Soybean Root Growth and Nutrient Uptake as Affected by Lime Rates and Plant Age. I. Al, Mn, P, and S[1]

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ABSTRACT

A growth chamber experiment was conducted to determine the effect of lime rates and time on soil acidity and nutrient availability, and on root growth and nutrient uptake by a determinate soybean cultivar (*Glycine max* Merr.). The study consisted of three lime rates (0, 3 and 6 Mg/ha) and four plant ages (2, 4, 6, and 8 weeks after emergence) in four randomized complete blocks. Root length increased linearly to week 6 and then stopped. Liming at the recommended rate of 3 Mg/ha was associated with longer and finer roots. Shoot to root ratios increased with plant age and with liming at the recommended rate. The high shoot to root ratios, based on dry weights, indicate that with adequate liming soybean roots may perform more efficiently because of longer and finer roots, lower Al and Mn toxicities, and higher nutrient availability in the soil. The effects of lime rates and plant age on shoot Al and shoot nutrient parameters were also determined. The parameters consisted of elemental concentration, total content, accumulation rate per shoot per day, and uptake rate per meter of root per day in the shoots. The elemental concentrations represented the balance between rate of nutrient uptake and rate of shoot growth, where nutrient uptake was conditioned by soil nutrient availability, root activity and plant requirements; and shoot growth constituted a diluting factor. The total elemental content was given by the concentration times the shoot dry weights. The accumulation rate represented the net influx into the shoots and was indicative of the general activity and nutritional requirements of the plant. The uptake rate per meter of root was related to root activity as determined by the balance between rate of root growth and rate of root aging and by the nutritional demands of the soybean plant. Shoot Al concentrations decreased with plant age in the unlimed pots, despite high soil Al. Al uptake per meter of root decreased with time. Shoot nutrient parameters for Mn, P and S behaved differently when compared to those of the non-nutrient Al. Shoot P parameters responded well to the high root length growth rates resulting from adequate liming, because of low soil P mobility.

COMPENDIO

El tamaño del sistema radicular aumentó con la edad de la planta pero la tasa de cambio varió con el parámetro radicular y el nivel de encalamiento. El largo del sistema radicular aumentó linearmente hasta la sexta semana y después permaneció constante. Este aumento fue atribuido a que el crecimiento fue mayor que la descomposición del sistema radicular durante este período. El encalamiento recomendado resultó en sistemas radiculares más largos y con raíces más finas. La proporción tallo/raíz aumentó con la edad de la planta y con el encalado recomendado. Esta alta proporción de tallo a raíz indica que, con un encalado adecuado, la planta de soya funciona más eficientemente debido al largo y finura de las raíces, a la baja toxicidad de Al y Mn, y a la alta disponibilidad de los nutrimentos. El aumento de la proporción tallo/raíz también fue debido a sistemas radiculares más eficientes, lo cual se atribuyó al incremento de la longitud radicular por unidad de peso de las raíces. La tasa de absorción de nutrimentos en función de la edad de la planta, también varió significativamente según el parámetro nutrimental y el nivel de encalamiento. Los parámetros de absorción de nutrimentos utilizados fueron: concentración, contenido total en el tallo, tasa de acumulación por tallo por día, y tasa de absorción por metro de raíz por día. La concentración elemental representó el balance entre la tasa de absorción de nutrimentos y la tasa de crecimiento del tallo (factor diluyente). El contenido elemental total resultó de la concentración y el peso seco del tallo. La tasa de acumulación representó el influjo neto en el tallo y fue indicativa de la actividad y requerimientos nutricionales de la planta. La absorción de nutrimentos por metro de raíz fue relacionada con la actividad radicular, determinada por el balance entre la tasa del crecimiento radicular y la tasa de envejecimiento (lignificación y reducción en permeabilidad) de las raíces. En cuanto a la concentración, ésta disminuyó para Al y S, pero tendió a aumentar para Mn y P, aún cuando el crecimiento del tallo ejerció un efecto diluyente. El contenido elemental total siempre aumentó con la edad de la planta, debido al incremento del peso seco del tallo, aún cuando la concentración del nutrimento pudo disminuir. La tasa de acumulación nutrimental por tallo por día, tendió a aumentar con la edad de la planta y generalmente alcanzó el valor máximo entre la cuarta y sexta semana. La tasa de absorción nutrimental por metro de raíz por día tendió a disminuir con la edad de la planta debido al crecimiento radicular o menor demanda de absorción por cada metro de raíz, y a la pérdida de la actividad radicular causada por la lignificación y baja permeabilidad de las raíces más viejas.

