THE ABSORPTION AND TRANSLOCATION OF STRONTIUM BY PLANTS[1]

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Introduction

The relationship of strontium to plants has been investigated a number of times in the past (**3, 4, 5, 6, 9**) with results which usually indicate that it reacts much as calcium. The uptake has been successfully followed from both a soil and a nutrient solution, but in no case known to the authors has work been done on the factors influencing the uptake of strontium from a controlled nutrient environment. Since strontium has assumed recent importance as a product of nuclear fission, it is of interest to define these factors and to determine the rate of incorporation and the amount of retention by plants.

While the ultimate interest is concerned with the behavior of this element in the soil, it was felt that the many variables involved could be studied most effectively under the more precisely controlled conditions of nutrient culture. Experiments on the effect of nutrient strontium concentration and pH on the uptake, distribution and retention of strontium in various plants and plant parts were therefore conducted. Controlled nutrient culture techniques were employed with Sr^{90} as a tracer. In addition, experiments were performed using one soil typical of the south central Washington area.

Materials and methods

Red Kidney bush beans (*Phaseolus vulgaris* L.) were used as the principal experimental plant. The seed was of pure line stock and was obtained from the California Crop Improvement Association.[2] Four other plants were used: Rutgers tomatoes (*Lycopersicum esculentum*), White Russian wheat (*Triticum vulgare*), Belsford Beardless Barley (*Hordeum vulgare*), and Russian thistle (*Salsola pestifer*). The seed of the latter was collected locally.

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Plants were cultured in six liters of nutrient solution in enameled refrigerator plans (6 plants per pan) according to a previously outlined technique (**1**). Nutrient solutions were continuously aerated and consisted of the following salts and concentrations: KNO_3—0.0025 M; $Ca(NO_3)_2 \cdot H_2O$—

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0.0025 M; $MgSO_4 \cdot 7\,H_2O$—0.0010 M; and KH_2PO_4—0.0005 M. The micro nutrients were as follows: H_3BO_3—0.5 p.p.m. B; $CuCl_2 \cdot 2\,H_2O$—0.02 p.p.m. Cu; $MnCl_2 \cdot 4\,H_2O$—0.5 p.p.m. Mn; $ZnCl_2$—0.05 p.p.m. Zn; and $Fe(NO_3)_3 \cdot 9\,H_2O$—1.0 p.p.m. Fe. The pH of the medium was adjusted to 6.0, except where varied as an experimental condition, "carrier-free" Sr^{90} (< 0.0001 p.p.m. in final solution) was employed as a tracer at levels of approximately 10^{-4} μc./ml. Except where varied as an experimental condition, inactive strontium as $Sr(NO_3)_2$ was added at a concentration of 1.0 p.p.m. Solutions were maintained at the original volume by daily additions of distilled water, after which the pH was adjusted with 1 *N* NaOH or 1 *N* H_2SO_4. Solutions were changed every 4 days.

Some of the experiments were conducted under greenhouse conditions, others in a special growth chamber which permitted close control over temperature, humidity, and lighting. Details of this growth chamber will be described in a subsequent publication.

The soil culture experiments were carried out by the standard Neubauer seedling technique (**10**), with slight modification. The soil used was an Ephrata fine sandy loam with a pH of 7.6 by the thick paste method. It contained about 10 p.p.m. of strontium, was low in available nutrients, especially nitrogen, and contained very little organic material. Carrier-free Sr^{90} was thoroughly mixed with 100 g. of this soil. It was then dried and placed in a shallow crystallizing dish according to the standard procedure outlined in the reference above. One hundred Belsford beardless barley seeds were planted in the dish and the culture placed in a water bath at $25 \pm 1°$ C under artificial light consisting of a ratio of one daylight fluorescent tube to three white fluorescent tubes at 1000 ± 50 f.c. Above ground parts only were harvested after 18 days.

In the nutrient culture experiments the samples taken from the six plants growing in a single pan were combined for analysis. Results reported are the average of two such composite samples. Roots were analyzed as they came from the solution (omitting any washing which might remove adsorbed and absorbed nutrients). Samples were placed in tared, standard taper Erlenmeyer flasks. The fresh weight was obtained and the material then dried for two days at 70° C. After determining dry weights, the samples were digested with concentrated nitric acid. Ten to 20 ml. of acid was placed in the flask, a 6-inch standard taper chimney fitted to the top of the flask, and the assembly placed on the hot plate at low heat. After the plant material had been reduced to a brown syrupy liquid, the hot plate was turned to medium heat and the flasks allowed to reflux until the contents were clear. Chimneys were then removed and the contents evaporated just to dryness. The residue was dissolved in 5 to 50 ml. of 5 *N* nitric acid, depending on the size of the sample.

