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THE UPTAKE AND TRANSLOCATION OF YTTRIUM BY HIGHER PLANTS

August 21, 1953

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By

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Biology Section
Radiological Sciences Department

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THE UPTAKE AND TRANSLOCATION OF YTTRIUM BY HIGHER PLANTS

INTRODUCTION

Yttrium has not been demonstrated to be an essential element for plant growth. However, in nuclear fission reactions various isotopes of yttrium are produced in rather large amounts. Because of this the study of the absorption of yttrium by plants has assumed importance in recent years.

Spooner[8] has shown that even such similar plants as red and brown algae differ in their uptake of this element. He concluded that the removal of yttrium from sea water by algae appeared to be partly a matter of ionic exchange with yttrium already associated with a cell and partly of adsorption.

Jacobson and Overstreet[2] have shown that dwarf pea plants are able to concentrate yttrium in their leaves only about 0.034 times as great as the concentration in the soil. A somewhat greater uptake was found for barley plants from a clay suspension but even this was relatively low. The above work indicates that yttrium is readily fixed by soils and not readily translocated to the aerial portions of plants.

The purpose of this paper is to elucidate further the problem of the absorption of yttrium, particularly to study the various nutrient factors such as pH and concentration which may effect the uptake of this element using several representative species of plants. This information is then correlated with the uptake which will occur from a representative local soil.

MATERIALS AND METHODS

Detailed methods for these studies have appeared previously.[4] Red Kidney bush beans (Phaseolus vulgaris L.) were used as the principal experimental plant. This seed was of pure line stock and obtained from the California Crop Improvement Association.[1] Three other plants were used: Rutgers tomatoes (Lycopersium esculentum), White Russian wheat (Triticum vulgare), and Russian thistle (Salsola pestifer). The seed of the latter was collected locally.

The bean plants were cultured in six-liter enameled refrigerator pans, six plants per pan, according to the previously outlined standard technique. This culture period normally lasted 12 days, with the nutrient solutions being changed every 4 days. A slightly modified Hoaglands nutrient solution was used employing ferric nitrate as the source of iron.

The pH values of the solutions were maintained at 6.0 except where varied as an experimental condition. "Carrier-free" Y^{91} (<0.0001 μg/ml in final solution) was used as the tracer in a concentration between 10^{-4} and 10^{-3} μc/ml. The concentration of stable yttrium, except where varied experimentally, was 1.0 μg/ml. All plants were grown under greenhouse conditions except for those indicated experiments where a controlled environment chamber was used.

Soil experiments were conducted using the Neubauer seedling technique[(9)]. One hundred Belsford Beardless barley seeds were planted in 100 g of Ephrata fine sandy loam soil. This is a soil representative of the south-central Washington area which contains about 1 μg/g of yttrium and has a normal pH of 7.6. The Y^{91} was introduced into the soil as the chloride in a "carrier-free" solution. At the completion of the experiment the aerial portions were dried and prepared for analysis.

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1. University of California, Davis, California.

RESULTS

The accumulation of yttrium by the bean plant

This experiment was conducted to determine the uptake of yttrium by beans over an extended period of time comparable to the normal life of the plant. The plants were grown in a controlled environment chamber with a fluorescent light source of 1300 ± 100 foot candles with a 16-hour day. The temperature was maintained at 29 ± 1.5°C during the light hours and 24 ± 1°C during the dark hours with wet bulb temperatures of 22 ± 1°C and 20 ± 1°C respectively.

Plants were grown for 32 days with cultures being harvested every 4 days. At each time of harvest the solutions were changed in the remaining cultures. In addition to the nutrient salts, 1.0 μg/ml of yttrium as $Y(NO_3)_3$ with about 10^{-4} μc/ml of Y^{91} was added to the nutrient solutions. After the 12th day yttrium was added to only half of the remaining cultures.

The plants were divided into samples as follows: roots, stems and petioles, primary leaves, axillary trifoliate leaves and original trifoliate leaves along the main stem from 1 (oldest) to 6 (youngest). Only a few of these samples of particular interest are reported here; however, all samples were analyzed and are in general agreement with the data reported.