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INTRODUCTION

Liming is an essential practice in the southeastern United States because of the need to reduce toxic levels of Al and Mn, and other acidity-induced plant stresses. Relationships among liming, soil acidity and plant growth has been the subject of much research (2, 3, 8, 9, 13, 22, and 26). One of the conclusions that has surfaced from this work is that overliming highly weathered soils should be avoided because of detrimental effects related to nutrient availability, incidence of soil-borne diseases and plant performance (14, 15 and 16).

Although much work has been done with plant shoots, the limited research characterizing root development and activity has created a vacuum in understanding the plant's performance in developing crop and soil management models to optimize yields. Basic research conducted during the last few years on root growth and nutrient uptake has laid the foundation for more applied work in this area (6, 11, 21, 23, 24, 25, and 29). Information on the rate of root growth, expressed in terms of length rather than weight, has provided insight into the role played by the root system in relation to crop responses to various soil properties and treatments (4, 7, 12, 20, 27, and 28).

The main objective of this investigation was to determine the effect of lime rates and time on soil acidity and nutrient availability, and on root growth and nutrient uptake by a determinate soybean cultivar (*Glycine max* Merr.). Root length, as opposed to root weight or volume, was selected as the most useful parameter for characterizing root growth and its impact on nutrient uptake and shoot performance.

MATERIALS AND METHODS

A growth chamber study was conducted with soil from the A horizon of a Cecil sandy loam (**Typic Hapludult**). A factorial design in four randomized complete blocks was used. The experimental factors were: three lime rates (0, 3 and 6 Mg/ha) applied two weeks before planting and four plant ages (2, 4, 6 and 8 weeks after emergence). Three Mg/ha was the recommended lime rate based on the Adams-Evans buffer method (1). Dolomitic limestone with a 100% Ca CO_3 equivalent was applied. All pots received 25 ug/g of N, 100 ug/g of P and 50 ug/g of K, applied as 5-10-10 and 0-20-0 at planting time. Soil and materials were mixed in a twin-shell dry blender to insure uniform distribution. The treated soils were packed at a bulk density of approximately 1.15 Mg/m^3 in plastic containers (PVC pipes) 10 cm in diameter and 60 cm deep. The soil columns, open at the bottom, were placed on sand-filled aluminum plates and maintained at or near field capacity with distilled water.

Eight inoculated Bragg soybean seeds were planted per pot and seedlings were thinned to four plants per pot two days after emergence. The growth chamber was maintained at 27°C, 50% relative humidity, and 15 h of light per day with an intensity of 2 000 to 3 000 cd. Fresh roots were collected by wet sifting the soil through stainless steel sieves, washed with distilled water, blotted dry and weighed. Root volume was measured by water displacement in a graduated cylinder. The average root diameter was calculated from the volume equation for a cylinder ($V = \pi r^2 L$). Root length was determined by the root-line intersection method proposed by Newman (21) and Tennant (28), using the equation: $L = N (\pi A/2H)$ Where L = root length, N = number of intercepts (average of 50 readings), A = sieve area, and H = length of intercepting line. Nutrient influx in μmol/m of root per day was calculated using the Williams equation (6, 29): $I = [(U_2 - U_1)/(t_2 - t_1)] [(\ln L_2/L_1)/(L_2 - L_1)]$, where I = nutrient uptake rate, U = nutrient content of the plants, t = uptake time, and L = root length.

