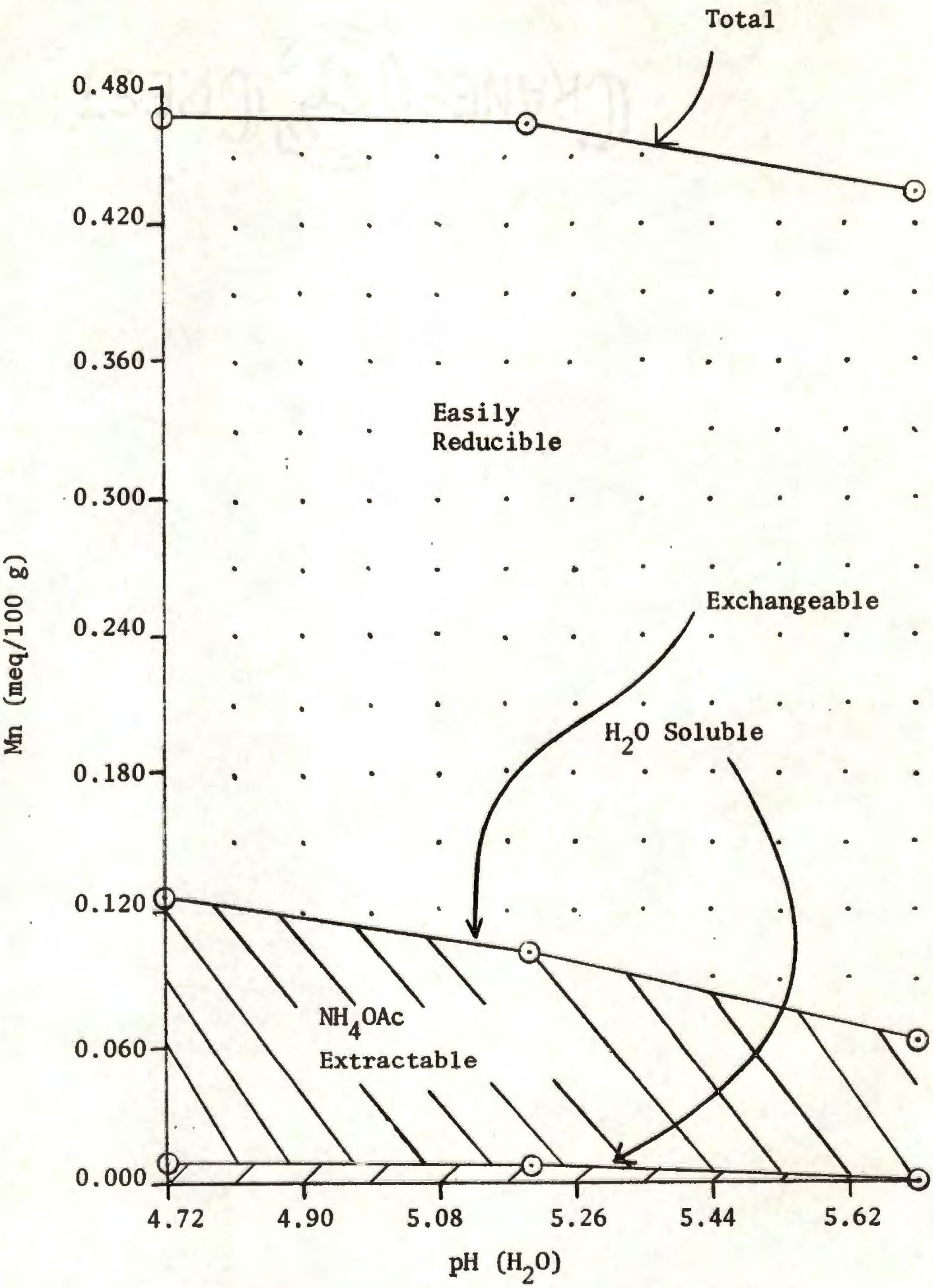

Figure 2. Effect of changing pH on the various fractions of extractable manganese in Leadvale soil.

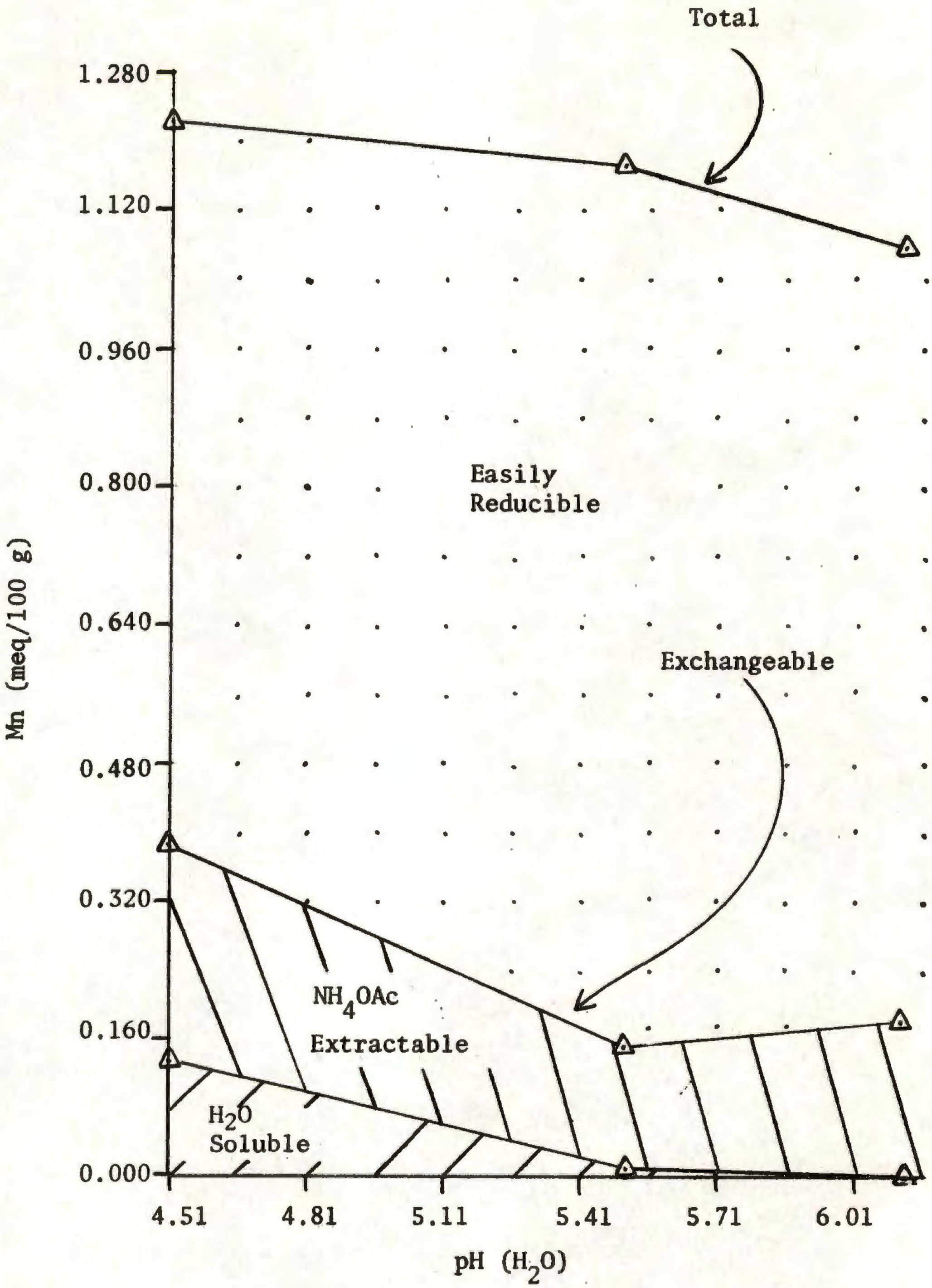

Figure 3. Effect of changing pH on the various fractions of extractable manganese in Jefferson soil.

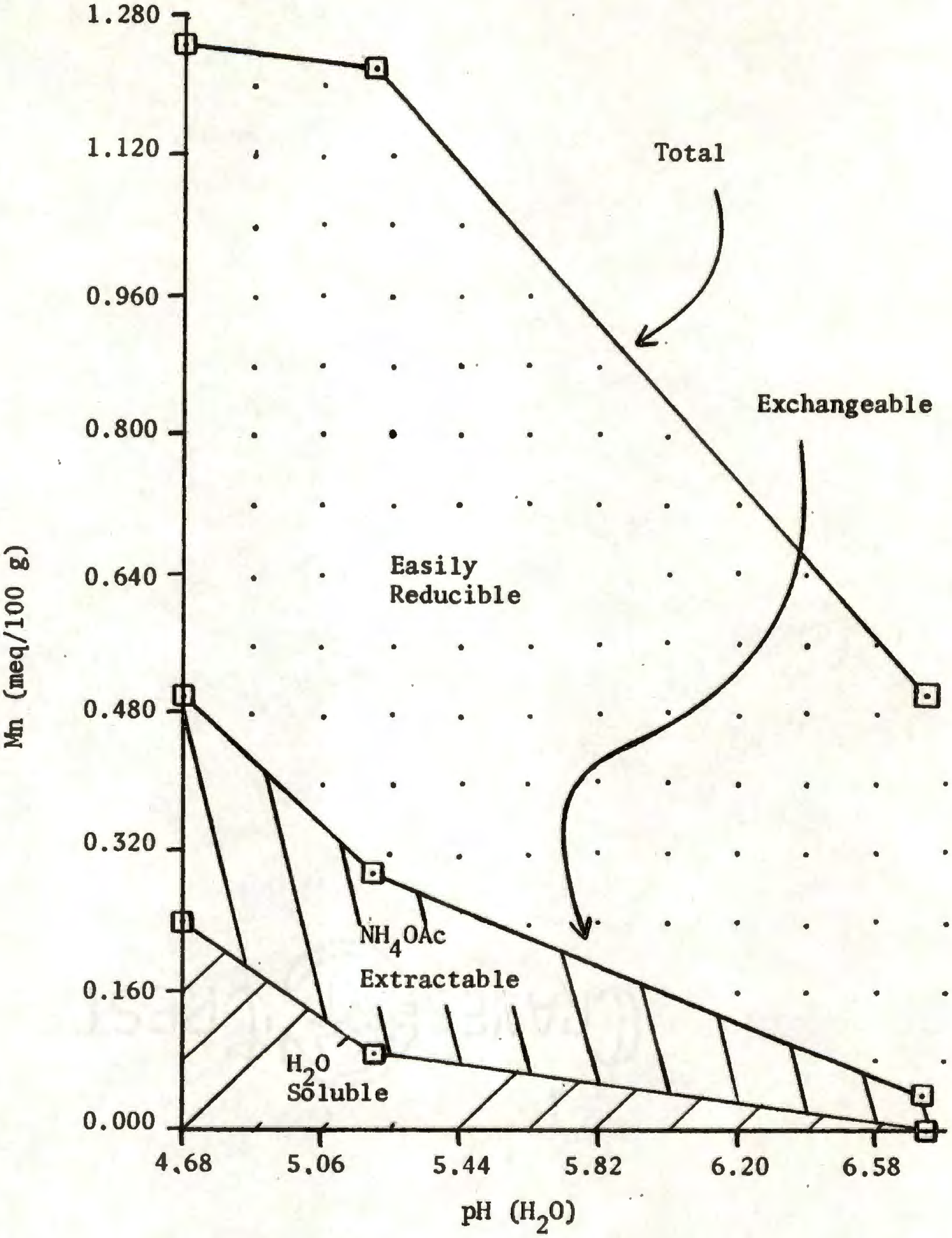

Figure 4. Effect of changing pH on the various fractions of extractable manganese in Huntington-Bewleyville soil.

Table 3. Various Fractions of Extractable Manganese in Soils Correlated With Each Other, the Manganese Concentration of the Plant and Soybean Yield Data (r Values)

Variables	H_2O Mn	Exch. Mn	NH_4OAc Mn	Red. Mn	Total Mn	Mn Conc. in Leaves	Plant Weight	Seed Weight
pH (H_2O)	-0.619*	-0.657*	-0.633*	-0.089	-0.338*	-0.831*	+0.552*	+0.634*
H_2O Mn	---	+0.956*	+0.811*	+0.350*	+0.652*	+0.855*	-0.361*	-0.591*
Exch. Mn	---	---	+0.947*	+0.525*	+0.793*	+0.852*	-0.282*	-0.581*
NH_4OAc Mn	---	---	---	+0.662*	+0.869*	+0.762*	-0.168	-0.511*
Red. Mn	---	---	---	---	+0.934*	+0.223	+0.305*	-0.152
Total Mn	---	---	---	---	---	+0.518*	+0.100	-0.351*
Mn Conc. in Leaves	---	---	---	---	---	---	-0.471*	-0.680*
Plant Weight	---	---	---	---	---	---	---	+0.653*

*Significant at the P .05 level.

Table 4. Plant Height in Centimeters of Soybeans Grown in Soils With Varying pH

	Soils With Varying pH (H_2O)					
Variety	Leadvale -	pH	Jefferson -	pH	Huntington-Bewleyville -	pH
Forrest	54.6 abcd*	4.72	55.7 abcd	4.50	40.7 f	4.67
Lee 68	44.5 ef	4.71	62.7 a	4.52	50.5 cde	4.68
Forrest	51.3 bcde	5.20	51.3 bcde	5.51	58.3 abc	5.36
Lee 68	49.7 de	5.20	57.2 abcd	5.51	55.2 abcd	5.37
Forrest	54.7 abcd	5.66	59.0 ab	6.13	56.4 abcd	6.73
Lee 68	49.5 de	5.76	56.8 abcd	6.11	54.5 abcd	6.71

*Means followed by the same letter are not significantly different at the P .05 level.

plant height of Lee 68 was greater than Forrest at the lowest pH values of the Jefferson and Huntington-Bewleyville soils. [Hereafter any reference to exact pH values will be to pH (H_2O) to the nearest tenth and will be an average of the soils planted with Forrest and Lee 68 varieties. Furthermore, all comments on significance will be at the P .05 level unless otherwise stated.] At the intermediate and highest pH values of each soil Forrest generally had a greater height than Lee 68 except for the Jefferson soil at pH 5.5.

Plant heights of both varieties were greater on the Jefferson and Huntington-Bewleyville soils. Values for these two soils were approximately the same except at the lowest pH values where plants grown on the

Huntington-Bewleyville soil were significantly shorter than those grown on the Jefferson soil. Plants grown at pH 4.7 on the Huntington-Bewleyville soil showed the greatest symptoms of Mn toxicity, especially with the Forrest variety. Leaves were wrinkled, chlorotic at the tips and exhibited necrotic areas. Plants grown on the Jefferson and Leadvale soils at the lower pH values also showed these symptoms but to a lesser extent than on the Huntington-Bewleyville soil. As was previously noted, the pH of the soil negatively correlated quite well with the Mn concentration in the leaves (r = -0.831). Manganese toxicity symptoms were dramatically less evident as the pH increased.

Somewhat in contrast to plant heights, Lee 68 plant weights were approximately the same or greater than those of Forrest variety in every soil regardless of pH (Table 5). In most instances Lee 68 plant weights

Table 5. Plant Weight in Grams of Soybeans Grown in Soils With Varying pH

	Soils With Varying pH (H_2O)					
Variety	Leadvale -	pH	Jefferson -	pH	Huntington-Bewleyville -	pH
Forrest	40.59 def*	4.72	42.87 def	4.50	23.09 f	4.67
Lee 68	37.99 def	4.71	56.66 abcd	4.52	34.92 ef	4.68
Forrest	43.31 def	5.20	42.95 def	5.51	68.26 ab	5.36
Lee 68	47.39 cde	5.20	69.32 ab	5.51	67.89 ab	5.37
Forrest	41.95 def	5.66	75.80 a	6.13	68.15 ab	6.73
Lee 68	54.80 bcde	5.76	67.43 ab	6.11	66.01 abc	6.71

*Means followed by the same letter are not significantly different at the P .05 level.

were greater. Both varieties tended to increase in plant weight as the pH increased. The most marked increase was from the low to intermediate pH values of each soil. This increase, however, was significant only in the Huntington-Bewleyville soil.

As with plant heights, plant weights were generally greatest in the Jefferson and Huntington-Bewleyville soils except at the lowest pH of the latter. Forrest variety grown in this soil at the lower pH yielded plant weights nearly 50 percent less than those grown on the other two soils. Symptoms of Mn toxicity indicated that this decrease in weight was probably due mostly to the high available Mn in the soil and the subsequent concentration of toxic levels in the plant. Exchangeable Al levels in the soil also increased with decreasing pH; however, these values did not correlate well with any yield data (r values < 0.347).