It appears from Figure 1 that the accumulation of yttrium by the leaves is dependent on the age of the leaf. The primary leaves (oldest) accumulate by far the greatest concentration of yttrium. This may be due to a situation where the uptake per unit of aerial tissue is greatest in the early stages of growth. It appears more likely however, from the data presented that yttrium is preferentially deposited in the primary leaves. This is particularly apparent in Figure 2 where it is demonstrated that the total amount of yttrium in the primary leaves continues to increase up to the point of senescence at the 24th day, which is 12 days after the first trifoliate leaves had reached maximum yttrium content. The difference in age of these two tissues is obviously small.

The primary leaves from those plants receiving yttrium in the nutrient solution for the full 32 days had a greater accumulation of yttrium than the same tissues from those plants not receiving yttrium after the 12th day. The difference observed in the 1st trifoliate leaf tissue of these same groups of plants was negligible.

This lack of difference in leaf tissues other than the primary leaves may be influenced by the high yttrium level maintained on the roots. There was only a slight loss of yttrium from the roots when the plants were placed in fresh solution containing no yttrium. Those roots growing in yttrium-containing solutions for the full 32 days continued to increase in total yttrium content.

An experiment similar to the one above was conducted to determine the uptake of this element into the fruiting bodies of tomato, bean, wheat, and Russian thistle. In no case was it found that the concentration of yttrium in the fruit of these plants exceeded the concentration found in the leaves and in general averaged about one order of magnitude less. Thus when evaluating the potential hazard of the element in the aerial portions of these plants the concentration of yttrium in the leaves could be considered as the maximum expected concentration and would serve as a safety factor in the consideration of other tissues.

The above data indicates that yttrium may be preferentially absorbed by the primary leaves of the bean plant with most other tissues retaining a comparatively low concentration. The primary leaves are also the only tissue which increased in yttrium concentration after about the 12th day of exposure. That yttrium which is deposited in the leaf appears to be relatively immune to retranslocation.

The effect of concentration on yttrium uptake

The effect of the concentration of yttrium on the uptake of this ion has been previously investigated only tentatively. Robinson(6) found that the addition of gadolinite to the soil apparently increased the uptake of rare earths in general.

In the following work bean plants were grown at a pH of 6.0 with concentrations of yttrium from 0.0001 μg/ml to 50 μg/ml with 1.0×10^{-4} μc of Y^{91}/ml added to the cultures as a tracer. These plants were grown under greenhouse conditions for 12 days. The yttrium additions were made during the last four days of the experimental period.

In general it was found that the uptake into the aerial portions of the plant and the amount of yttrium associated with the roots was proportional to the concentration of yttrium added to the nutrient solution. The concentration associated with the roots, as shown in Figure 3, is at least 3 orders of magnitude greater than the concentration in the leaves.

It has been found that this massive accumulation of yttrium associated with the roots is nearly all adsorbed yttrium. When bean roots, previously killed by drying, were immersed in a solution containing 1.0 μg/ml of yttrium at a pH of 6.0, the yttrium adsorbed on the root surfaces amounted to 1070 μg/g (dry weight) and was within the limits of error the same as found associated with living roots under similar conditions. It was found necessary in this experiment to add a small amount of phenol to the solutions containing the dead roots. If phenol was not added microfloral action increased the accumulation on the roots to as much as 1550 μg Y/g dry tissue.

Thus the concentration present in the adsorbed state on the root is much greater than the concentration of yttrium remaining in solution and as such would be the primary source of yttrium available for absorption. The availability of adsorbed material on the root having previously been demonstrated,[1] the leaf:root ratios for yttrium can thus be considered as a valid measure of uptake efficiency.[4] These ratios as plotted in Figure 3 indicate an increase in permeability at concentrations of yttrium greater than 1.0 μg/ml added to the nutrient solution. This increase may well be associated with the toxic symptoms observed at 50 μg/ml. These symptoms are probably due to impaired root function being evidenced by wilting of the leaves under high transpirational stress. This is understandable since the concentration of yttrium associated with the roots at this level is about 10 mg/g of dry tissue.