Soil pH was determined in water (1:1) potentiometrically; exchangeable Al was extracted with 1 M KCl and measured colorimetrically using the aluminon method (19); Mn and P were extracted with the Mehlich I solution (0.05 M HCl and 0.013 M H_2SO_4), Mn was measured by atomic absorption spectrophotometry, and P was determined colorimetrically with the molybdenum blue method using $SnCl_2$ as a reducing agent (10). SO_4-S was extracted with neutral, 1M NH_4OAc and determined colorimetrically by the $BaCl_2$ turbidimetric method (5). Plant tissues were digested using the double acid (HNO_3 and $HClO_4$) method and element concentrations were determined as indicated for soil samples.

Table 1. Shoot dry weights as affected by lime rates and plant age.

Lime Applied	Plant Age – Weeks			
(Mg/ha)	2	4	6	8
	(g/plant)			
0	1.25	2.94	6.34	10.01
3	1.51	3.07	7.64	12.17
6	1.19	2.25	5.05	8.19
LSD (0.05) =	0.18	0.56	1.21	2.11

RESULTS AND DISCUSSION

Shoot weight (Table 1) changed slowly early in the plant life cycle but increased rapidly after week four. Liming at the recommended rate of 3 Mg/ha (1X) increased shoot weight but liming with twice the recommended rate (2X) and not liming (0X) reduced it.

Root measurements (Fig. 1) also increased with plant age, but the rate of change during the growth period varied with root parameter and lime treatment. Root length increased linearly up to week six and then remained constant up to week eight when the plants were harvested (Fig. 1b). The increase in root length up to week six meant that root growth rates were greater than the root decay rates. At week eight, these two parameters were the same and consequently net growth was zero. Root systems produced in the growth chamber lacked well-defined taproots, relative to field-grown soybean plants (17, 18). Liming at the recommended rate resulted in longer root systems and also finer roots at week six and eight (Fig. 1). Liming at twice the recommended rate was generally detrimental to root growth, partly because of P deficiency as shown by soil analysis (Fig. 3c) and shoot composition (Fig. 6).

As indicated by the low root density values, the root systems were never pot-bound. Average root densities at week eight were 0.70, 0.78 and 0.59 Mcm/m^3 of soil in the 0X, 1X and 2X treatments, respectively.

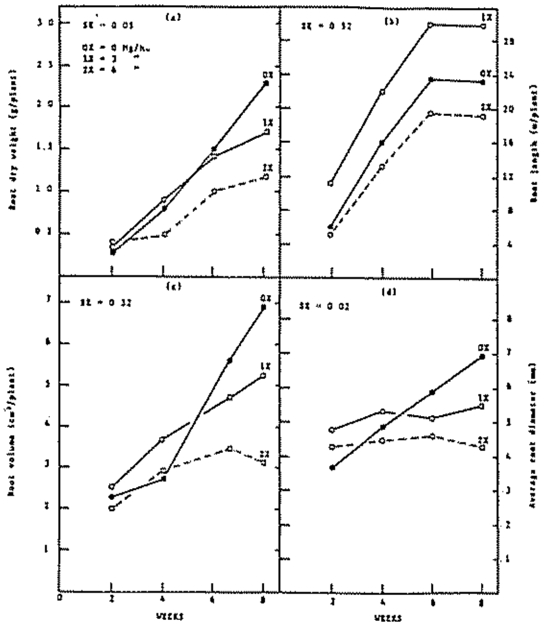

Fig. 1. Root growth parameters as affected by lime rates and plant age.

Shoot to root ratios (Table 2) increased with plant age, regardless of lime treatment. Liming at the recommended rate resulted in the highest ratios during the experiment. These high ratios (based on dry weights) indicate that with adequate liming the soybean root system performs more efficiently because of its longer and finer roots, lower Al and Mn toxicities, and higher nutrient availability. It is well known that one of the symptoms of Al toxicity is the development of short and stubby root systems (9, 15 and 16).

The increase in shoot to root weights with plant age (Table 2) suggests an increase in the efficiency of the soybean plant or an increase in shoot size at the expense of the roots, which may lead to higher yield potentials. The increase in shoot to root ratios with time is also indicative of a more efficient root system due to an increase in root length per unit of root weight, up to week four or six, particularly when soils were limed (Table 3).