Seed yields of soybeans are presented in Table 6. Forrest variety seed weights were greater at every pH of each soil except at the lowest pH of the Huntington-Bewleyville soil, where Forrest seed weights were only half the seed weights of Lee 68 variety. At the intermediate pH of the Jefferson soil, Forrest also yielded less than Lee 68, but values were not significantly different. Seed yields tended to increase with increasing pH in every soil, with the greatest differences occurring from the lowest to the intermediate pH values, and then generally equalizing thereafter.

Both varieties had higher seed yields when grown on the Jefferson and Huntington-Bewleyville soils at the higher pH values than those

Table 6. Seed Weight in Grams of Soybeans Grown in Soils With Varying pH

	Soils With Varying pH (H_2O)					
Variety	Leadvale -	pH	Jefferson -	pH	Huntington-Bewleyville -	pH
Forrest	11.50 cde*	4.72	5.78 fg	4.50	2.94 g	4.67
Lee 68	9.47 de	4.71	5.03 g	4.52	4.66 g	4.68
Forrest	14.02 bc	5.20	9.09 ef	5.51	18.17 a	5.36
Lee 68	11.78 cde	5.20	10.03 de	5.51	12.77 cde	5.37
Forrest	13.35 cd	5.66	17.36 ab	6.13	17.28 ab	6.73
Lee 68	11.84 cde	5.76	10.80 cde	6.11	11.15 cde	6.71

*Means followed by the same letter are not significantly different at the P .05 level.

grown on the Leadvale soil. However, at the lowest pH values of these soils seed weights were inversely related to the Mn content of the soils. Seed weights of both varieties were significantly higher when grown on the Leadvale soil than when grown on the other soils at low pH values. Figure 5 shows the relationship of seed yield to the Mn concentration in the leaves of soybeans grown on the soils. Generally, seed weights decreased when leaf concentrations of Mn became high.

Apparently, at low pH values Mn is the primary growth limiting factor in all of these soils. Forrest variety appears to be more susceptible than Lee 68 to acid soil conditions (Mn toxicity). At higher pH values, however, Forrest has higher yields than Lee 68. The highest pH at which Mn toxicity symptoms were evident was 4.7 in the Leadvale soil. This pH was associated with a soil exchangeable Mn

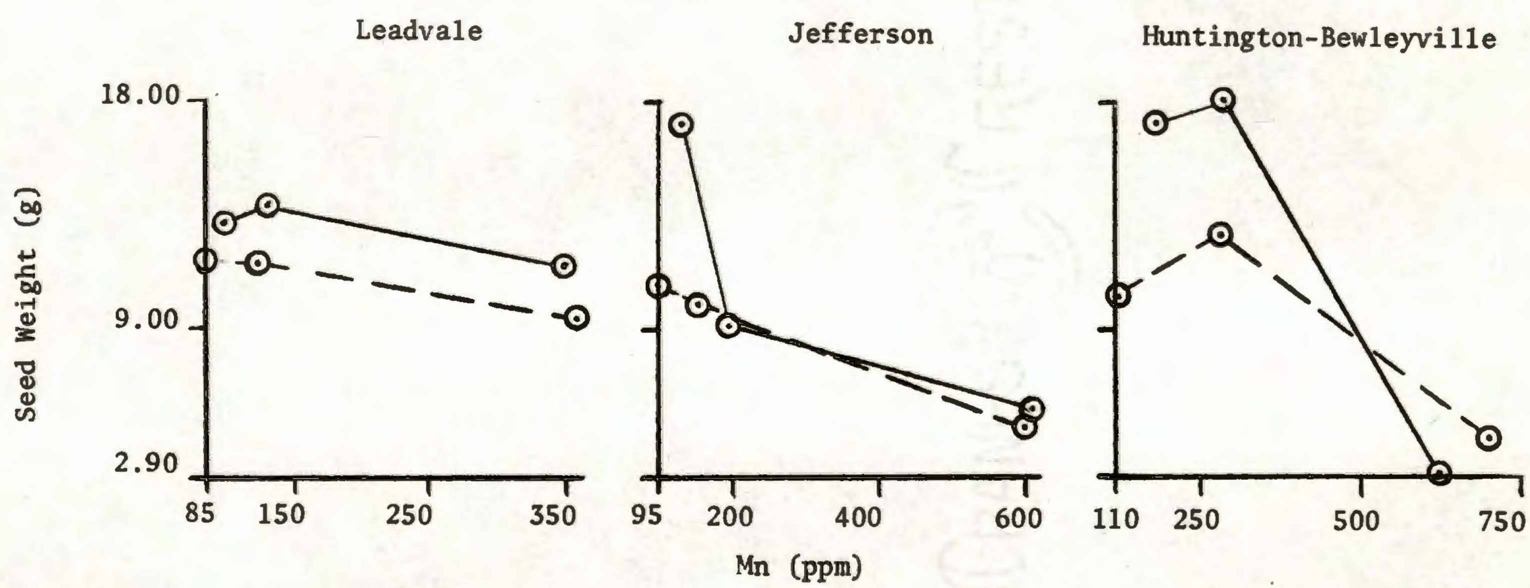

Figure 5. Effect of changing manganese concentration in soybean leaves on the seed yield of Forrest (——) and Lee 68 (---) soybeans.

level of 0.127 meq/100 g and an average Mn leaf concentration in both varieties of 353 ppm. Considering all the soils in this study, the optimum pH for growth and yield of soybeans appears to lie between approximately 5.2 and 6.1. However, the optimum pH varied among the soils.

The lower yields reported by Graves (17) of Forrest variety when grown on the Huntington-Bewleyville soil in the field at its original pH (6.7) was not readily apparent in this study. But the seed weights, plant weights and plant heights of both varieties in this study increased slightly when the original pH was lowered to 5.4. Perhaps the lower yields reported by Graves at the original pH of this soil was due to nutrient deficiencies, possibly Mn deficiency. The increase in exchangeable Ca in this soil when the pH was lowered may be a factor also. The lower yields at the high pH of this soil may become significant in larger studies in the field.

Effect of Soil pH, Al Content and Mn Content on the Concentrations of Nutrients in the Leaves of Soybeans

Table 7 gives correlation coefficients for soil pH, exchangeable Al and exchangeable Mn with the nutrient concentrations in the leaves of soybeans. (Hereafter any reference to the plant nutrient concentration refers to the amounts measured in the leaves.) The Al concentration in the plant is presented in Table 8 and shown graphically in Figure 6. Aluminum absorption by the plant did not correlate well with the soil pH or exchangeable Al in the soil. Both varieties grown on the Leadvale

Table 7. Soil pH, Exchangeable Aluminum and Exchangeable Manganese Correlated With the Nutrient Concentrations in Soybean Leaves (r Values)

Variables	Al	Mn	Mo	B	K	Ca	Mg	P
pH (H_2O)	+0.223	-0.831*	+0.272*	-0.480*	+0.211	-0.146	-0.102	-0.032
Exch. Al	+0.316*	+0.166	-0.082	-0.241	+0.221	-0.528*	-0.465*	-0.153
Exch. Mn	-0.480*	+0.852*	-0.230	+0.717*	-0.436*	+0.666*	+0.458*	+0.077
Al in Leaves	---	-0.499*	+0.208	-0.554*	+0.562*	-0.582*	-0.428*	-0.015
Mn in Leaves	---	---	-0.314*	+0.721*	-0.417*	+0.521*	+0.367*	+0.032

*Significant at the P .05 level.

Table 8. Parts Per Million Aluminum in Leaves of Soybeans Grown in Soils With Varying pH

	Soils With Varying pH (H_2O)					
Variety	Leadvale -	pH	Jefferson -	pH	Huntington-Bewleyville -	pH
Forrest	286 ab*	4.72	119 d	4.50	117 d	4.67
Lee 68	332 a	4.71	146 cd	4.52	144 cd	4.68
Forrest	256 ab	5.20	239 ab	5.51	289 ab	5.36
Lee 68	319 a	5.20	212 bc	5.51	323 a	5.37
Forrest	193 bcd	5.66	222 bc	6.13	247 ab	6.73
Lee 68	197 bcd	5.76	289 ab	6.11	253 ab	6.71

*Means followed by the same letter are not significantly different at the P .05 level.

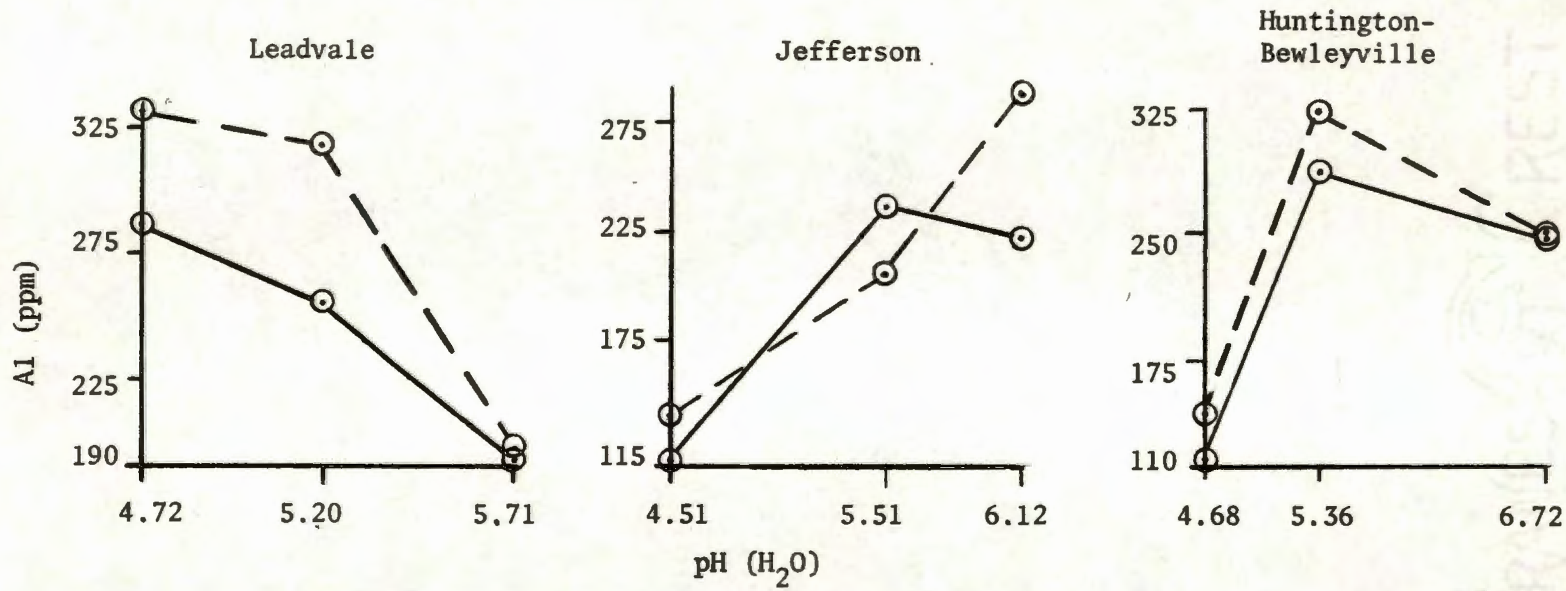

Figure 6. Effect of varying soil pH on the aluminum concentration in the leaves of Forrest (——) and Lee 68 (---) soybeans.

soil decreased in Al concentration as the pH increased. Plants grown on the other two soils were quite variable in Al concentration. Quite surprisingly the lowest levels of Al concentration occurred in those plants grown on the Jefferson and Huntington-Bewleyville soils at their lowest pH values. Forrest tended to concentrate more Al in the leaves than Lee 68, but this difference was not significant.

In contrast to Al, the Mn concentration in the leaves varied more with the pH as expected. Table 9 and Figure 7 show the change in Mn concentration with changing pH. The Mn concentration in the plant decreased as the pH increased in each soil. These decreases were significant with each pH increase in the Huntington-Bewleyville soil and from the low to intermediate pH values of the other soils. Since greater total growth of the plant was recorded at the higher pH values

Table 9. Parts Per Million Manganese in Leaves of Soybeans Grown in Soils With Varying pH

	Soils With Varying pH (H_2O)					
Variety	Leadvale -	pH	Jefferson -	pH	Huntington-Bewleyville -	pH
Forrest	348 c*	4.72	610 b	4.50	620 b	4.67
Lee 68	358 c	4.71	603 b	4.52	700 a	4.68
Forrest	133 de	5.20	187 d	5.51	280 c	5.36
Lee 68	123 de	5.20	155 de	5.51	278 c	5.37
Forrest	100 de	5.66	127 de	6.13	177 de	6.73
Lee 68	85 e	5.76	98 de	6.11	112 de	6.71

*Means followed by the same letter are not significantly different at the P .05 level.

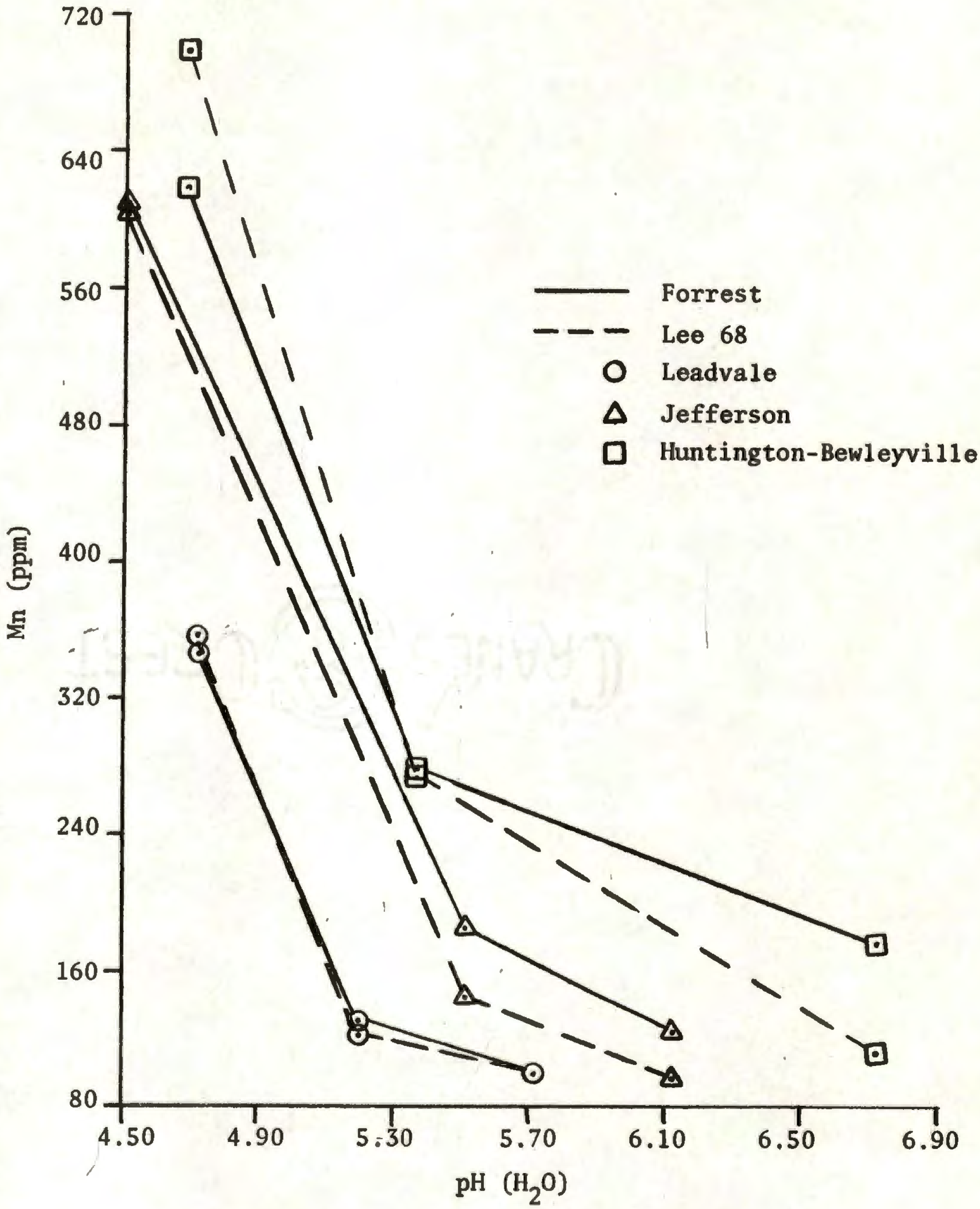

Figure 7. Effect of varying soil pH on the manganese concentration of soybean leaves.

of these soils, part of this decrease in Mn concentration in the plant may be due to a dilution effect. Forrest variety concentrated more Mn at all pH values of every soil except at pH 4.7 in the Leadvale and Huntington-Bewleyville soils. Lee 68 contained significantly more Mn when grown at pH 4.7 in the Huntington-Bewleyville soil. The difference in Mn concentration in both varieties varied across soils directly with the total Mn content of the soils.