The effect of pH on yttrium uptake

The effect of pH on uptake was studied in bean plants grown under greenhouse conditions in nutrient solution cultures. The solutions contained 0.0001 μg/ml yttrium as the nitrate with 10^{-3} μc/ml of Y^{91} as a tracer. The solution pH was adjusted daily.

Data presented in Figure 4 indicate that the concentration of yttrium on the roots increases as the pH decreases. This differs from previous results of alkaline earth and alkaline metal ions,[4, 5] but is similar to the reaction of iron.[3] The solubility of yttrium increases with a decreasing pH,[7] but the accumulation of yttrium on the roots continues to increase.

The uptake of yttrium into the trifoliate leaves markedly increases as the pH decreases. It is quite probable that this is not only a matter of having a greater concentration on the root available for absorption, but the uptake is probably associated with the solubility as well.

Examination of the leaf:root ratio demonstrates that the uptake efficiency does increase in nearly a proportional response to the decrease in pH.

The effect of plant species on yttrium uptake

The uptake of yttrium by four plants -- Red Kidney beans, tomatoes, wheat, and Russian thistle -- was determined. They were cultured under greenhouse conditions in a nutrient solution at a pH of 6.0. During the final 4 days of the experiment, 0.0001 μg/ml of yttrium was added to the solutions with 10^{-3} μc/ml of Y^{91}.

Figure 5 illustrates the data of this experiment. The absolute values indicate that yttrium accumulates on the roots of plants in concentrations at least 2 or 3 orders of magnitude greater than the leaves when grown in nutrient solution. The Russian thistle was found to have the greatest total concentration on the roots as well as in the leaves. However, when the data is expressed as leaf:root ratios (Figure 5) it is apparent that the Russian thistle has a low uptake efficiency. Of the large nutrient accumulation on the root only a relatively small percentage is absorbed.

Tomato shows the greatest uptake efficiency for yttrium with a leaf:root ratio of 0.002. The bean is next with 0.0006, and Russian thistle and wheat follow with 0.00006 and 0.00003 respectively.

SOIL STUDIES

The maximum uptake of yttrium from an Ephrata fine sandy loam soil was determined using the Neubauer seedling technique. Results are shown in Table I. The average of six samples indicate that the barley plant will absorb into its aerial portions a maximum of about 0.006 per cent of the total yttrium available in a given volume of soil, or this plant can concentrate only about 0.006 times the concentration present in the soil. The concentration factor is in general agreement with that of Jacobson and Overstreet[2] using dwarf pea plants.

DISCUSSION

Unlike strontium[4] and cesium[5], yttrium is sparingly absorbed by plants. With the possible exception of the primary leaves of the bean plant none of the aerial tissues examined exhibited any tendency to accumulate yttrium in significant amounts.

The data of Figure 3 indicate that the uptake of yttrium responds in an essentially linear fashion to nutrient concentration at least in the lower range. Because of the heavy yttrium accumulations which occur on the root it becomes a problem to determine the concentration of yttrium to which the absorptive mechanism was actually exposed. Since the yttrium associated with the root is nearly all adsorbed in a heterogenous accumulation of iron and other adsorbed or precipitated compounds and is available for absorption, the actual concentration of yttrium associated with the root would approximate the true nutrient concentration. A plot of these data is made in Figure 6. At concentrations of yttrium less than 100 μg/g the uptake response is linear. At higher concentrations the permeability to this ion increases. As has been mentioned before, this increased permeability may be correlated with the toxic nature of the ion at these concentrations.

These data may now be used to correct the Neubauer concentration factor for conditions of any yttrium concentration which may occur in the soil under study. It should be emphasized, however, that the Neubauer concentration factor is representative of the maximum uptake which will occur before uptake is limited by soil nutrient exhaustion. These values will then adequately cover the odd times when all conditions are optimum to allow maximum uptake from a natural environment as well as serve as a safety factor in more adverse situations.

There are other factors which have been evaluated which will tend to modify these Neubauer data, such as the pH of the nutrient environment. It was found that the uptake efficiency (L/R) increased in a linear response to the hydrogen ion concentration. The species of plant also will contribute to variations in uptake values and must be considered when evaluating the uptake which will occur from a natural environment.