One ml. aliquots of these solutions were pipetted onto 1-inch stainless steel plates in duplicate, dried under a heat lamp and counted with a Geiger tube having a 3.0 mg./cm.^{2} window.

Results

The accumulation of strontium by the bean plant

This experiment was designed to determine the rate of accumulation and the total amount of strontium accumulated by the Red Kidney bean plant under controlled environmental conditions over an extended period of time. Plants were grown in the controlled environment chamber. Temperature was maintained at 29 ± 1.5° C during the light hours and 24 ± 1° C during the dark hours with relative humidities of 50 and70% respectively. The temperature of the root environment was maintained constant at 26 ± 0.5° C. Plants were illuminated in 16-hour periods at 1300 ± 100 f.c. from a source containing a 1 : 1 ratio of white and cool white fluorescent tubes.

Plants were grown for a period of 32 days with cultures being harvested every 4 days. At each harvest the nutrient solutions were changed in the remainder of the cultures. In addition to the nutrient salts, 1.0 p.p.m. of strontium as $Sr(NO_3)_2$ was added, containing 9.9×10^{-5} μc. of Sr^{90} per ml. as a tracer. After the twelfth day strontium was added to only half of the remaining cultures to allow a study to be made of the retention as well as the absorption of this element.

The sampling procedure was designed to follow the progress of strontium accumulation and translocation as precisely as possible. Plants were cut into samples as follows: roots, stems and petioles, primary leaves, axillary leaves, and the original trifoliate leaves along the main stem from 1 (oldest) to 6 (youngest). The 6th trifoliate leaf was fully formed about the 20th day. Flowering began about the 24th day. Data obtained after the 28th day are of doubtful validity since maximum growth in the space available was attained at this time. Although data for only a comparatively few of the tissues are recorded here, the data for all tissues were obtained and agree with the conclusions expressed.

The greatest concentration of strontium was always attained in the oldest leaves with a progressively smaller concentration as the age of the leaf decreased. Thus, the primary leaves attained the highest concentration of strontium of any tissue, 660 μg. Sr/gm. of dry tissue in 24 days. Figure 1 indicates that the first trifoliate leaf had a consistently greater concentration of strontium at any particular time than the sixth or youngest trifoliate leaf. This probably results from a time lag in absorption between the leaves of various ages, since the rates of accumulation for the leaf tissues are approximately equal. As far as the trifoliate leaves were concerned, concentration of strontium within the leaf was not a factor in determining the rate of accumulation of strontium by that leaf.

The first trifoliate leaf of those plants which received no strontium after 12 days retained a high concentration of strontium for the remainder of the 32 days. On the other hand, the sixth trifoliate leaf retained a comparatively low and constant concentration. The obvious conclusion is that there was no significant redistribution of strontium even when a comparatively high concentration gradient existed.

This condition of immobility is confirmed when comparisons of the total strontium present in each tissue are made as in figures 2 and 3. It is apparent that the total strontium in the tissues of those plants which received no strontium after the 12th day remained fairly constant. This indicates that once the strontium has been deposited in the tissues, there is very little redistribution.

The tissues varied markedly in their ability to accumulate strontium. For the plants exposed to strontium for 32 days, the six initial trifoliate leaves rapidly accumulated the greatest amount; most of this total being confined to the older leaves in a progression increasing with age. The axillary trifoliates, being younger than the initial trifoliates, never attained a total strontium content as great as the initial trifoliates; even though the