The effects of lime rates and time on selected soil properties are depicted in Figs. 2 and 3. Soil properties responded as expected. Liming at the recommended rate raised soil pH to adequate levels, reduced the extractable soil Al and Mn, and increased the availability of P and S. Liming with twice the recommended rate reduced the amount of available soil P, possibly due to the formation of some tricalcium phosphate. Most of the lime-induced adjustments on soil properties took place by week two. This was particularly significant in reducing Al toxicity and promoting the development of long and fine root systems. The effect of time on the amounts of available nutrients in the soil was similar in all cases. Nutrient supply first increased due to fertilization and the impact of liming and then decreased as a result of nutrient uptake and other soil-nutrient interactions. The decrease of extractable soil nutrients began at week six for Mn, week four or six for P, and week two for S.

Table 2. Shoot to root ratio as affected by lime rates and plant age*.

Lime Applied (Mg/ha)	Plant Age – Weeks 2	4	6	8
0	3.66	3.82	4.28	4.31
3	4.21	4.41	5.58	6.91
6	3.35	4.17	4.95	6.77

LSD (0.05) = 0.5

* Shoot to root ratios based on dry weights.

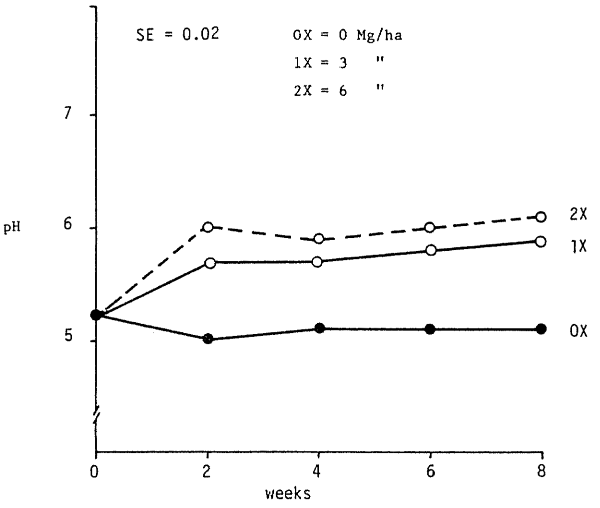

Fig. 2. Effect of lime rates and time on soil pH.

The effects of lime rates and plant age on shoot Al and shoot nutrient parameters are presented in Figs. 4 through 7. The parameters consisted of elemental concentration, total content, accumulation rate per shoot per day, and uptake rate per meter of root per day in the shoots. The elemental concentrations represented the balance between rate of nutrient uptake and rate of shoot growth, where nutrient uptake was conditioned by soil nutrient availability, root activity and plant requirements; and shoot growth constituted a diluting factor. The total elemental content was given by the concentration times the shoot dry weights. The accumulation rate represented the net influx into the shoots and was indicative of the general activity and nutritional requirements of the plant. The uptake rate per meter of root was related to root activity as determined by the balance between rate of root growth and rate of root aging and by the nutritional demands of the soybean plant.

Table 3. Ratio of root length to root weight as affected by lime rates and plant age*.

Lime Applied	Plant Age – Weeks			
(Mg/ha)	2	4	6	8
0	3.05	5.67	4.19	3.30
3	3.83	6.19	6.21	5.29
6	2.74	6.15	6.49	6.44
LSD (0.05) = 0.5				

* Root length in meters per unit of fresh root weight per plant.

Shoot Al concentrations (Fig. 4a) were negligible in the limed pots, regardless of plant age, because of reduced soil Al activity (Fig. 3a). Shoot Al concentrations in the unlimed pots were high but decreased with plant age due to dilution by shoot growth (Table 1) and decreasing uptake rates (Fig. 4d) in spite of high soil Al (Fig. 3a).

Total shoot Al (Fig. 4b) in limed pots was much lower than in unlimed pots. Total shoot Al in the unlimed pots increased with plant age, despite decreasing shoot Al concentrations (Fig. 4a), because of fast shoot growth rates (Table 1) and high soil Al activity (Fig. 3a).