These experiments demonstrate, however, that the isotopes of yttrium are not apt to be as important as other fission products in the hazard evaluation of fission product absorption by plants. The uptake efficiency for yttrium varies from 2 to 4 orders of magnitude less than strontium(4) depending upon the plant and nutrient environment. The Neubauer experiments indicate a difference of about 3 orders of magnitude between strontium and yttrium in absorption by barley from an Ephrata fine sandy loam soil.

SUMMARY

Plants were grown in nutrient solutions to determine the effect of some of the factors important in the uptake of yttrium using Y^{91} as a tracer. It was found that in general the uptake was proportional to the amount of yttrium added to the solution; however, the uptake efficiency did tend to increase at added concentrations above 1 ppm. Within the range of pH 5 to 7 the uptake efficiency was proportional to the hydrogen-ion concentration. Tomato exhibited the greatest uptake efficiency for yttrium with a leaf:root ratio of 2×10^{-3}. Red Kidney bean was next with 6×10^{-4} and Russian thistle and wheat following with 6×10^{-5} and 3×10^{-5}, respectively. Further data indicates that comparatively the uptake of yttrium is low as exemplified by the bean plant with the primary leaves attaining the greatest concentration. There was little retranslocation from the aerial tissues and little loss occurred from the massive accumulations on the roots even when the plants were changed to solutions in which yttrium was absent. Neubauer experiments indicate a concentration factor $\left(\frac{\text{conc. aerial tissues}}{\text{conc. in soil}}\right)$ of 0.006 on a dry weight basis for barley from an Ephrata fine sandy loam soil.

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TABLE I

The uptake of Y^{91} from an Ephrata fine sandy loam soil which normally contains about 1 ppm of yttrium at a pH of 7.6. The Neubauer seedling technique was employed using barley plants.

Sample	Dry wt. Tops (g)	Conc. factor Dry wt. basis Conc. in tops / Conc. in soil	Per cent of Total soil Y Absorbed into Aerial portions
1	1.006	0.0064	0.0064
2	1.008	.0073	.0074
3	1.045	.0052	.0055
4	1.017	.0053	.0054
5	.925	.0071	.0066
6	.921	.0053	.0048

LEGENDS TO FIGURES

Figure 1 The concentration of yttrium at different ages in 3 leaf tissues of bean plants grown in a nutrient solution containing 1.0 ppm of yttrium as $Y(NO_3)_3$ at a pH of 6.0. The broken lines represent those cultures in which yttrium was absent after the 12th day. Each point is the average of 6 plants from one culture.

Figure 2 The total yttrium associated with the tissues of the bean plant grown in a nutrient solution containing 1.0 ppm yttrium as $Y(NO_3)_3$ at a pH of 6.0. The broken line represents those cultures in which yttrium was absent after the 12th day. Each point represents the average of 6 plants from one culture.

Figure 3 The uptake of yttrium from a nutrient solution at pH 6.0 containing various concentrations of Y as $Y(NO_3)_3$. Each point represents the average of duplicate cultures. The leaf:root ratio (L/R) represents a measure of uptake efficiency.

Figure 4 The influence of pH on the uptake of Y^{91} from a nutrient solution containing about 0.0001 ppm yttrium as $Y(NO_3)_3$. Each point represents the average of duplicate cultures. The leaf:root ratio (L/R) represents a measure of uptake efficiency.

Figure 5 The uptake of Y^{91} from a nutrient solution by four kinds of plants. The nutrient solution contained 0.0001 ppm yttrium as $Y(NO_3)_3$ at a pH of 6.0. Each plot is the average of 2 cultures of 6 plants each. The leaf:root ratios are plotted at the right.

Figure 6 The uptake of yttrium from a nutrient solution at a pH of 6 by bean plants as influenced by the actual concentration of yttrium available to the root. This is derived from the adsorbed yttrium associated with the roots.