As was mentioned earlier the Mn concentration in the plant tended to vary directly with the exchangeable Mn in the soil. This is presented graphically in Figure 8. The NH_4OAc fraction of extractable Mn in the Jefferson soil increased with liming, resulting in an increase in exchangeable Mn with liming (Table 2, page 16, Figure 3, page 25). Manganese absorption by the plant was not proportionate to this increase (Table 9, Figure 8). This indicates that possibly an error was made in the course of the experiment which gave an erroneous value for the NH_4OAc fraction of Mn in the Jefferson soil at pH 6.1.

Percent K in the plant was quite variable across the pH values of each soil and among soils (Table 10). Correlation coefficients for percent K with pH, exchangeable Al and exchangeable Mn were less than 0.500. Percent K in both varieties was significantly lower when grown at the lowest pH values of the Jefferson and Huntington-Bewleyville soils. However, percent K in the plants grown on the Leadvale soil was significantly higher than the other soils at the two higher pH values. There was no significant difference or general relationship between varieties. All values of percent K in Table 9 are in the K

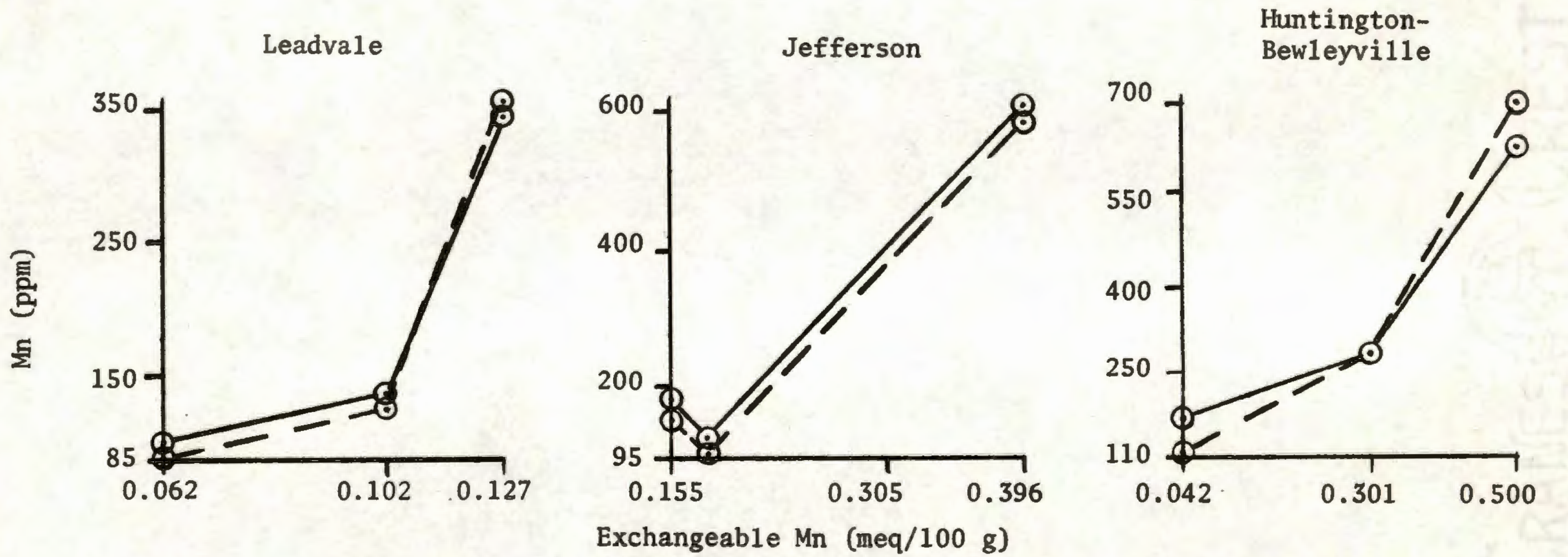

Figure 8. Effect of exchangeable manganese on the manganese concentration in the leaves of Forrest (——) and Lee 68 (---) soybeans.

Table 10. Percent Potassium in Leaves of Soybeans Grown in Soils With Varying pH

	Soils With Varying pH (H_2O)					
Variety	Leadvale -	pH	Jefferson -	pH	Huntington-Bewleyville -	pH
Forrest	1.12 a*	4.72	0.40 fg	4.50	0.20 g	4.67
Lee 68	0.95 ab	4.71	0.50 efg	4.52	0.52 defg	4.68
Forrest	0.63 bcdef	5.20	1.12 a	5.51	0.76 bcde	5.36
Lee 68	0.52 defg	5.20	1.17 a	5.51	0.93 abc	5.37
Forrest	0.58 cdef	5.66	0.86 abcd	6.13	0.89 abc	6.73
Lee 68	0.42 efg	5.76	0.97 ab	6.11	0.95 ab	6.71

*Means followed by the same letter are not significantly different at the P .05 level.

deficient range reported by Jones (23); however, no visual symptoms of K deficiency were noted during the growth of these plants.

Percent Ca in the plant tended to correspond closer to the exchangeable Ca level in the soil rather than to the pH of the soil (Table 11). Figure 9 presents the data graphically. Calcium concentrations were generally greater in Forrest variety. Calcium concentrations in the plant tended to increase in order of Leadvale < Jefferson < Huntington-Bewleyville at the low and intermediate pH values of these soils. Values are approximately the same across soils at the highest pH values.

Percent Ca in the plants increased with increasing pH in the Leadvale soil while Ca concentration reached a minimum at the intermediate pH of the Jefferson soil. Plants grown on the Huntington-Bewleyville

Table 11. Percent Calcium in Leaves of Soybeans Grown in Soils With Varying pH

	Soils With Varying pH (H_2O)					
Variety	Leadvale -	pH	Jefferson -	pH	Huntington-Bewleyville -	pH
Forrest	1.15 gh*	4.72	2.14 b	4.50	2.78 a	4.67
Lee 68	1.03 h	4.71	1.82 bcdef	4.52	2.86 a	4.68
Forrest	1.50 efg	5.20	2.00 bcd	5.51	2.14 b	5.36
Lee 68	1.36 fgh	5.20	1.58 cdefg	5.51	1.65 cdef	5.37
Forrest	1.96 bcde	5.66	2.04 bc	6.13	1.85 bcde	6.73
Lee 68	1.59 cdefg	5.76	1.70 bcdef	6.11	1.56 defg	6.71

*Means followed by the same letter are not significantly different at the P .05 level.

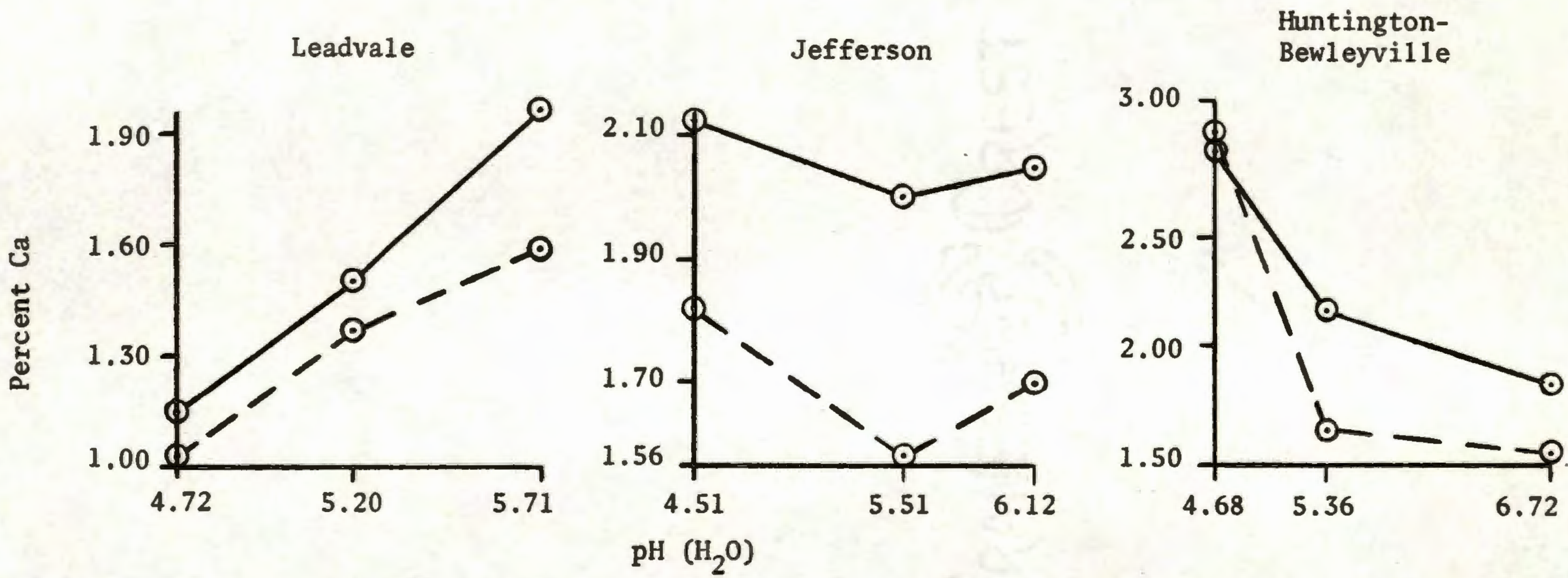

Figure 9. Effect of varying soil pH on the calcium concentration in the leaves of Forrest (——) and Lee 68 (---) soybeans.

soil decreased in Ca concentration as the pH increased, which corresponded to the levels of exchangeable Ca in the soil.

Table 12 shows there were no differences between varieties in Mg concentration in the plant. Percent Mg of both varieties was significantly lower at pH 4.7 than at higher pH values in the Leadvale and

Table 12. Percent Magnesium in Leaves of Soybeans Grown in Soils With Varying pH

	Soils With Varying pH (H_2O)					
Variety	Leadvale -	pH	Jefferson -	pH	Huntington-Bewleyville -	pH
Forrest	0.27 f*	4.72	0.52 ab	4.50	0.52 ab	4.67
Lee 68	0.30 ef	4.71	0.48 abcd	4.52	0.59 a	4.68
Forrest	0.44 bcd	5.20	0.48 abcd	5.51	0.35 cdef	5.36
Lee 68	0.46 abcd	5.20	0.41 bcdef	5.51	0.40 bcdef	5.37
Forrest	0.43 bcde	5.66	0.42 bcde	6.13	0.34 def	6.73
Lee 68	0.48 abc	5.76	0.47 abcd	6.11	0.39 bcdef	6.71

*Means followed by the same letter are not significantly different at the P .05 level.

Huntington-Bewleyville soils. There was no significant difference in the Mg concentration in the plants grown on the Jefferson soil. Plants grown on the Huntington-Bewleyville and Jefferson soils had significantly higher Mg concentrations than the plants grown on the Leadvale soil at the lower pH values of each soil. At higher pH values percent Mg in the plant did not differ significantly among soils.

Phosphorus concentrations in the plants grown on Leadvale soil were quite low (Table 13). Jones (23) reported that less than 0.15 percent P in the upper fully mature trifoliate leaves sampled prior to pod set results in deficiency in soybeans. However, there were no visual

Table 13. Percent Phosphorus in Leaves of Soybeans Grown in Soils With Varying pH

	Soils With Varying pH (H_2O)					
Variety	Leadvale -	pH	Jefferson -	pH	Huntington-Bewleyville -	pH
Forrest	0.03 e*	4.72	0.26 ab	4.50	0.29 a	4.67
Lee 68	0.05 e	4.71	0.18 cd	4.52	0.21 bc	4.68
Forrest	0.02 e	5.20	0.21 bc**	5.51	0.15 cd	5.36
Lee 68	0.01 e	5.20	0.19 cd	5.51	0.15 d	5.37
Forrest	0.06 e	5.66	0.18 cd	6.13	0.16 cd	6.73
Lee 68	0.05 e	5.76	0.18 cd	6.11	0.17 cd	6.71

*Means followed by the same letter are not significantly different at the P .05 level.

**One replication contained an exorbitant amount of P (3.23 percent). This value was omitted and replaced with the mean of the other two replications.

symptoms of P deficiency noted during the growth of these plants. Percent P in the plants grown on the Jefferson and Huntington-Bewleyville soils were significantly higher than those grown on the Leadvale soil regardless of pH. Percent P in the plant was significantly higher at the lower pH values of the Jefferson and Huntington-Bewleyville soils, and at these pH values Forrest absorbed significantly more P than did Lee 68.

If P became more soluble when the soil was acidified, as found by Pratt (43), then this may account for the increased P absorption by the plants grown at the lower pH values of Jefferson and Huntington-Bewleyville soils. Furthermore, if the ability of the plant to tolerate high levels of Al in the soil is related to its ability to absorb and utilize P in the presence of Al (16), then this may account for the absence of any apparent effect of Al on soybeans in the soils study.

The concentration of Mo in the plants is presented in Table 14. Generally, Forrest contained more Mo than Lee 68; however, differences were not significant. There was no well defined relationship of Mo in the plant to the pH of the soil. Furthermore, as evidenced by

Table 14. Parts Per Million Molybdenum in Leaves of Soybeans Grown in Soils With Varying pH

	Soils With Varying pH (H_2O)					
Variety	Leadvale -	pH	Jefferson -	pH	Huntington-Bewleyville -	pH
Forrest	1.88 abc*	4.72	1.29 c	4.50	0.99 c	4.67
Lee 68	1.46 bc	4.71	0.71 c	4.52	0.48 c	4.68
Forrest	1.77 bc	5.20	1.60 bc	5.51	4.14 a	5.36
Lee 68	1.68 bc	5.20	1.62 bc	5.51	2.33 abc	5.37
Forrest	1.56 bc	5.66	2.40 abc	6.13	1.63 bc	6.73
Lee 68	1.28 c	5.76	1.63 abc	6.11	3.88 ab	6.71

*Means followed by the same letter are not significantly different at the P .05 level.

correlation coefficients in Table 7, page 34, the Al and Mn content of the soil or plants had very little, if any, effect on the Mo concentration in the plant. There were no significant differences among soils as to Mo concentration in the plant.

Plants of Forrest variety contained a higher concentration of B than Lee 68 at almost every pH of each soil (Table 15). These varietal differences were significant at the P .05 level with the Jefferson and Huntington-Bewleyville soils at their lowest pH values and at the P .10 level with the Leadvale and Jefferson soils at their higher pH values. Plants grown on Jefferson and Huntington-Bewleyville soils contained significantly higher concentrations of B than those grown on the Leadvale soil. Consistent with the trends noted by Lessman et al. (25), increasing pH tended to decrease the B concentration in the plant.

Table 15. Parts Per Million Boron in Leaves of Soybeans Grown in Soils With Varying pH

	Soils With Varying pH (H_2O)					
Variety	Leadvale -	pH	Jefferson -	pH	Huntington-Bewleyville -	pH
Forrest	36 ef*	4.72	65 a	4.50	65 a	4.67
Lee 68	32 fg	4.71	48 bcd	4.52	56 bc	4.68
Forrest	27 g	5.20	53 bc	5.51	41 def	5.36
Lee 68	25 g	5.20	47 cd	5.51	44 cde	5.37
Forrest	34 fg	5.66	43 de	6.13	39 def	6.73
Lee 68	25 g	4.76	36 ef	6.11	37 ef	6.71

*Means followed by the same letter are not significantly different at the P .05 level.

Effect of Growing Soybeans on the Exchangeable Al and Mn in the Soil

The exchangeable Al content of the soil was generally higher after harvest than before planting. There were no noticeable differences between varieties grown on the soils as far as increasing Al in the soils was concerned. Exchangeable Mn also was generally increased in all the soils. However, at the lowest pH of Huntington-Bewleyville, where Mn toxicity symptoms were most evident, exchangeable Mn in the soil was reduced over 30 percent, apparently partly due to absorption by soybeans. The variety grown made no difference in the amounts of exchangeable Mn in the soils. Levels of exchangeable Al and Mn in the soils before planting and after harvest are presented in Table 16.