The rates of Al accumulation (Fig. 4c) and Al uptake per meter of root (Fig. 4d) were similar and followed the same general trend of shoot Al concentrations (Fig. 4a). Shoot Al accumulation rates were high in the unlimed pots but decreased with plant age because of dilution by shoot growth and lack of plant demands. Aluminum uptake per meter of root per day was also high in the unlimed pots but decreased with plant age. This reduction in Al uptake per meter of root with time represents the normal trend and is due to dilution by shoot growth and decreasing root activity. The decrease in root activity per unit length was attributed to aging of roots and increasing length of young roots, which reduced the uptake demands by each meter of root.

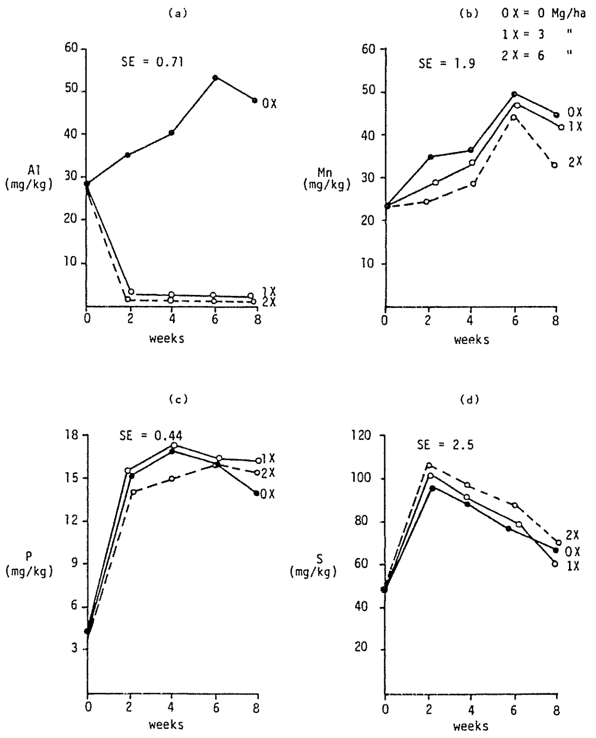

Fig. 3. Effect of lime rates and time on soil Al, Mn, P, and S.

Shoot parameters for Mn (Fig. 5), P (Fig. 6) and S (Fig. 7) were different when compared to those of Al (Fig. 4) in that increases were larger and decreases were smaller with time. These results were attributed to the nutritional requirements of the soybean plant and the high availability of these nutrients in the soil (Fig. 3).

Shoot Mn concentrations (Fig. 5a) in the limed pots were lower than in the unlimed pots, regardless of plant age and despite the longer root systems (Fig. 1b). These results were attributed to reduced soil Mn activity (Fig. 3b). Shoot Mn concentrations increased with age for all treatments up to week six and then decreased at week eight. Shoot growth failed to dilute concentrations during the first six weeks because of the relatively large plant nutrient requirements (Fig. 5c), high uptake rates (Fig. 5d) and high soil Mn availability (Fig. 3b).

Total shoot Mn (Fig. 5b) increased with plant age, regardless of treatment and particularly after week four, because of fast shoot growth rates (Table 1) and high shoot Mn concentrations (Fig. 5a).

Shoot Mn accumulation (Fig. 5c) increased with age up to week six because of the high nutritional demands of the soybean plant, high root activity, and high soil Mn availability (Fig. 3b). The increase in Mn uptake per meter of root up to week six (Fig. 5d), despite increasing root length (Fig. 1b), indicated high root activity, largely induced by the high nutritional demands of the plant. The increase in shoot to root ratios with time (Table 2), in spite of increasing root length up to week six (Fig. 1b), was partly responsible for the large nutritional demands and high root activity. The decrease in Mn uptake per meter of root after week six (Fig. 5d), without an increase in root length (Fig. 1b), was attributed to reduced nutrient demands, less root activity and lower soil Mn availability (Fig. 3b).