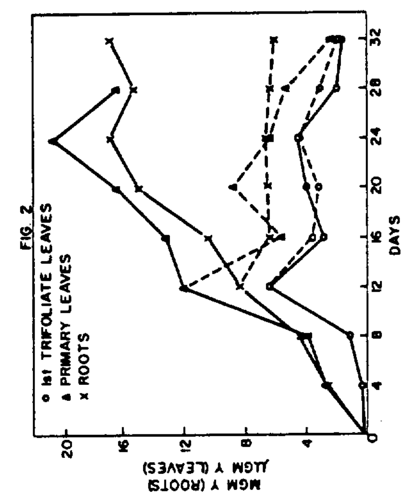


FIG. 2
o 1st TRIFOLIATE LEAVES
Δ PRIMARY LEAVES
x ROOTS
MGM Y (ROOTS)
μGM Y (LEAVES)
DAYS

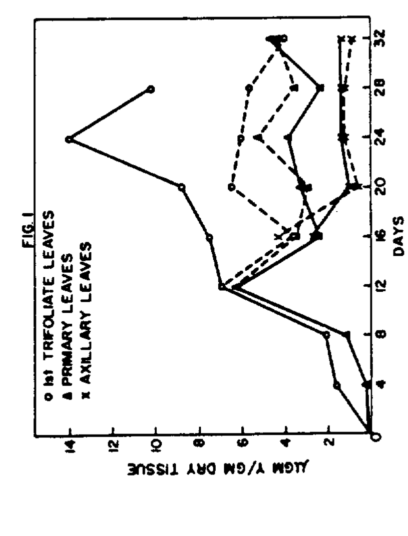


FIG. 1
o 1st TRIFOLIATE LEAVES
Δ PRIMARY LEAVES
x AXILLARY LEAVES
μGM Y/GM DRY TISSUE
DAYS

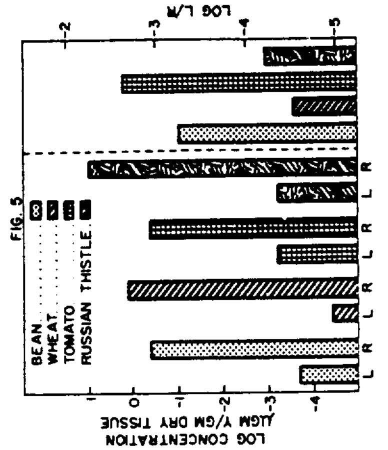


FIG. 5
BEAN
WHEAT
TOMATO
RUSSIAN THISTLE
LOG CONCENTRATION μGM Y/GM DRY TISSUE
LOG L/R

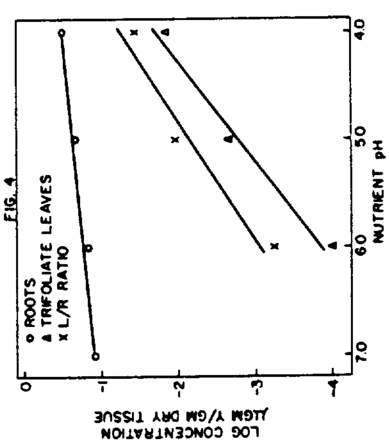


FIG. 4
o ROOTS