II. NUTRIENT SOLUTION STUDY ONE

Effect of Different Levels of Added Al and Mn in Nutrient Solution on the Concentrations of These Elements in Soybean Leaves

Correlation coefficients for added Al and Mn levels with various aspects of growth and nutrient concentrations in the plant are presented in Table 17. Several repetitions of the plant analysis for Al failed to obtain consistent values for replications or treatment means (Table 18). Added Al in solution did not correlate well with the concentration of Al in the plant, and there was no significant difference between treatment means. There appears to be no pattern to the Al concentrations in the plants of this study. Even where no Al was added very high concentrations of Al in the plant were found. As mentioned earlier, perlite probably released Al to the solution when no Al was

Table 16. Soil Aluminum and Manganese Content Before Planting and After Harvest (meq/100 g)

Variety	pH (H_2O) Before	Exchangeable Al[b] Before	Exchangeable Al[b] After	Exchangeable Mn[b] Before	Exchangeable Mn[b] After
		Leadvale			
Forrest	4.72[a]	0.977	0.923	0.125	0.201
Lee 68	4.71[a]	1.090	0.867	0.128	0.198
Forrest	5.20	0.189	0.385	0.104	0.169
Lee 68	5.20	0.188	0.440	0.097	0.165
Forrest	5.66	0.036	0.228	0.063	0.097
Lee 68	5.76	0.025	0.220	0.062	0.084
		Jefferson			
Forrest	4.50	0.128	0.295	0.395	0.563
Lee 68	4.52	0.150	0.211	0.397	0.694
Forrest	5.51[a]	0.014	0.040	0.157	0.218
Lee 68	5.51[a]	0.016	0.038	0.154	0.161
Forrest	6.13	0.000[c]	0.011	0.183	0.177
Lee 68	6.11	0.000	0.012	0.177	0.171
		Huntington-Bewleyville			
Forrest	4.67	0.040	0.041	0.465	0.317
Lee 68	4.68	0.046	0.041	0.535	0.364
Forrest	5.36	0.007	0.009	0.312	0.296
Lee 68	5.37	0.005	0.011	0.292	0.320
Forrest	6.73[a]	0.000	0.002	0.040	0.150
Lee 68	6.71[a]	0.000	0.001	0.045	0.144

[a]Original pH.

[b]All values are an average of three replications.

[c]A value of 0.000 indicates none measurable.

Table 17. Correlation of Added Levels of Aluminum and Manganese in Nutrient Solution Study One With the Growth and Nutrient Concentrations of Soybeans (r Values)

Variables	Al in Plants	Mn in Plants	K	Ca	Mg	P	Plant Height	Plant Weight	Root Weight
Al Added	-0.080	+0.046	+0.599*	+0.067	-0.389*	-0.694*	+0.055	-0.058	-0.018
Mn Added	-0.116	+0.649*	+0.341*	+0.128	+0.408*	+0.405*	-0.181	-0.568*	-0.587*
Al in Plants	---	+0.144	-0.175	-0.296*	-0.175	+0.092	-0.021	-0.105	-0.032
Mn in Plants	---	---	+0.363*	+0.221	+0.517*	+0.226	-0.049	-0.458*	-0.467*

*Significant at the P .05 level.

Table 18. Parts Per Million Aluminum in Leaves of Soybeans Grown in Nutrient Solution Study One With Different Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm) 0.5	2.5	5.0
Forrest	0.0	113 a*	555 a	665 a
Lee 68		642 a	228 a	235 a
Forrest	4.0	694 a	314 a	111 a
Lee 68		209 a	208 a	296 a
Forrest	8.0	520 a	190 a	297 a
Lee 68		396 a	238 a	415 a

*Means followed by the same letter are not significantly different at the P .05 level.

added unless high amounts of Al contaminated the solution from other sources. Regardless of the amounts of Al found in the plant, added Al did have an effect on the P concentration in the plant. Absorption of P and other nutrients by the plant will be discussed later.

Treatment means for the Mn concentration in the plant are presented tabularly in Table 19 and graphically in Figure 10. Increasing Mn in nutrient solution increased the Mn concentration in the plant across all levels of Al. Increasing levels of Al in nutrient solution tended to increase the concentration of Mn in the plant when the nutrient solution also contained either 0.5 or 2.5 ppm Mn; however, these increases were not significant. There was no significant difference in Mn concentration in the plant between varieties at any level of either Al or Mn.

Table 19. Parts Per Million Manganese in Leaves of Soybeans Grown in Nutrient Solution Study One With Different Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm)		
		0.5	2.5	5.0
Forrest	0.0	75 d*	243 bcd	573 abc
Lee 68		72 d	212 d	603 ab
Forrest	4.0	132 d	248 bcd	323 bcd
Lee 68		123 d	260 bcd	315 bcd
Forrest	8.0	148 d	257 bcd	343 bcd
Lee 68		182 d	300 bcd	700 a

*Means followed by the same letter are not significantly different at the P .05 level.

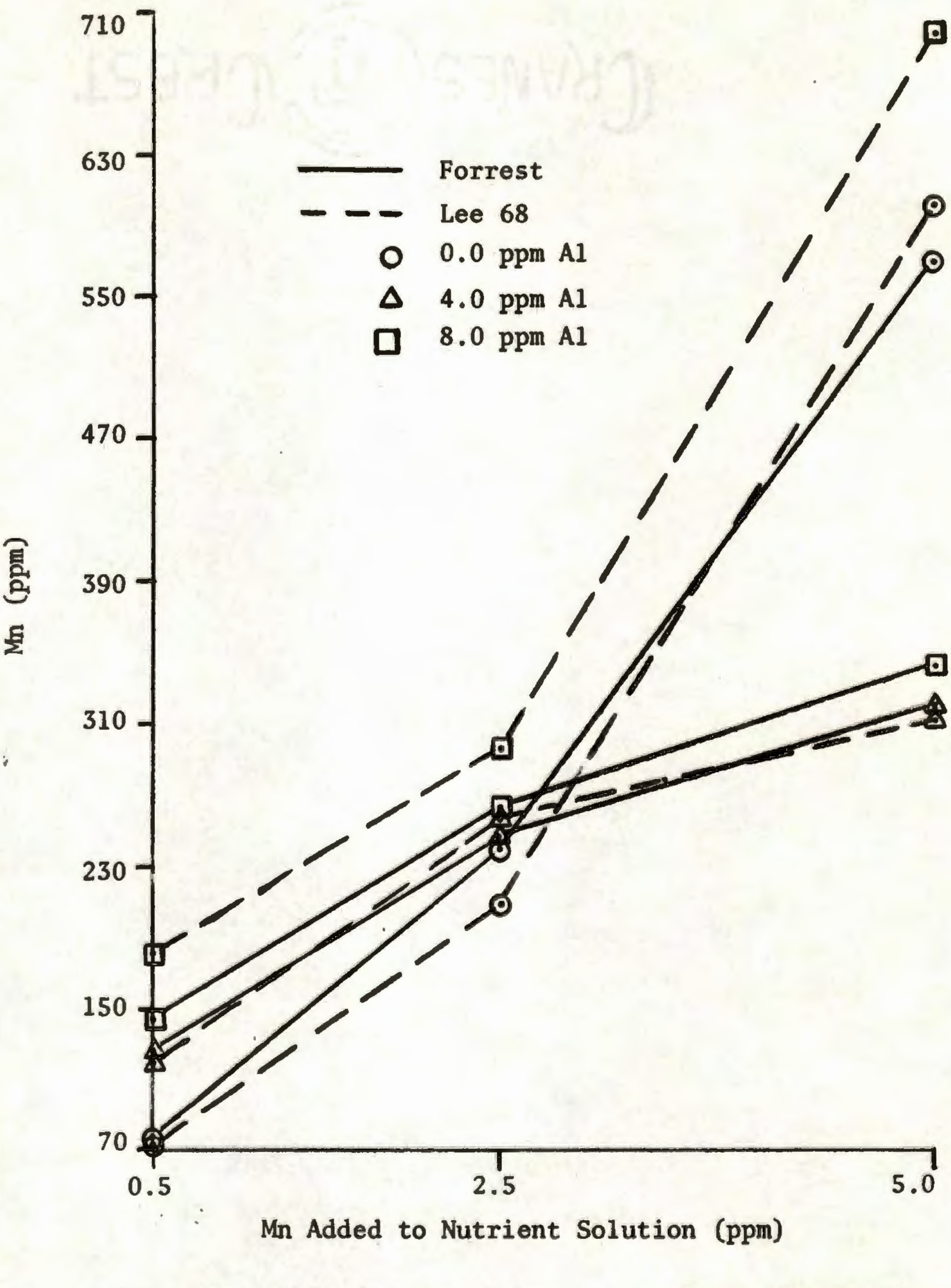

Figure 10. Effect of different levels of aluminum and manganese added to nutrient solution on the manganese concentration in soybean leaves of study one.

Effect of Different Levels of Added Al and Mn in Nutrient Solution and Their Concentrations in the Plant on the Growth of Soybeans

Plant heights are presented in Table 20. Increasing the Al in nutrient solution to 4.0 ppm tended to increase the plant heights of both varieties when grown with 0.5 ppm Mn in solution. Lee 68 also had a slightly greater height at the 4.0 ppm level of Al when the Mn in

Table 20. Plant Height in Centimeters of Soybeans Grown in Nutrient Solution Study One With Different Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm) 0.5	2.5	5.0
Forrest	0.0	54.7 cde*	54.8 cde	56.7 bcde
Lee 68		54.8 cde	54.3 cde	56.0 cde
Forrest	4.0	59.3 abc	56.3 bcde	52.2 ef
Lee 68		57.8 bcd	63.3 a**	56.7 bcde
Forrest	8.0	52.3 def	61.7 ab**	47.5 f
Lee 68		56.5 bcde	61.8 ab**	55.0 cde

*Means followed by the same letter are not significantly different at the P .05 level.

**These means contained measurements from plants grown in larger pots (12 liters).

nutrient solution was 5.0 ppm. However, these increases were not significant. There was no significant difference in plant heights across Mn levels, nor was there any significant difference between varieties.

Plant weights and root weights varied similarly (Tables 21 and 22, respectively). Figure 11 shows that at each Mn level both varieties increased in plant weight at the 4.0 ppm Al level over the other two Al levels. As shown in Figure 12, Lee 68 variety roots also showed an increase in weight at the 4.0 ppm level of Al in solution in two instances. Other root weights did not change appreciably with Al levels. Foy et al. (14) found a similar increase in root weight with Chief variety of soybeans at an Al level of 4.0 ppm in nutrient solution.

Plant weights of Lee 68 variety were greater than Forrest at every combination of Al and Mn except at the lowest levels of each. A Mn concentration in nutrient solution of 5.0 ppm caused a significant decrease in plant weights and root weights of both varieties from that of plants grown at the 0.5 and 2.5 ppm levels. There was no significant difference in plant or root weights between varieties at the two lower levels of Mn, but at the 5.0 ppm Mn level Lee 68 plant and root weights were significantly greater than Forrest variety. Forrest variety was obviously more susceptible to toxic levels of Mn in nutrient solution.

Manganese toxicity symptoms were evident only at the 2.5 and 5.0 ppm levels of Mn in nutrient solution. The first noticeable symptoms were necrotic areas appearing on the underside of the lowest single leaflet. Later, these necrotic areas appeared in the upper trifoliate leaves and on the top side of the lower leaves. The uppermost, younger leaves showed interveinal chlorosis progressing inward from leaflet tips and margins, and these leaflets curled down and in toward the middle. All these symptoms in the plant became more prevalent with increasing time

Table 21. Plant Weight in Grams of Soybeans Grown in Nutrient Solution Study One With Different Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm)		
		0.5	2.5	5.0
Forrest	0.0	15.60 abc*	13.31 c	8.14 d
Lee 68		14.25 bc	15.97 abc	13.42 c
Forrest	4.0	17.30 ab	14.10 bc	8.36 d
Lee 68		18.08 a	17.29 ab	15.74 abc
Forrest	8.0	13.99 bc	12.72 c	7.01 d
Lee 68		14.73 abc	16.12 abc	13.26 c

*Means followed by the same letter are not significantly different at the P .05 level.

Table 22. Root Weight in Grams of Soybeans Grown in Nutrient Solution Study One With Different Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm)		
		0.5	2.5	5.0
Forrest	0.0	3.79 abc*	3.04 bcd	1.35 e
Lee 68		3.24 abcd	3.86 abc	2.95 cd
Forrest	4.0	3.49 abc	3.02 cd	1.34 e
Lee 68		4.06 a	3.64 abc	3.69 abc
Forrest	8.0	3.74 abc	2.52 d	1.19 e
Lee 68		3.53 abc	4.01 ab	2.99 cd

*Means followed by the same letter are not significantly different at the P .05 level.

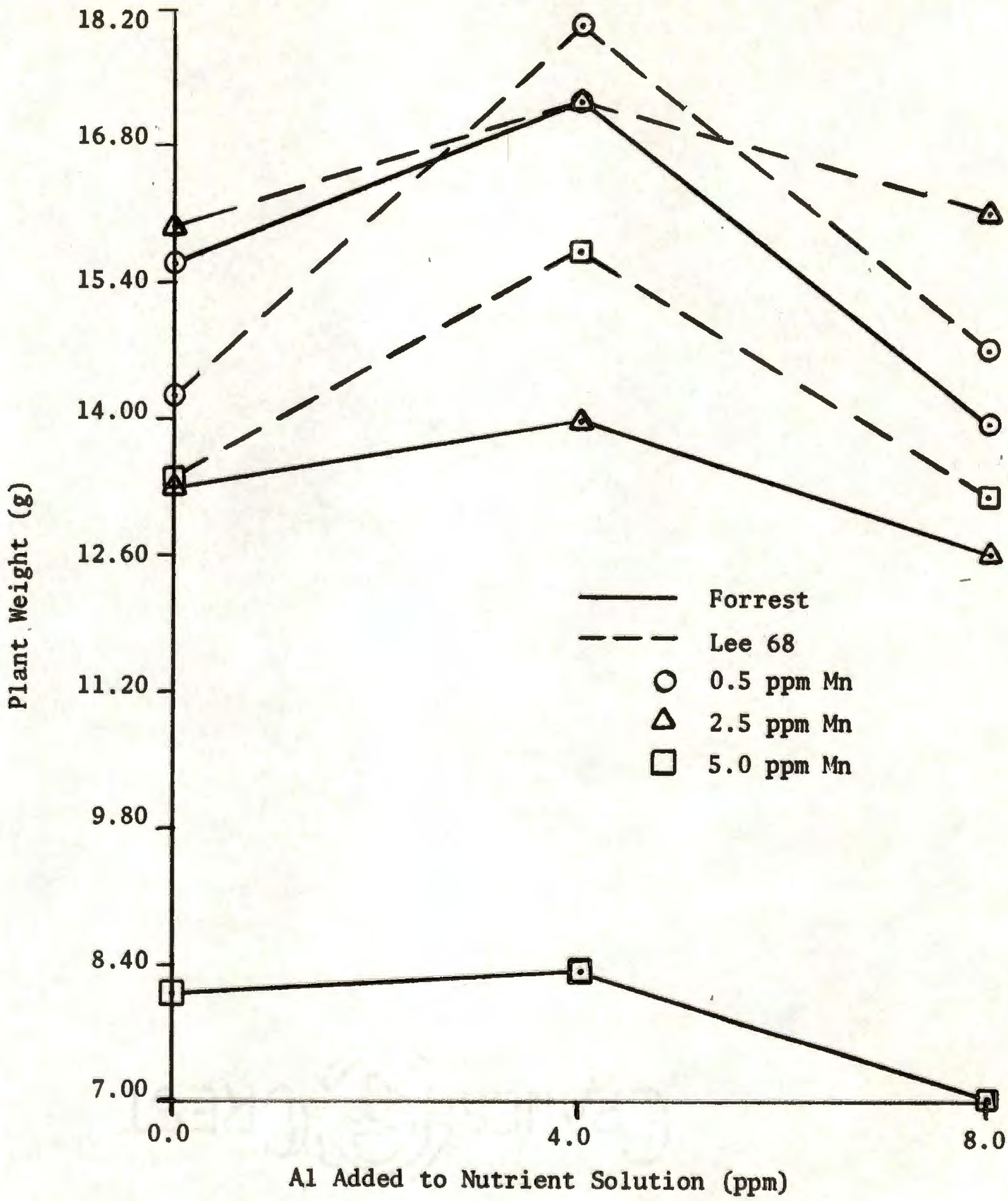

Figure 11. Effect of different levels of aluminum and manganese added to nutrient solution on soybean plant weights of study one.