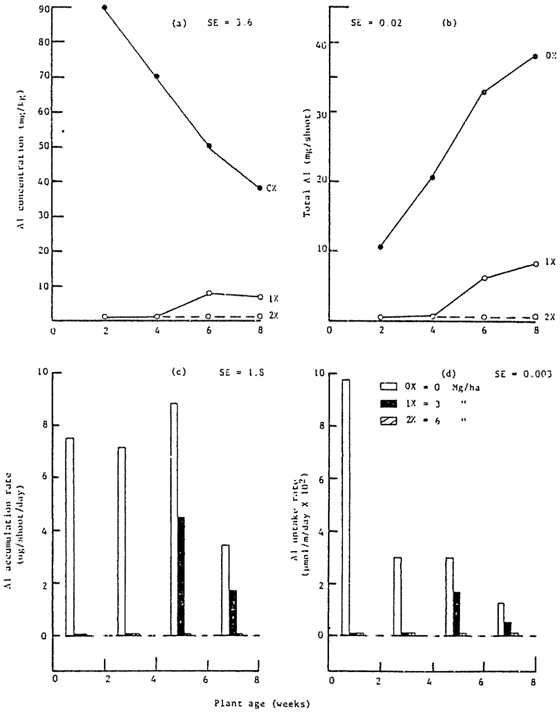

Fig. 4. Shoot Al parameters as affected by lime rates and plant age.

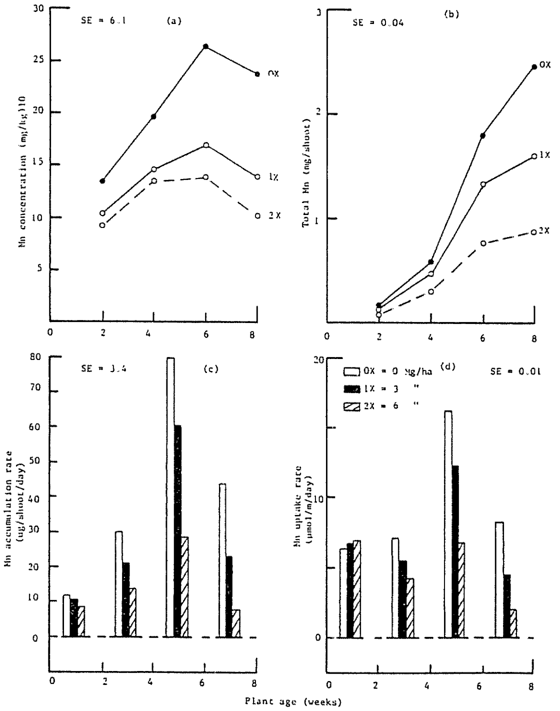

Fig. 5. Shoot Mn parameters as affected by lime rates and plant age.

Shoot P concentrations (Fig. 6a), accumulation rates (Fig. 6c), and daily uptake per meter of root (Fig. 6d) increased with plant age up to week six or eight, depending on the variable. The increases in shoot P, as opposed to the decreases noted for shoot Al, were largely attributed to high nutritional demands, large root activity, and high soil P availability (Fig. 3c). Shoot P parameters (Fig. 6) benefitted from fast root length growth rates up to week six (Fig. 1b), particularly when liming at the recommended rate.

Liming at the recommended rate was beneficial to all shoot P parameters because of the longer (Fig. 1b) and finer (Fig. 1d) root systems and higher soil P availability (Fig. 3c). Liming with twice the recommended rate was detrimental to the various shoot P parameters (Fig. 6) because of reduced root length (Fig. 1d) and lower soil P activity (Fig. 3c).

Shoot S concentrations (Fig. 7a) did not increase with plant age as was the case with P and Mn but they did not decrease as fast as shoot Al concentrations because of the S required by the soybean plant. Plant S demands became evident with the increasing shoot S accumulation rates up to week six (Fig. 7c). The general reduction of shoot S uptake per meter of root with plant age (Fig. 7d) was attributed to decreasing plant S requirements after week six (Fig. 7c), diminishing root activity with aging, and lower soil S availability (Fig. 3d). Shoot S concentrations (Fig. 7a) correlated better with S uptake per meter of root (Fig. 7d) than with S accumulation rates (Fig. 7c). These results were attributed to the strong role played by roots on nutrient uptake rates.