Δ TRIFOLIATE LEAVES
x L/R RATIO
LOG CONCENTRATION μGM Y/GM DRY TISSUE
NUTRIENT pH

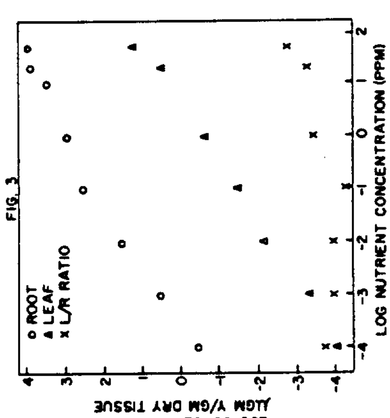
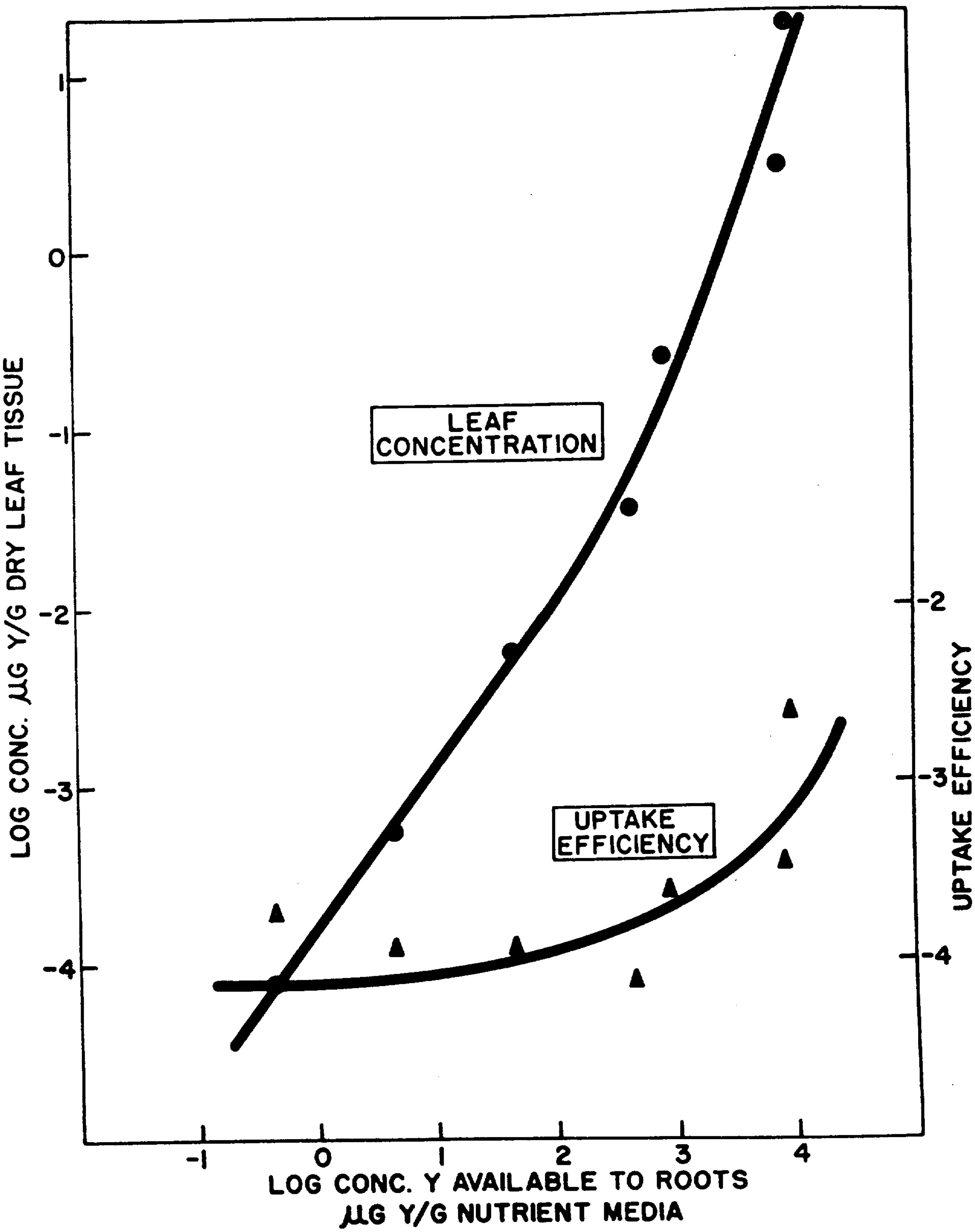


FIG. 3
o ROOT
Δ LEAF
x L/R RATIO
LOG CONCENTRATION μGM Y/GM DRY TISSUE
LOG NUTRIENT CONCENTRATION (PPM)

FIGURE 6


LOG CONC. μG Y/G DRY LEAF TISSUE
1
0
-1
-2
-3
-4
LEAF
CONCENTRATION
UPTAKE
EFFICIENCY
UPTAKE EFFICIENCY
-2
-3
-4
-1
0
1
2
3
4
LOG CONC. Y AVAILABLE TO ROOTS
μG Y/G NUTRIENT MEDIA