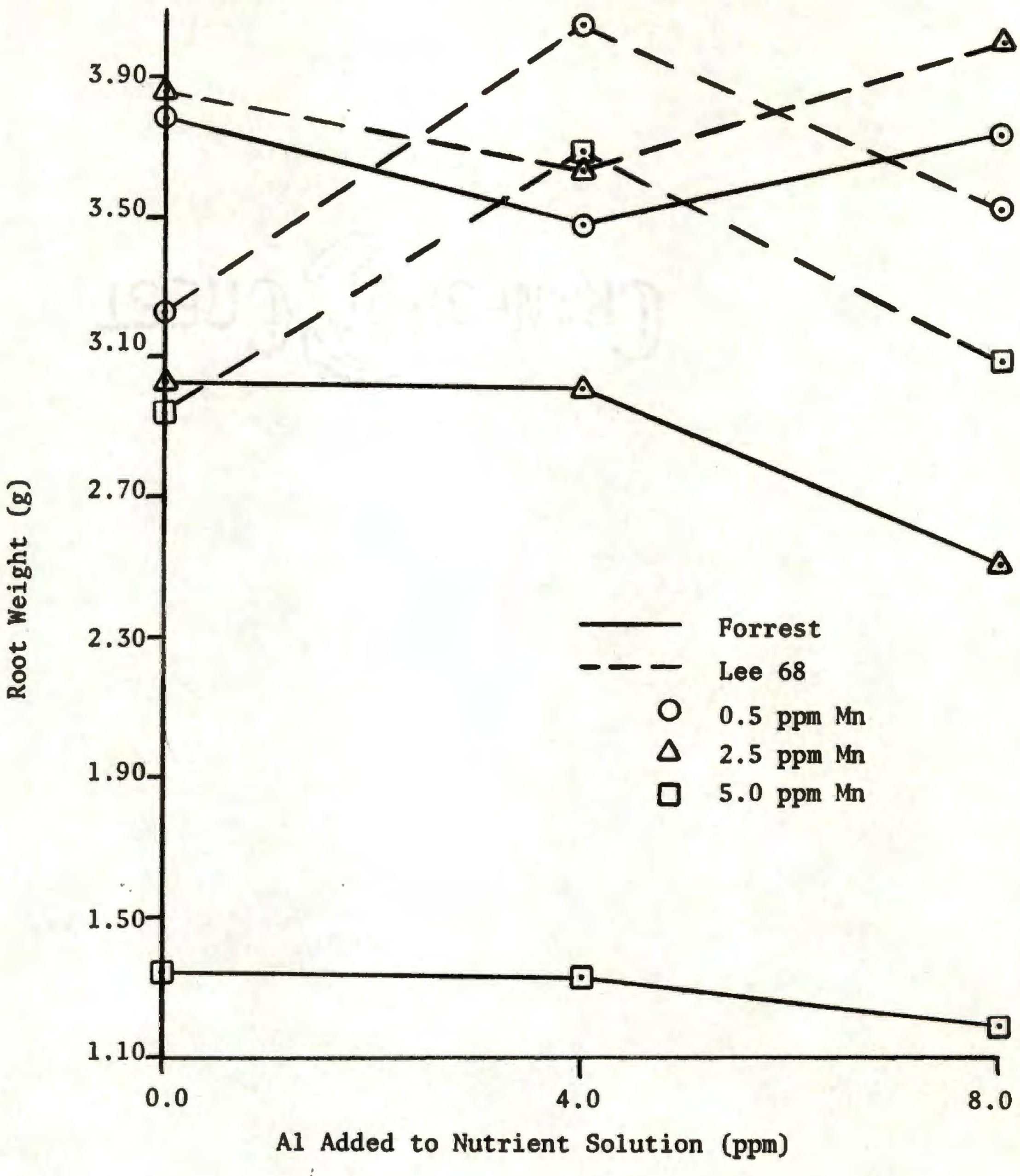

Figure 12. Effect of different levels of aluminum and manganese added to nutrient solution on soybean root weights of study one.

in the solutions. The symptoms were much more intense at the 5.0 ppm level of Mn, and Forrest variety was affected more than Lee 68 at each level. There were no visual symptoms of Al toxicity, nor did increasing Al levels in nutrient solution have any apparent effect on the expression of Mn toxicity symptoms. The average Mn concentrations in both varieties at 0.5, 2.5 and 5.0 ppm levels of Mn in nutrient solution were 122, 253 and 456 ppm, respectively.

<u>Effect of Different Levels of Added Al and Mn in Nutrient Solution and Their Concentrations in Soybean Leaves on the Concentrations of Other Nutrients in Soybeans</u>

Percent K in the plants was quite low in this study (Table 23). There was no significant difference between varieties as to K concentration in the plant. The percent K in the plants grown at the 5.0 ppm Mn

Table 23. Percent Potassium in Leaves of Soybeans Grown in Nutrient Solution Study One With Different Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm) 0.5	2.5	5.0
Forrest	0.0	0.20 ef*	0.30 def	0.51 cde
Lee 68		0.04 f	0.29 def	0.53 cde
Forrest	4.0	0.51 cde	0.48 cde	1.10 ab
Lee 68		0.78 bc	0.68 bcd	0.85 bc
Forrest	8.0	0.82 bc	1.06 ab	1.39 a
Lee 68		0.91 bc	0.70 bcd	1.40 a

*Means followed by the same letter are not significantly different at the P .05 level.

level was significantly higher than that in the plants grown at the 0.5 ppm Mn level in most instances. Neither added Al and Mn in nutrient solution nor the concentration of these elements in the plant correlated well with the K concentration in the plant. However, Figure 13 shows that increasing Al in nutrient solution increased the K concentration in the plant across all Mn levels. The percent K of the plants at the 8.0 ppm Al level was significantly greater than at the 0.0 Al level across all Mn levels.

Calcium concentrations in the plant were quite variable (Table 24). There was no apparent effect of Al and Mn levels in nutrient solution on the percent Ca in the plant. The Al and Mn concentrations in the plant did not correlate well with the Ca concentration in the plant.

Table 25 shows the variation in Mg concentration in the plant. Correlation coefficients for percent Mg with added Al and Mn levels in nutrient solution and the concentrations of these elements in the plant were low. There were no significant differences in percent Mg between varieties. There was a slight tendency for increasing Mn in nutrient solution to increase the Mg concentration in the plant, but this was not significant. The change in Mg concentration in the plant was variable across Al levels.

Phosphorus concentration in the plant varied inversely with the amounts of Al in nutrient solution (Table 26). The data are presented graphically in Figure 14. Percent P in both varieties was significantly lowered by addition of 4.0 ppm Al in nutrient solution, regardless of the Mn level. Furthermore, increasing Al in solution from 4.0 to

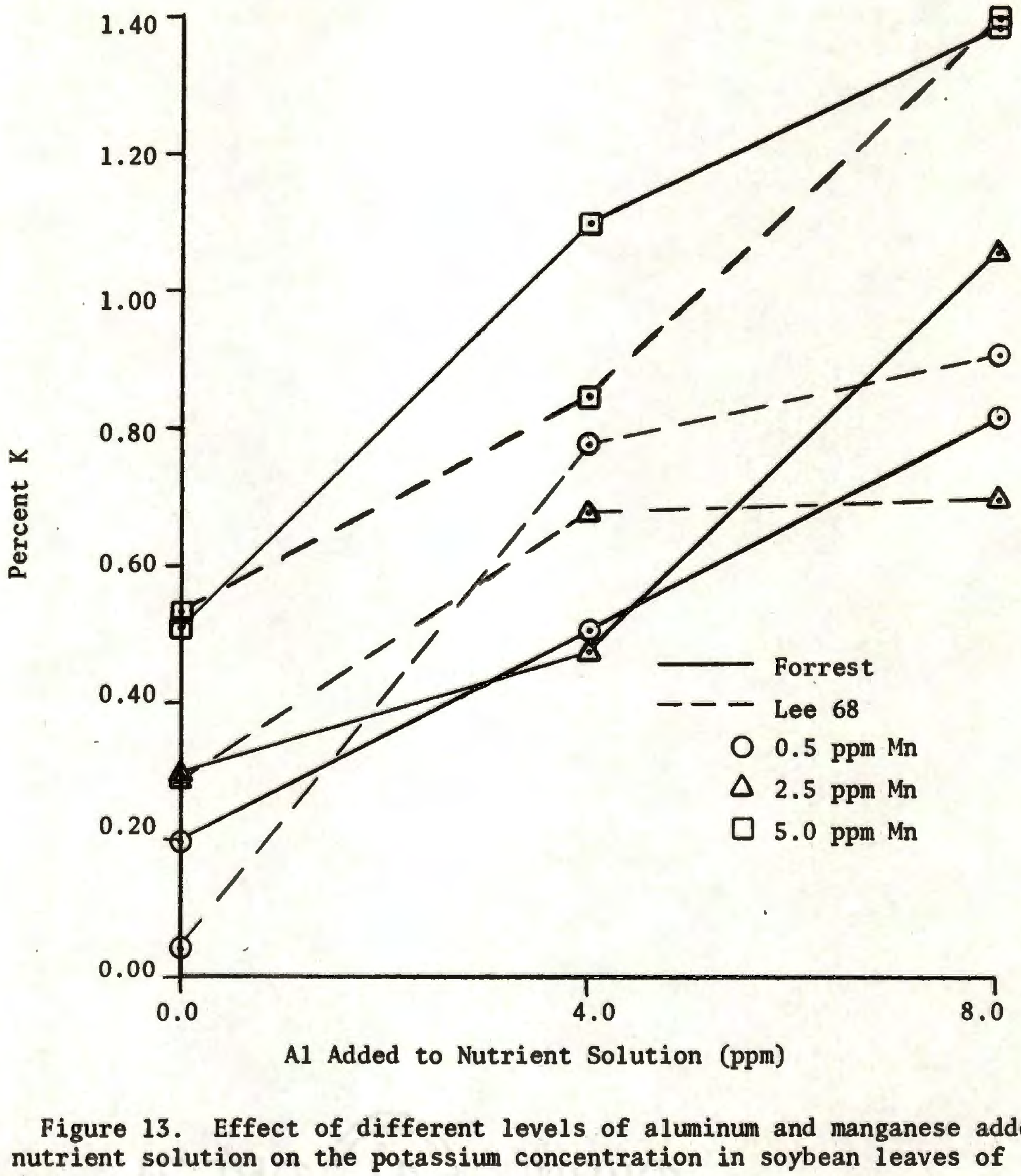

Figure 13. Effect of different levels of aluminum and manganese added to nutrient solution on the potassium concentration in soybean leaves of study one.

Table 24. Percent Calcium in Leaves of Soybeans Grown in Nutrient Solution Study One With Different Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm) 0.5	2.5	5.0
Forrest	0.0	1.48 ab*	1.50 ab	1.21 e
Lee 68		1.37 abcde	1.46 abc	1.46 abc
Forrest	4.0	1.26 cde	1.36 abcde	1.27 cde
Lee 68		1.24 de	1.40 abcde	1.31 bcde
Forrest	8.0	1.22 e	1.45 abc	1.51 ab
Lee 68		1.43 abcd	1.52 a	1.49 ab

*Means followed by the same letter are not significantly different at the P .05 level.

Table 25. Percent Magnesium in Leaves of Soybeans Grown in Nutrient Solution Study One With Different Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm) 0.5	2.5	5.0
Forrest	0.0	0.60 bcdef*	0.71 abcd	0.85 a
Lee 68		0.74 ab	0.64 bcdef	0.85 a
Forrest	4.0	0.51 f	0.72 abc	0.66 bcde
Lee 68		0.54 ef	0.59 cdef	0.62 bcdef
Forrest	8.0	0.58 def	0.63 bcdef	0.65 bcde
Lee 68		0.61 bcdef	0.62 bcdef	0.64 bcdef

*Means followed by the same letter are not significantly different at the P .05 level.

Table 26. Percent Phosphorus in Leaves of Soybeans Grown in Nutrient Solution Study One With Different Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm) 0.5	2.5	5.0
Forrest	0.0	0.28 cd*	0.31 bc	0.40 a
Lee 68		0.29 cd	0.26 de	0.28 cd
Forrest	4.0	0.18 ghi	0.22 ef	0.34 b
Lee 68		0.18 ghi	0.20 fg	0.21 fg
Forrest	8.0	0.14 i	0.19 fgh	0.28 cd
Lee 68		0.15 hi	0.16 hi	0.16 hi

*Means followed by the same letter are not significantly different at the P .05 level.

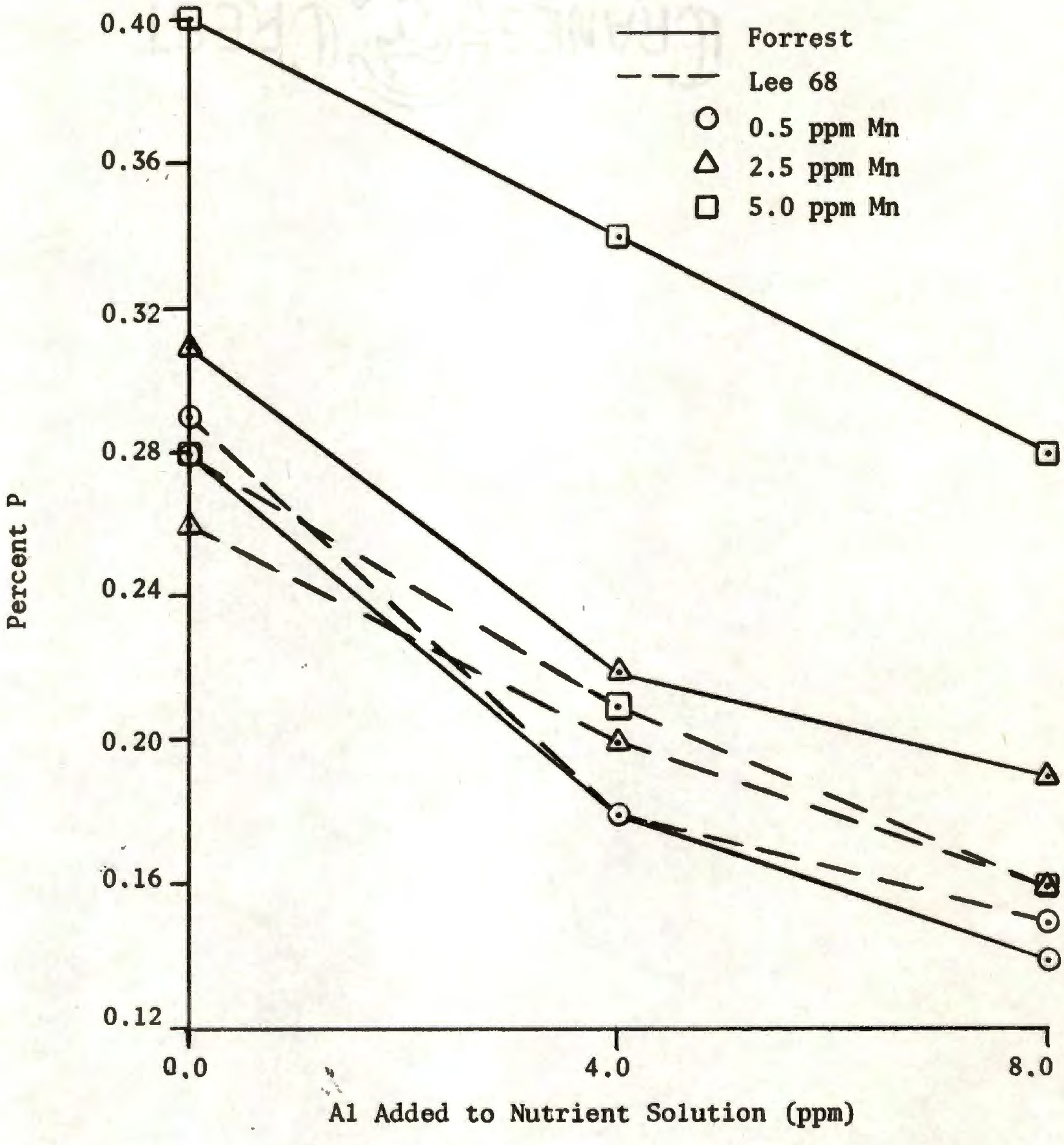

Figure 14. Effect of different levels of aluminum and manganese added to nutrient solution on the phosphorus concentration in soybean leaves of study one.

8.0 ppm resulted in a significant decrease in percent P in the Lee 68 variety when the nutrient solution also contained 2.5 ppm Mn. The percent P in both varieties was decreased somewhat by increasing Al in solution from 4.0 to 8.0 ppm when the solution also contained 5.0 ppm Mn. Increasing Mn in solution to 5.0 ppm significantly increased the P concentration in Forrest variety over those plants grown at 0.5 and 2.5 ppm Mn in solution. Forrest contained significantly more P than Lee 68 across all Al levels in nutrient solution containing 5.0 ppm Mn. The P concentration in Forrest was also greater than Lee 68 across all Al levels of solutions containing 2.5 ppm Mn, but these differences were not significant. Percent P in the plants was approximately the same for both varieties when grown at the 0.5 ppm Mn level.