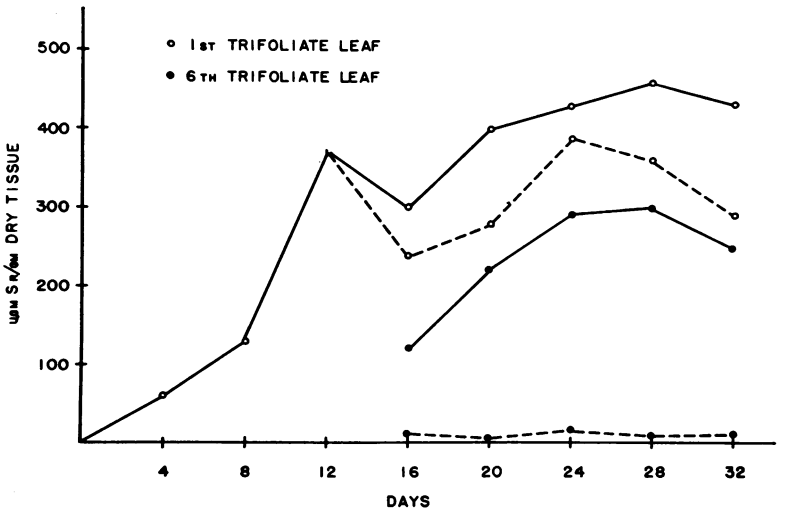

FIG. 1. The concentration of strontium in the first trifoliate leaf (oldest) and sixth trifoliate leaf (youngest) of bean plants grown in a nutrient solution containing 1.0 p.p.m. strontium as $Sr(NO_3)_2$ at pH 6.0. Each point represents the average concentration found in one culture of six plants. The dotted line represents those cultures from which strontium was removed after the 12th day.

dry weight of the axillary leaves was greater. This suggests that the roots are limited in their rate of strontium absorption. And since the total aerial portion was increasing much more rapidly in size than the roots, it follows that the rate of accumulation per aerial unit would have to decrease if strontium distribution were equal. However, both the axillary and initial trifoliate leaves continued to increase in total strontium concentration until general senescence began. The primary leaves, on the other hand, soon reached a point of saturation at about 150 μgm. of strontium; the stems appeared saturated at about 120 μgm. of strontium, even though the stem dry weight continued to increase. The roots continued to increase in strontium content throughout most of the 32-day period. As later evidence will indicate, these saturation values are dependent on the concentration of strontium in the nutrient environment.

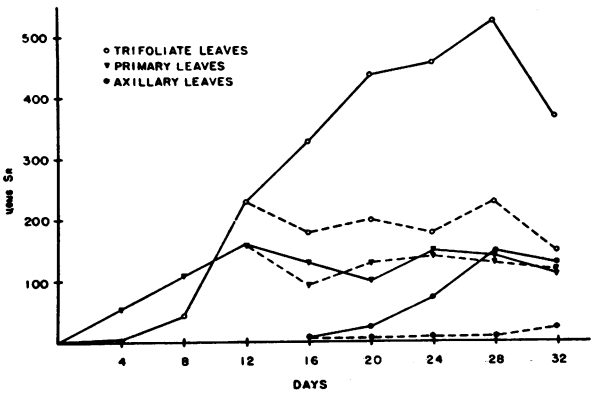

FIG. 2. The total strontium content of the leaf tissue of the bean plant when grown in a solution containing 1.0 p.p.m. of strontium at pH 6.0. The brokent line represents those cultures from which the strontium was removed after the 12th day.

THE EFFECT OF CONCENTRATION ON STRONTIUM UPTAKE

Strontium has not usually been considered an element toxic to plant growth; although some authors (**4, 5, 11**) found it to be toxic at very high concentrations. To determine the effect of nutrient strontium concentration on the uptake of the ion, an experiment was conducted over a range of concentrations from 0.0001 to 100 p.p.m., strontium concentration varying by powers of ten. The calcium concentration was maintained at 140 p.p.m. Bean plants were grown for 12 days in nutrient solutions under greenhouse conditions. Strontium was added to the nutrient solution only during the last four days of the experimental period.

It can be seen from figure 4 that the uptake of strontium was generally proportional to the concentration added to the nutrient solution over the entire range of 0.0001 to 100 p.p.m. No toxic symptoms were observed at any concentration. When "carrier-free" Sr^{90} was added to the nutrient solu-

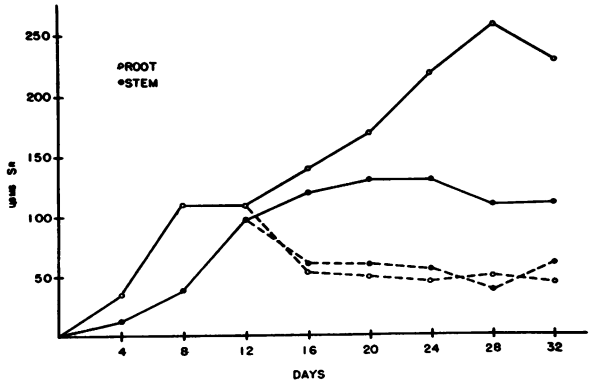

FIG. 3. The total strontium content of root and stem tissue of the bean plant when grown in a solution containing 1.0 p.p.m. of strontium at pH 6.0. The dotted line represents those cultures from which the strontium was removed after the 12th day.

tion, the same proportion was absorbed as when definite amounts of carrier were added.