Total shoot S (Fig. 7b) also increased with plant age. Liming at the recommended rate was beneficial, but liming with twice the recommended rate was generally detrimental to total shoot S.

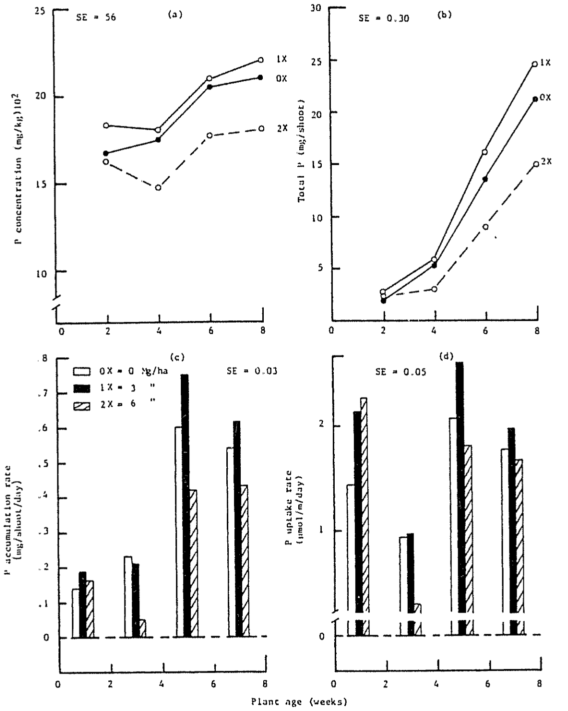

Fig. 6. Shoot P parameters as affected by lime rates and plant age.

CONCLUSIONS

It is well known that liming acid soils produces higher crop yields because of greater nutrient availability, enhanced N fixation, and elimination of elemental toxicity problems. Data presented in this paper showed that when a soil was limed at the recommended rate, the soybean root system performed more efficiently. These results were attributed to longer and finer roots particularly in the older plants, elimination of Al and Mn toxicities, and higher nutrient availability in the soil.

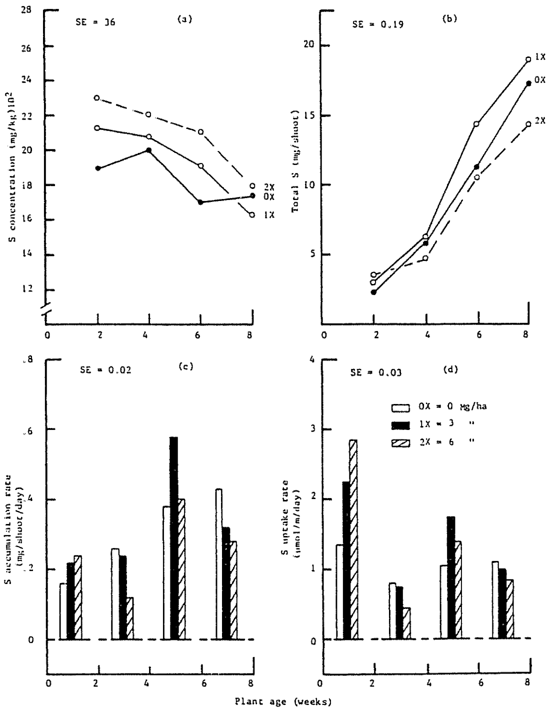

Fig. 7. Shoot S parameters as affected by lime rates and plant age.

Liming also produced higher shoot to root ratios. These data suggest an improvement in plant efficiency, i.e., an increase in shoot weight at the expense of the roots, which may be conducive to higher yield potentials, particularly under low stress conditions. The increase in shoot to root ratios was also associated with a more efficient root system, which was attributed to an increase in root length per unit of root weight. Root length increased rapidly during the first six weeks and then remained constant up to week eight. The increase in root length was attributed to a high rate of root growth relative to the rate of root decay.

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