This same effect of Al on P absorption has been found by other workers using various plant species (3,4,15,28). Whether Al in solution reduced the P in solution, resulting in decreased P concentrations in the plant, or whether Al acted within the plant to reduce P concentrations in the plant, or both, could not be determined from this study.

III. NUTRIENT SOLUTION STUDY TWO

Effect of Different Levels of Added Al and Mn in Nutrient Solution on the Concentrations of These Elements in Soybean Leaves

Correlation coefficients for added Al and Mn levels with various aspects of growth and nutrient concentrations in the plant are presented in Table 27. Differing from the first nutrient solution study, Al concentrations in the plants of this study increased as the Al level

Table 27. Correlation of Added Levels of Aluminum and Manganese in Nutrient Solution Study Two With the Growth and Nutrient Concentrations of Soybeans (r Values)

Variables	Al in Plants	Mn in Plants	K	Ca	Mg	P	Plant Height	Plant Weight	Root Weight
Al Added	+0.740*	-0.113	+0.312*	-0.958*	-0.948*	-0.868*	-0.790*	-0.656*	+0.039
Mn Added	+0.098	+0.703*	+0.210	-0.143	-0.146	+0.196	+0.117	-0.333*	-0.682*
Al in Plants	---	-0.074	+0.160	-0.765*	-0.678*	-0.561*	-0.624*	-0.535*	-0.124
Mn in Plants	---	---	+0.295*	+0.056	+0.064	+0.084	+0.186	-0.189	-0.400*

*Significant at the P .05 level.

in solution increased. The Al concentrations in the plants grown in solutions containing 20 ppm Al were significantly increased over the Al concentrations of those plants grown in solutions containing only 4.0 ppm Al (Table 28, Figure 15). Concentrations of Al in the plant did not differ significantly between varieties, and Al concentrations in the plant were variable across Mn levels. The Al concentrations in the plant, averaged across Mn levels, for 4.0, 12.0 and 20.0 ppm Al in solution were 340, 483, and 747 ppm, respectively.

Table 28. Parts Per Million Aluminum in Leaves of Soybeans Grown in Nutrient Solution Study Two With Varying Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm) 0.5	1.5	3.0
Forrest	4.0	288 fg*	247 g	423 efg
Lee 68		321 fg	429 defg	332 fg
Forrest	12.0	571 bcdef	418 efg	450 defg
Lee 68		441 defg	573 bcdef	447 defg
Forrest	20.0	726 abcd	887 a	695 abcde
Lee 68		538 cdefg	772 abc	862 ab

*Means followed by the same letter are not significantly different at the P .05 level.

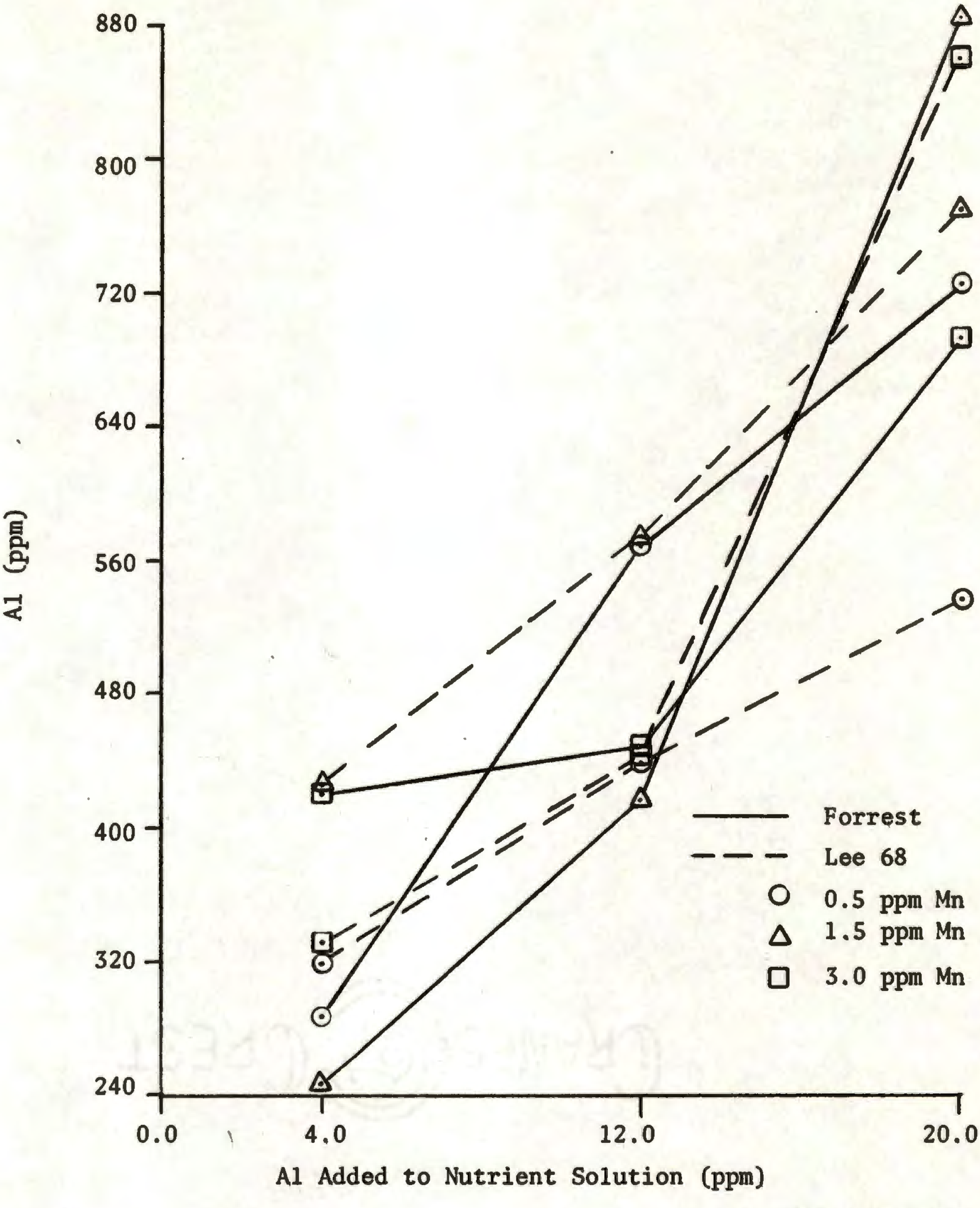

Figure 15. Effect of different levels of aluminum and manganese added to nutrient solution on the aluminum concentration in soybean leaves of study two.

Manganese concentrations in the plant are presented in Table 29. Increasing Mn in nutrient solution increased the Mn concentration in the plant except at the lowest level of Al in solution where increasing the Mn level in solution to 3.0 ppm resulted in a decrease in the Mn concentration in both varieties. The Mn concentration did not differ significantly between varieties.

Table 29. Parts Per Million Manganese in Leaves of Soybeans Grown in Nutrient Solution Study Two With Varying Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm)		
		0.5	1.5	3.0
Forrest	4.0	192 gh*	310 cd	282 de
Lee 68		207 fgh	333 bc	310 cd
Forrest	12.0	242 ef	277 de	448 a
Lee 68		215 fgh	368 b	455 a
Forrest	20.0	200 fgh	238 efg	303 cd
Lee 68		185 h	245 ef	320 cd

*Means followed by the same letter are not significantly different at the P .05 level.

Increasing Al to 20.0 ppm in nutrient solution tended to decrease the Mn concentration in both varieties. Figure 16 shows this more dramatically. This occurrence is interesting in that during the growth of these plants, the necrotic areas (due to Mn toxicity) found on the leaves were less noticeable with higher levels of Al in solution. This

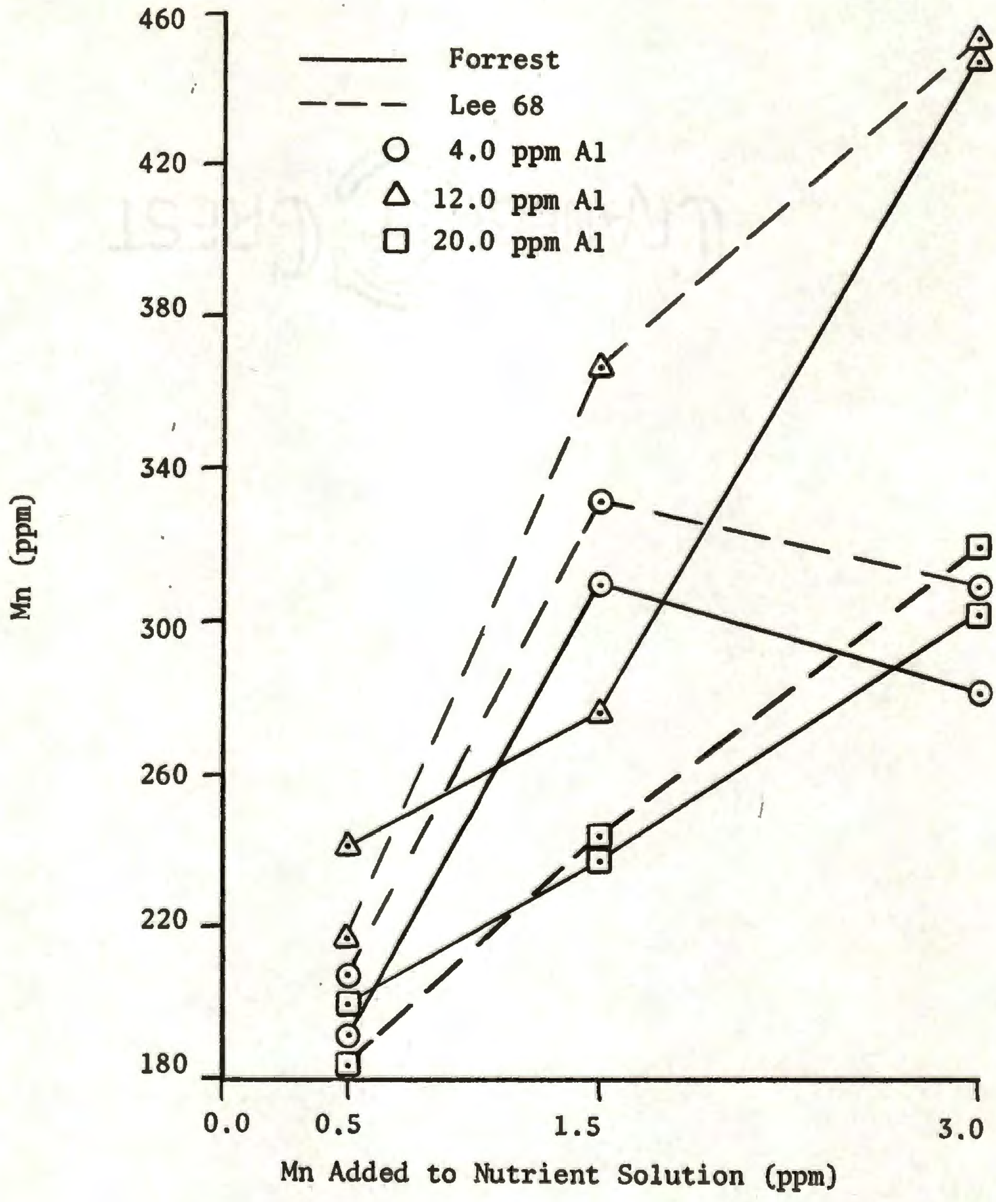

Figure 16. Effect of different levels of aluminum and manganese added to nutrient solution on the manganese concentration in soybean leaves of study two.

suggests that Al may have a detoxifying effect on Mn toxicity in soybeans. Aside from this, the only visual symptom of Al toxicity was the decrease in plant height.

Manganese toxicity symptoms were the same as described in the first nutrient solution study. However, in this study slight symptoms were apparent in plants grown at the 0.5 ppm Mn level, and the symptoms of those plants grown at 1.5 ppm Mn in solution were as severe as those grown at 2.5 ppm in the first nutrient solution study. The plants also contained more Mn at the lower two levels of this study than at the lower two levels of the first study. This may be due to changing environmental conditions in the greenhouse from one study to the next. Near harvesting the leaves of those plants grown at a 3.0 ppm Mn level began to fall. The Mn concentrations in the plant averaged across Al levels at 0.5, 1.5 and 3.0 ppm Mn in solution were 207, 295 and 353 ppm, respectively.

Effect of Different Levels of Added Al and Mn in Nutrient Solution and Their Concentrations in the Plant on the Growth of Soybeans

The Al in nutrient solution and Al in the plant correlated quite well with plant height. Increasing Al in nutrient solution decreased plant height of both varieties except in one instance (Table 30, Figure 17). The effect of Mn on plant heights of both varieties was variable. There was no significant difference between varieties, but probably as a result of a greater susceptibility to Mn toxicity in Forrest variety, Lee 68 plant heights were generally greater at the highest level of Mn.

Table 30. Plant Height in Centimeters of Soybeans Grown in Nutrient Solution Study Two With Varying Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm) 0.5	1.5	3.0
Forrest	4.0	61.8 a*	59.1 ab	52.1 bcde
Lee 68		55.1 abc	54.6 abcd	59.3 ab
Forrest	12.0	47.1 cdef	45.2 efg	46.9 def
Lee 68		47.5 cdef	54.7 abcd	53.9 abcd
Forrest	20.0	43.1 fg	42.5 fg	43.3 fg
Lee 68		38.1 g	42.5 fg	49.6 cdef

*Means followed by the same letter are not significantly different at the P .05 level.

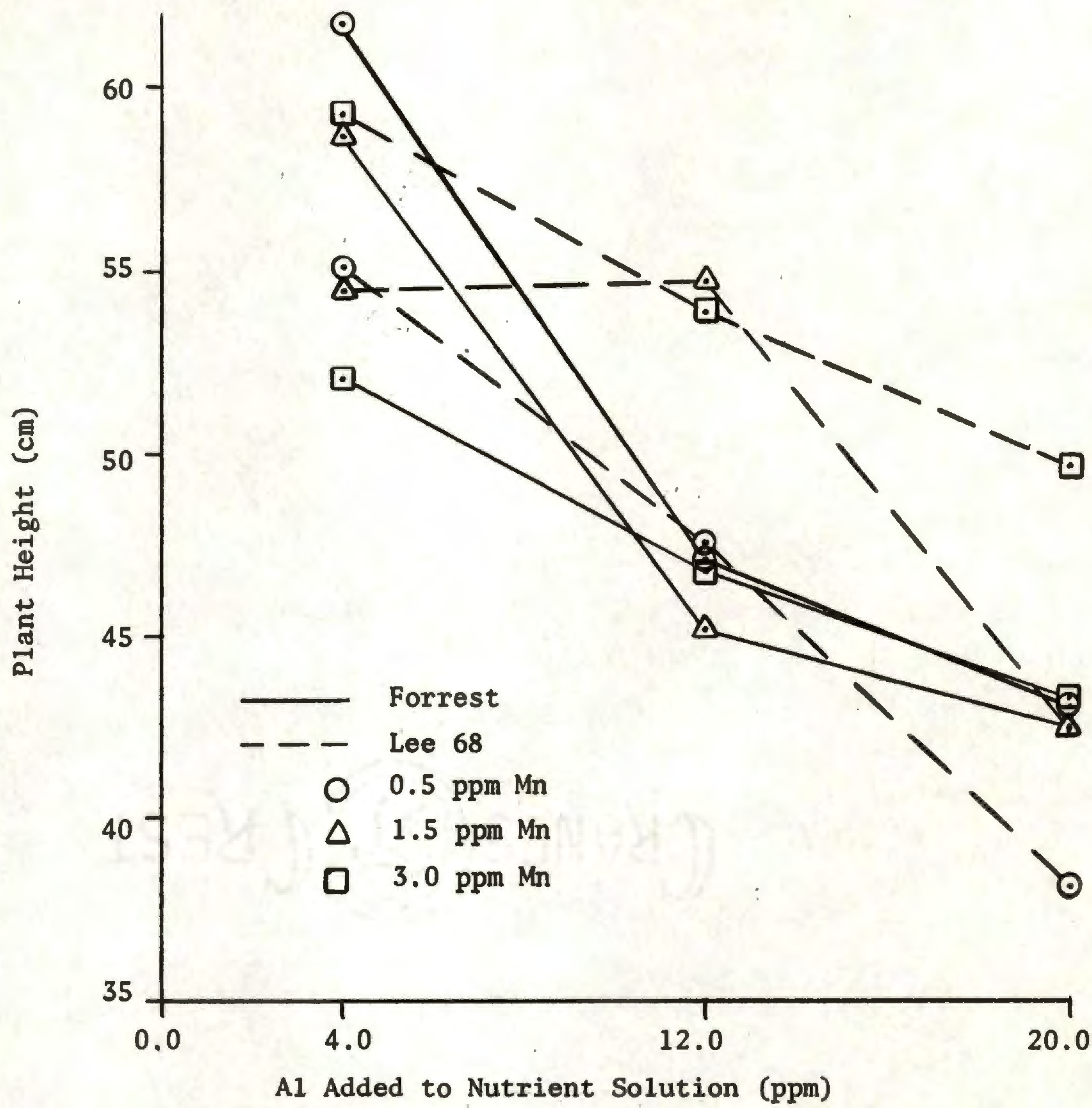

Figure 17. Effect of different levels of aluminum and manganese added to nutrient solution on soybean plant heights of study two.