The amount of strontium associated with the roots was also proportional to the amount added to the nutrient solution, and was always greater than the concentration found in the leaves, suggesting that the strontium associated with the roots was probably composed of adsorbed as well as absorbed strontium. To test this hypothesis, an experiment was performed to determine the difference between strontium accumulation by living roots and by

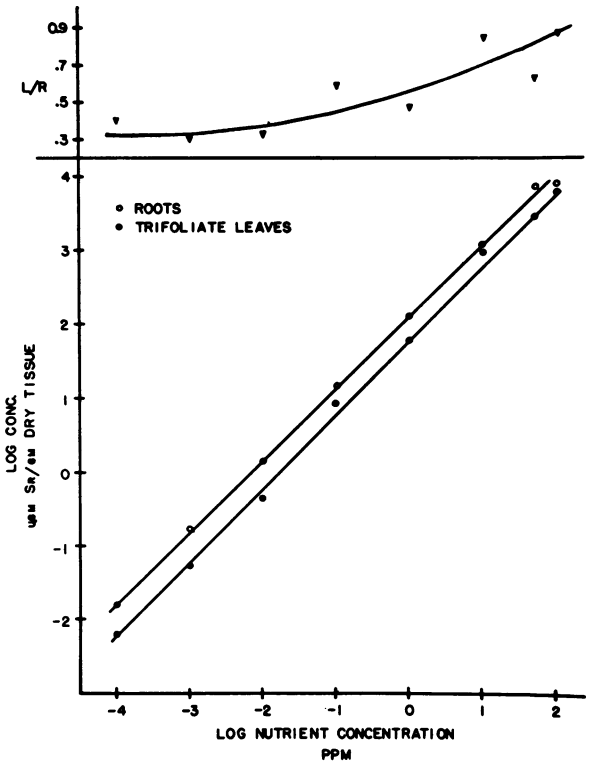

FIG. 4. The uptake of strontium from a nutrient solution containing several concentrations of strontium at pH 6.0. The uptake is expressed as μgm. Sr/gm. of dry tissue. Each point represents the average of duplicate cultures. The L/R ratios are shown in upper graph.

dead roots prepared by drying at 70° C for 24 hours. After four days in a nutrient solution containing 1.0 p.p.m of strontium the dead roots had accumulated an average concentration of 120 μgm. Sr/gm. of dry root tissue which compares with 130 μgm. Sr/gm. accumulated by living roots under the same conditions. These results would seem to indicate that most of the strontium associated with living roots in a nutrient solution is adsorbed strontium, and not truly absorbed as a function of living tissues. JACOBSON and OVERSTREET (7) reached the same conclusion from experiments of shorter duration with excised barley roots. Since the concentration of strontium

associated with the roots is at least 10 times greater than the concentration of strontium in the originally prepared nutrient solution, it is perhaps more realistic to consider this concentration of strontium on the roots as the nutrient concentration of the element, or the concentration to which the absorptive mechanism is actually exposed.

Based on this viewpoint, the ratio of leaf strontium concentration to root strontium concentration (L/R) should be the best measure of strontium