Plant weights are presented in Table 31. Figure 18 presents the data graphically. Increasing Mn in nutrient solution from 0.5 to 3.0 ppm significantly reduced plant weights of Forrest while Lee 68 was virtually unaffected. Forrest was significantly lower in plant weight than Lee 68

Table 31. Plant Weight in Grams of Soybeans Grown in Nutrient Solution Study Two With Varying Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm) 0.5	1.5	3.0
Forrest	4.0	8.76 a*	5.98 bc	4.24 def
Lee 68		9.04 a	8.49 a	8.16 a
Forrest	12.0	5.92 bc	5.09 cde	3.60 f
Lee 68		6.53 b	6.19 bc	6.02 bc
Forrest	20.0	4.99 cdef	4.17 def	3.70 ef
Lee 68		4.39 def	5.03 cdef	5.17 bcd

*Means followed by the same letter are not significantly different at the P .05 level.

when grown in nutrient solution containing 3.0 ppm Mn. The difference in plant weights between varieties tended to lessen at lower levels of Mn in solution. Increasing Al in nutrient solution steadily decreased plant weights; however, it appeared that this decreasing effect of Al on Forrest variety was curtailed somewhat by increasing amounts of Mn in solution.

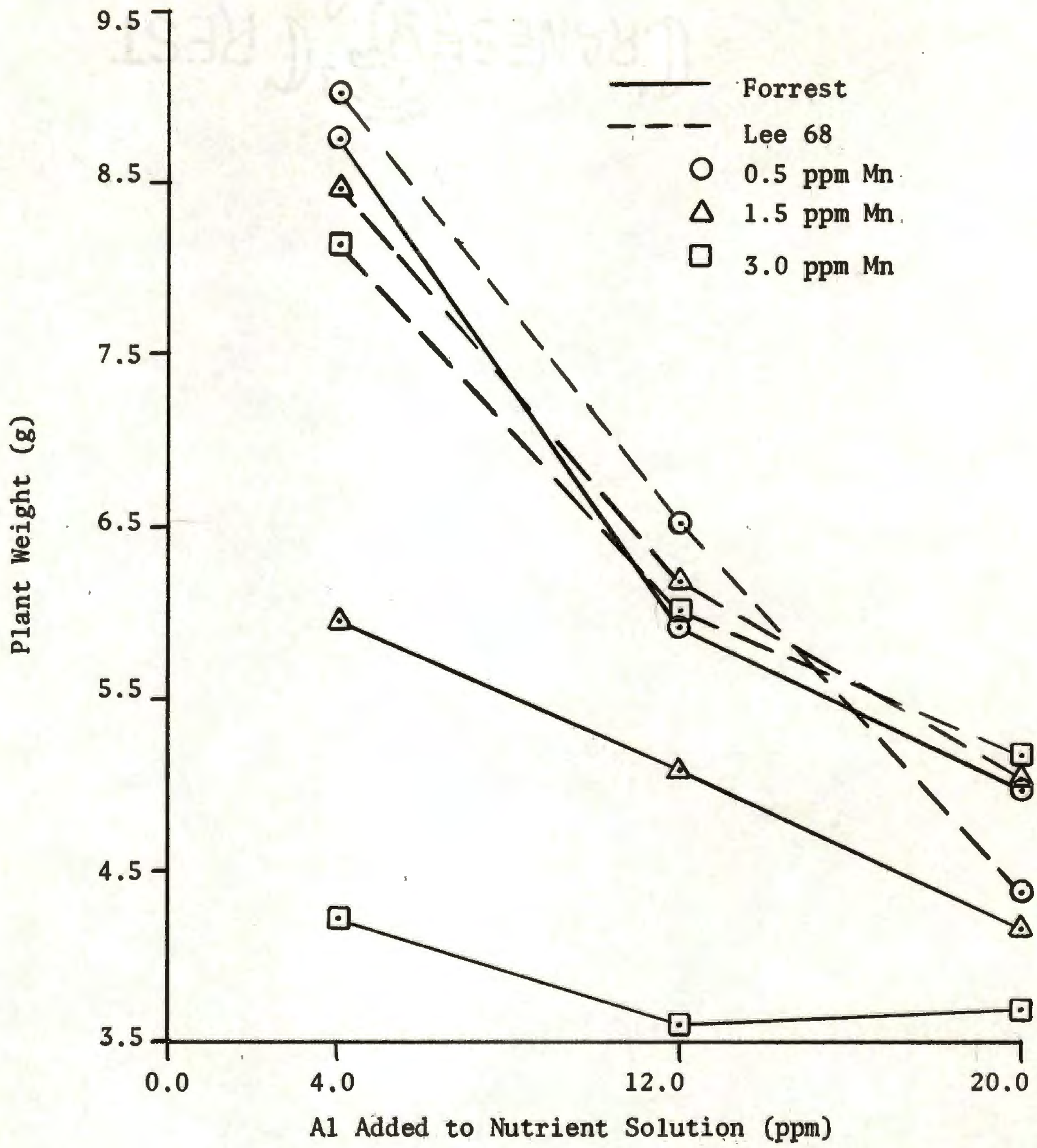

Figure 18. Effect of different levels of aluminum and manganese added to nutrient solution on soybean plant weights of study two.

One would expect root weights to vary along with plant heights and weights; however, this did not occur (Table 32, Figure 19). Root weights were increased by increasing added Al levels from 4.0 to 12.0 ppm. However, when the Al level was increased to 20.0 ppm the root weights were generally less than at the 12.0 level. Contrary to the reports of other workers (26,30,31,46), the primary effects of Al toxicity in this study were decreases in plant heights and weights rather than injury to the roots, as reflected by root weights.

The greatest effect on the roots was from the Mn in nutrient solution. Both the Mn level in solution and the Mn concentration in the plant correlated better with root weights than did Al. Root weights of Forrest grown in nutrient solution containing 1.5 ppm Mn were significantly reduced from those plants grown at the 0.5 ppm Mn level. Lee 68

Table 32. Root Weight in Grams of Soybeans Grown in Nutrient Solution Study Two With Varying Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm)		
		0.5	1.5	3.0
Forrest	4.0	1.50 cdef*	1.02 ijk	0.62 l
Lee 68		1.63 abc	1.46 cdefg	1.22 ghij
Forrest	12.0	1.84 a	1.42 cdefgh	0.81 kl
Lee 68		1.78 ab	1.60 abcd	1.29 efghi
Forrest	20.0	1.55 bcde	1.22 fghij	0.98 jk
Lee 68		1.41 cdefgh	1.34 defgh	1.16 hij

*Means followed by the same letter are not significantly different at the P .05 level.

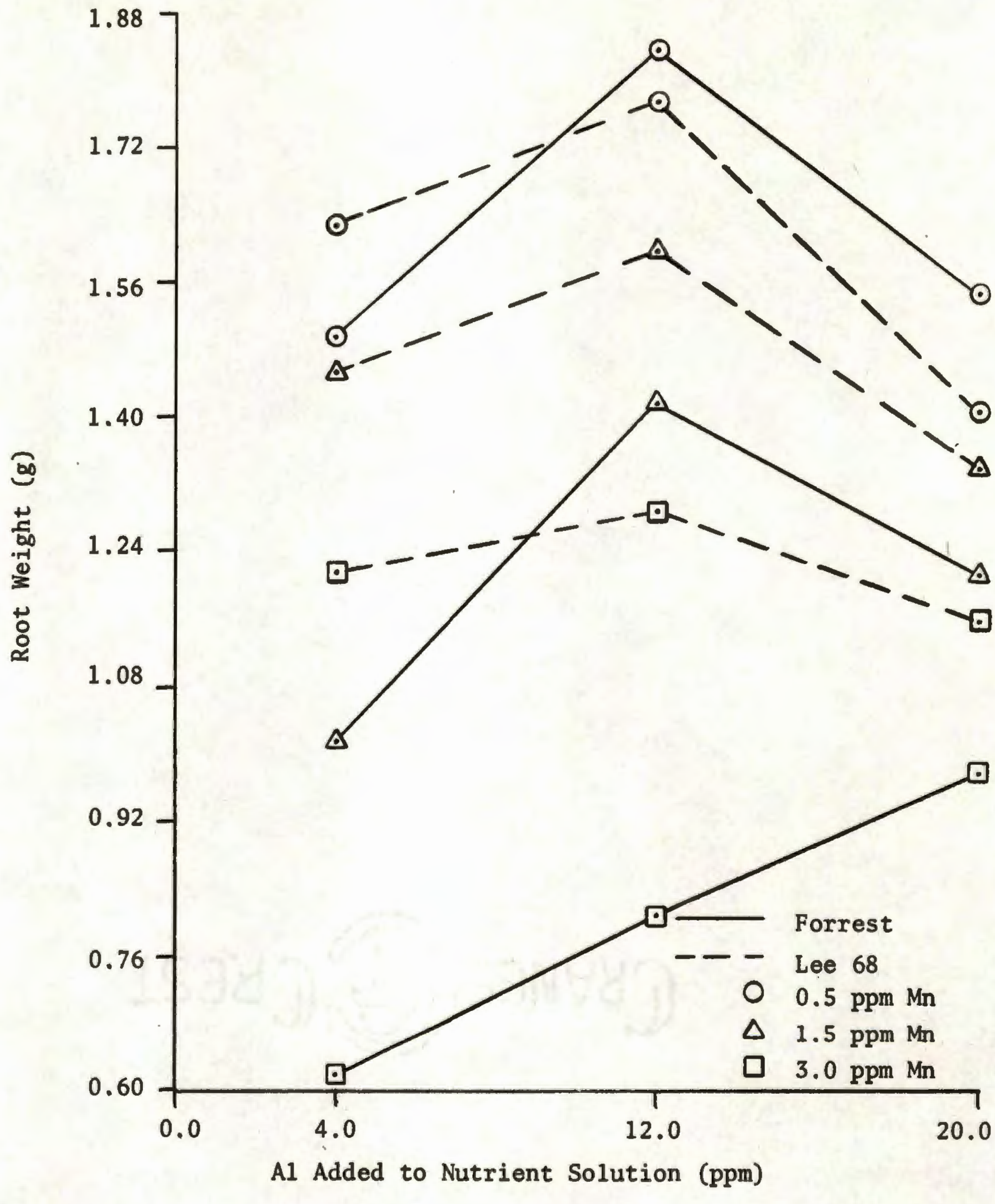

Figure 19. Effect of different levels of aluminum and manganese added to nutrient solution on soybean root weights of study two.

variety root weights were not significantly reduced until the Mn level in solution was increased to 3.0 ppm.

Effect of Different Levels of Added Al and Mn in Nutrient Solution and Their Concentrations in Soybean Leaves on the Concentrations of Other Nutrients in Soybeans

Table 33 shows the K concentration in the plants of this study. Values for percent K in this study are considerably higher than those of the first study. There are no noticeable patterns to the K concentrations in the plants of this study.

Table 33. Percent Potassium in Leaves of Soybeans Grown in Nutrient Solution Study Two With Varying Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm) 0.5	1.5	3.0
Forrest	4.0	2.26 gh*	2.47 defg	2.91 ab
Lee 68		2.31 fgh	2.44 efgh	2.09 h
Forrest	12.0	2.93 ab	3.00 a	2.88 abc
Lee 68		2.53 cdefg	2.68 abcdef	2.86 abc
Forrest	20.0	2.71 abcde	2.78 abcde	2.82 abcd
Lee 68		2.43 efgh	2.63 abcdefg	2.59 bcdefg

*Means followed by the same letter are not significantly different at the P .05 level.

Calcium concentration in the plant correlated very well with both Al in nutrient solution and the Al concentration in the plant. Increasing

Al in nutrient solution decreased the percent Ca in both varieties (Table 34). Manganese in nutrient solution had little effect on the Ca concentration of either variety; however, there was a tendency for increasing Mn in solution to decrease the Ca concentration in the plant.

Table 34. Percent Calcium in Leaves of Soybeans Grown in Nutrient Solution Study Two With Varying Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm) 0.5	1.5	3.0
Forrest	4.0	2.19 ab*	2.32 a	1.75 c
Lee 68		2.27 a	2.15 ab	2.02 b
Forrest	12.0	1.66 cd	1.74 c	1.38 ef
Lee 68		1.50 de	1.52 de	1.29 f
Forrest	20.0	0.60 g	0.56 g	0.48 g
Lee 68		0.63 g	0.60 g	0.55 g

*Means followed by the same letter are not significantly different at the P .05 level.

There were no significant differences between varieties as to the percent Ca in the plant. Figure 20 shows graphically the effect of Al and Mn levels in nutrient solution on the Ca concentration in the plant.

Correlation coefficients for Al in nutrient solution and Al concentration in the plant with percent Mg in the plant were high. Increasing Al to 20.0 ppm in nutrient solution significantly reduced the Mg

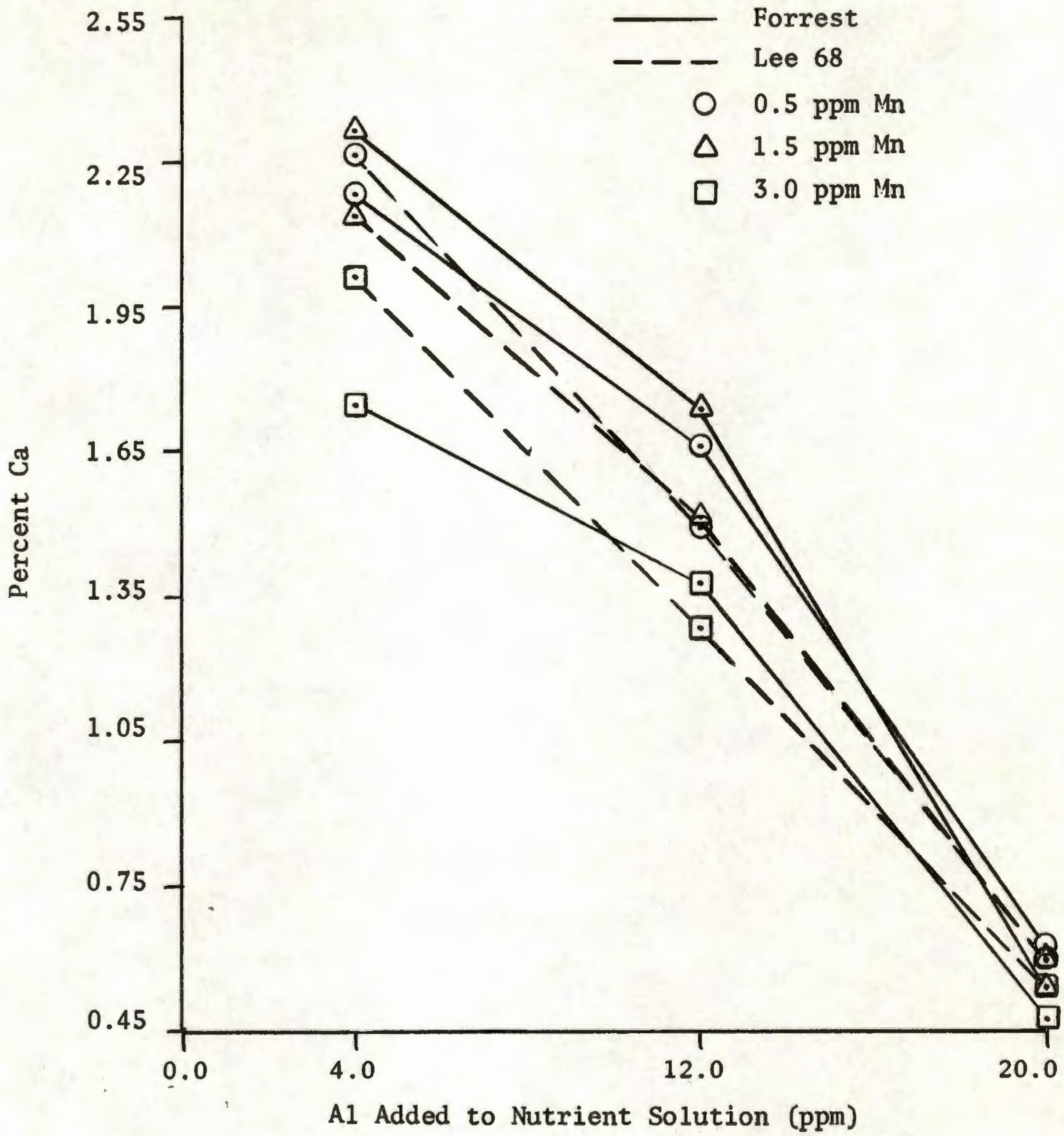

Figure 20. Effect of different levels of aluminum and manganese added to nutrient solution on the calcium concentration in soybean leaves of study two.

concentration in both varieties (Table 35, Figure 21). The Forrest variety tended to have higher concentrations of Mg than did Lee 68 variety. The levels of Mn in nutrient solution had very little effect on the percent Mg in the plant.

Table 35. Percent Magnesium in Leaves of Soybeans Grown in Nutrient Solution Study Two With Varying Aluminum and Manganese Levels.

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm)		
		0.5	1.5	3.0
Forrest	4.0	0.98 a*	1.01 a	0.89 b
Lee 68		0.99 a	0.99 a	0.89 b
Forrest	12.0	0.83 bcd	0.85 bc	0.79 cde
Lee 68		0.75 e	0.78 de	0.73 e
Forrest	20.0	0.62 f	0.62 f	0.57 f
Lee 68		0.59 f	0.57 f	0.55 f

*Means followed by the same letter are not significantly different at the P .05 level.

The effects of different levels of Al and Mn in nutrient solution on the percent P in the plants of this study were the same as in the first nutrient solution study. Phosphorus concentration in the plant correlated well with the Al levels in nutrient solution and the Al concentration in the plant. Increasing Al in nutrient solution steadily decreased the

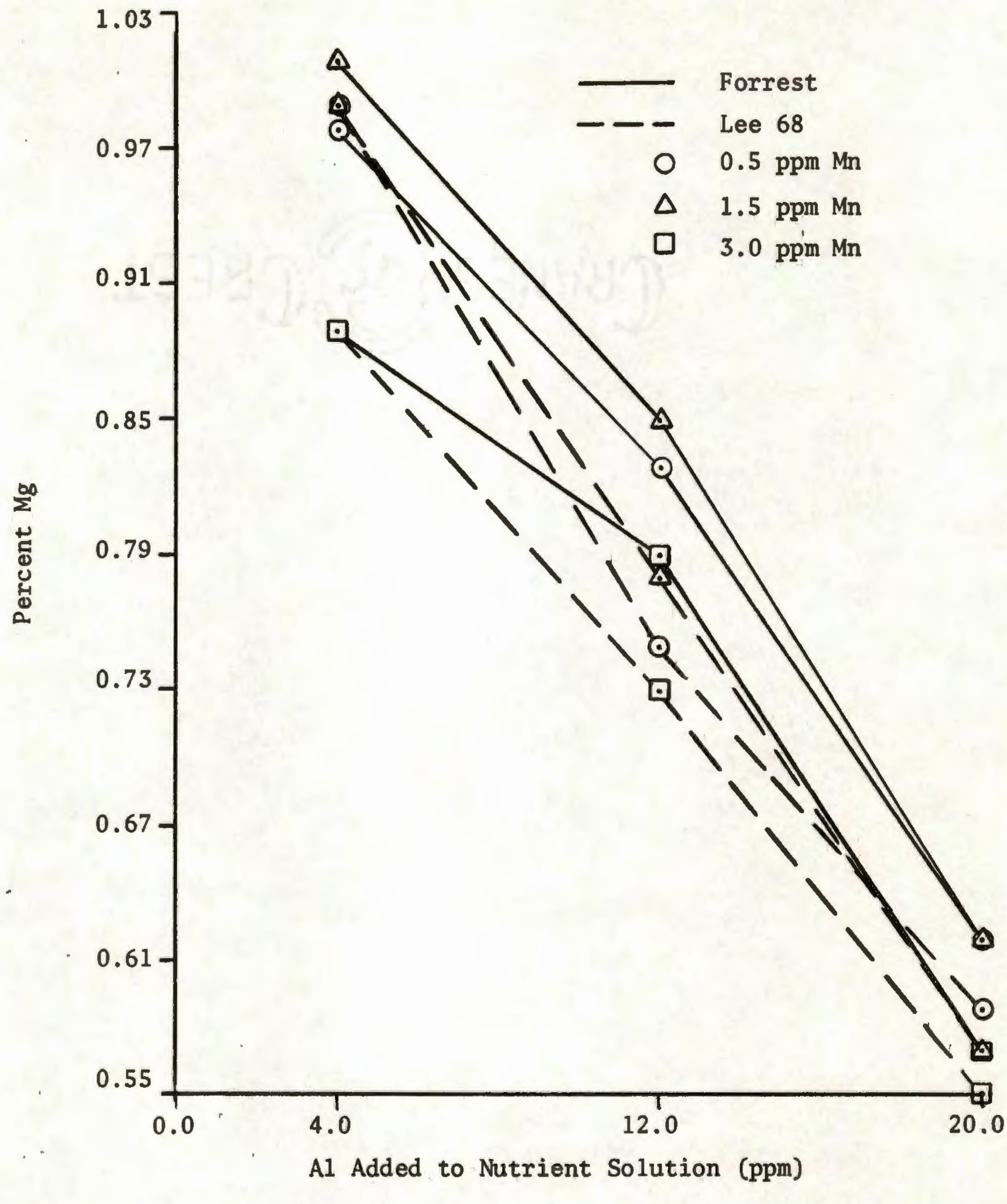

Figure 21. Effect of different levels of aluminum and manganese added to nutrient solution on the magnesium concentration in soybean leaves of study two.

percent P in both varieties (Table 36, Figure 22). Increasing Mn in nutrient solution tended to increase the P concentration in Forrest while Lee 68 was not affected. Although there were no significant differences in percent P between varieties at lower Mn levels, the increase in percent P in Forrest variety at higher levels of Mn resulted in significant differences between varieties at these levels.

Table 36. Percent Phosphorus in Leaves of Soybeans Grown in Nutrient Solution Study Two With Varying Aluminum and Manganese Levels

Variety	Al in Nutrient Solution (ppm)	Mn in Nutrient Solution (ppm)		
		0.5	1.5	3.0
Forrest	4.0	0.38 c*	0.44 b	0.55 a
Lee 68		0.36 c	0.38 c	0.38 c
Forrest	12.0	0.19 e	0.21 e	0.28 d
Lee 68		0.18 e	0.19 e	0.19 e
Forrest	20.0	0.14 f	0.18 e	0.20 e
Lee 68		0.13 f	0.14 f	0.15 f

*Means followed by the same letter are not significantly different at the P .05 level.

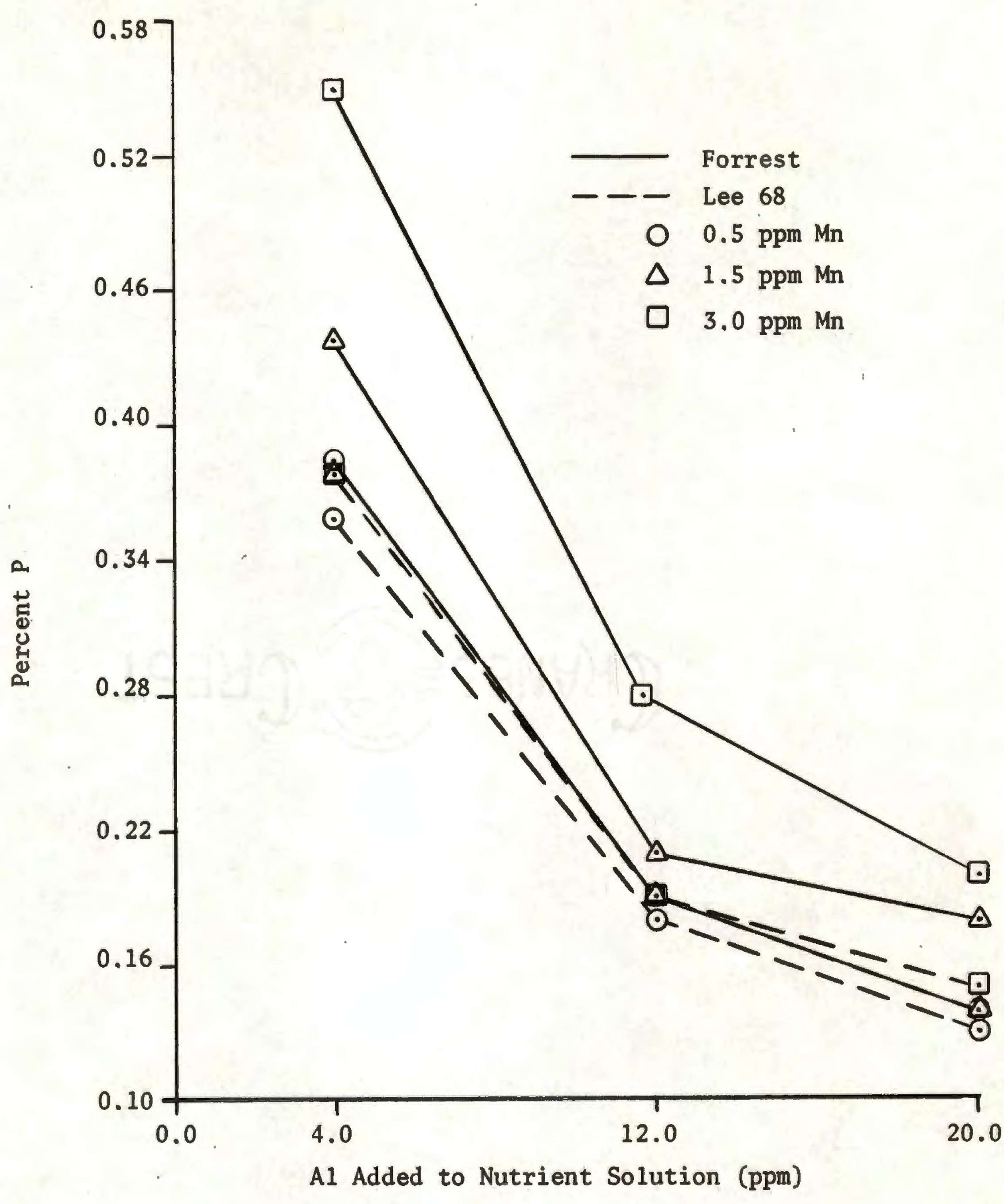

Figure 22. Effect of different levels of aluminum and manganese added to nutrient solution on the phosphorus concentration in soybean leaves of study two.

CHAPTER IV

SUMMARY AND CONCLUSIONS

Soils at lower pH values in this study contained considerably more exchangeable Al and Mn. The amounts of exchangeable Al and Mn generally increased across soils in the manner of Leadvale < Jefferson < Huntington-Bewleyville. The concentration of Mn in the plant gave the highest correlation coefficients with the water soluble and exchangeable fractions of soil Mn. The exchangeable Al in the soil did not correlate well with the Al concentration in the plant.

At higher soil pH values soybean growth and seed yield were much greater on the Jefferson and Huntington-Bewleyville soils than on the Leadvale soil. This was apparently due to the higher total nutrient supply of these soils at these pH values. However, at low pH values the higher levels of available Mn in the Jefferson and Huntington-Bewleyville soils resulted in smaller yields than in the Leadvale soil for both varieties. At these low pH values the lower yields indicated that the Forrest variety was more susceptible to Mn toxicity.

The effect of Al on soybeans in the Jefferson and Huntington-Bewleyville soils was apparently masked by the increased solubility of soil P as a result of adding acid to lower the pH. The percent P in the plants grown on these two soils increased as the pH decreased. Nutrient solution study two showed that percent P in Forrest variety increased with increasing Mn levels in nutrient solution and increasing

Mn concentration in the plant. Since both the exchangeable Mn and the Mn concentration in the plant increased with decreasing pH in these soils, part of the increase in P concentration in Forrest variety grown on these soils may have been a result of these high Mn levels. The Leadvale soil showed no differences in P concentration with changes in pH. However, the percent P in the plants grown on Leadvale soil were considerably lower than those plants grown on the other soils.

The highest pH at which Mn toxicity symptoms were still evident was 4.7 in the Leadvale soil. This soil at this pH contained 0.127 meq/100 g of exchangeable Mn and resulted in an average Mn leaf concentration in both varieties of 353 ppm. Since the significant negative correlation value reported in Table 3, page 27, for yield and Mn concentration of leaves indicates that as yield increased the Mn concentration decreased, part of the higher Mn concentration at this low pH may be due to the so-called dilution effect. Considering all the soils of this study, the optimum pH (H_2O) range for the growth of soybeans appears to be between approximately 5.2 and 6.1. However, the exact optimum pH varied among the soils.

The percent K in the plant was variable across soils and across the pH values of each soil. The Ca concentration of the plant tended to vary with the levels of exchangeable Ca in the soil rather than the pH. Forrest generally absorbed more Ca than Lee 68 on each soil. Percent Mg in the plant was greatest in the Jefferson and Huntington-Bewleyville soils, corresponding to the higher exchangeable Mg present in these soils. However, the Mg concentration in the plant tended to decrease with decreasing pH in each soil regardless of the amount in the soil. The soil pH had very little effect on either Mo or B in the plant; however, B concentration in the plant did tend to decrease as the pH increased in each soil. Furthermore, B concentrations in the plant were generally higher in the Jefferson and Huntington-Bewleyville soils than in the Leadvale soil.

Perlite, which was used as a growth medium in the nutrient solution studies, affected the Al levels in these studies. Perlite is not a good growth medium for the study of this element due to the ability of perlite to sorb and/or release Al in solution. The increase in growth as measured by plant weight at a level of 4.0 ppm Al in the first nutrient solution study may not be indicative of the actual situation. The concentration of Al actually present in solution at this level may be considerably different from the concentration added due to the effects of perlite. However, in the second nutrient solution study the decrease in growth as measured by both plant height and weight with increasing levels of Al indicates that the actual level in the solution did at least increase in the manner desired.

Since the top weights decreased as Al levels increased, the increase in root weights with addition of 12.0 ppm Al suggests that Al may have a stimulative effect on the roots of soybeans which increases their dry weights. The decrease in top weights, regardless of root weights, was the most important measure of Al toxicity in this study.

The effect of Al toxicity on soybeans may be due to indirect effects on other nutrients in the plant. The P concentration in the plant was lowered by increasing Al levels in both nutrient solution studies. This may have been a result of precipitation of P by Al in the nutrient solution or as a result of toxic effects of Al within the plant. Furthermore, percent Ca and Mg in the plant was lowered by increasing Al levels in nutrient solution. The first nutrient solution study indicates that K concentrations in the plant may be increased by low levels of Al in nutrient solution. The decrease in plant heights and weights due to Al toxicity were relatively the same for both varieties.

The nutrient solution studies substantiate the findings in the soil study that Forrest variety of soybeans is more susceptible to Mn toxicity than Lee 68 variety. Both plant weights and root weights of Forrest were reduced significantly more than Lee 68 by increasing Mn in nutrient solution. Furthermore, Forrest concentrated more Mn in the plant than did Lee 68. Although the effects were confounded by environmental changes in the greenhouse from one nutrient solution study to the next, the highest total growth of soybeans in these nutrient solution studies was associated with Mn levels of 0.5 and 1.5 ppm in nutrient solution, and these levels correspond to Mn concentrations in the plant of 122 and 295 ppm, respectively.

Increasing Mn in nutrient solution to toxic levels tended to decrease the Ca concentration in both varieties while percent K and Mg in the plant were not affected. The varieties differed with respect to the effect of Mn in nutrient solution on the P concentration in the plant. The more susceptible variety to Mn toxicity, Forrest, showed an increase in percent P with increasing Mn levels in nutrient solution while percent P in the Lee 68 variety was unaffected. The upset in the nutrient balance of the plant due to Mn toxicity was not as well defined as were the effects of Al toxicity on the nutrient balance of the plant.

There was some evidence of an Al-Mn interaction in nutrient solution study two. Increasing Al levels to 20.0 ppm tended to decrease the concentration of Mn in the plant. Furthermore, the severeness of one of the symptoms of Mn toxicity, necrotic areas, lessened as the Al in nutrient solution was increased. Conversely, the effect of decreasing plant weights by increasing Al levels in nutrient solution was slightly curtailed by higher Mn levels in nutrient solution, indicating that Mn may act to alleviate Al toxicity somewhat.

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VITA

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