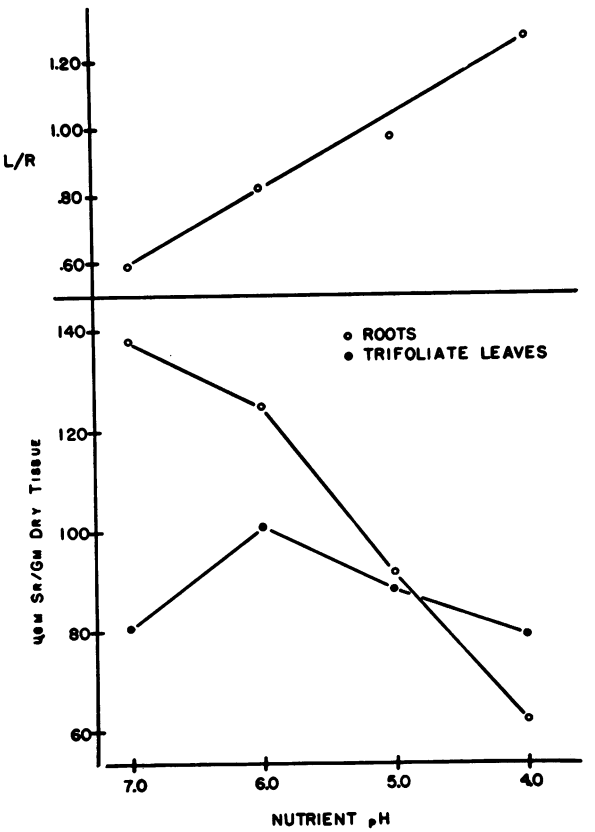

FIG. 5. The uptake of strontium by the bean plant from a nutrient solution containing 1.0 p.p.m. of strontium at various pH levels. The L/R ratios are shown in the upper graph.

uptake efficiency. In figure 4 this ratio is plotted against the concentration of strontium added to the nutrient solution. As the added strontium concentration increases, there is a tendency for L/R to increase, indicating an increased efficiency for strontium absorption.

THE EFFECT OF pH ON STRONTIUM UPTAKE

The effect of pH on strontium uptake was studied in bean plants grown under greenhouse conditions in nutrient solution containing 1.0 p.p.m. stron-

tium. The results are shown in figure 5. The concentration of strontium associated with the roots decreased as the hydrogen-ion concentration increased, due, no doubt, to increased strontium solubility.

The uptake of strontium, as indicated by leaf strontium concentration, is not a smooth function of pH, but exhibits a maximum at pH 6.0. This finding does not appear incongruous if we consider uptake efficiency as measured by the leaf : root ratio. The plot of L/R vs. pH shows that the efficiency of uptake steadily increases as the acidity increases. This increased efficiency at higher acidities is probably due largely to the greater availability of the strontium because of increased solubility. It may also be due in part to enhanced root permeability.

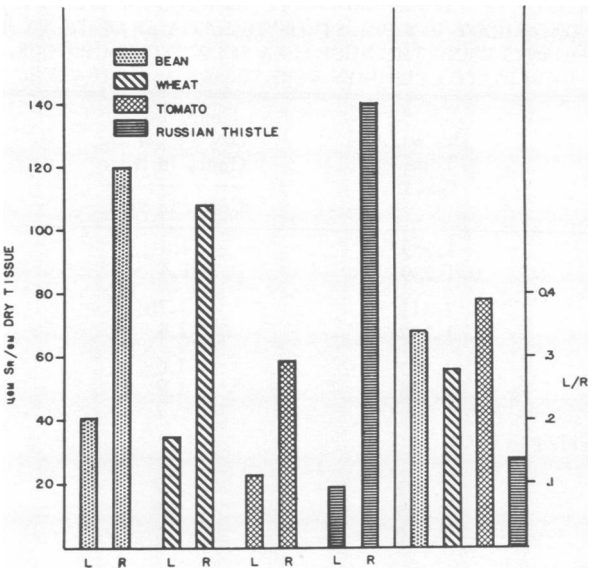

FIG. 6. The uptake of strontium from a nutrient solution at pH 6.0 and 1.0 p.p.m. strontium by four different species. The uptake is represented as μgm. Sr/gm. of dry leaf (L) or root (R) tissue. The L/R ratios are shown on the right.

THE EFFECT OF PLANT SPECIES ON STRONTIUM UPTAKE

Red Kidney beans, tomatoes, wheat and Russian thistle were used to determine the comparative response of these plants to strontium. The plants were grown under greenhouse conditions in a nutrient solution at pH 6.0. Strontium (1.0 p.p.m.) was added to the nutrient solutions during the final 4 days of growth preceding harvesting. Due to the different growth rates of the plants, they were started at different intervals so that all the plants would have an adequate tissue sample for analysis at harvest time. By this means all of the plants were exposed to the experimental conditions during the same 4-day period.

Figure 6 illustrates the differences observed, expressed both as absolute uptakes and as L/R ratios. Greatest variation is seen in the root accumula-

tion, which one might expect in view of the differences in root size and morphology.

As a measure of their absorptive efficiency tomato, bean, and wheat show leaf : root ratios of 0.39, 0.34, 0.28 respectively. Russian thistle is significantly lower with a L/R ratio of only 0.14.

Soil studies

Results of the Neubauer experiments with barley grown in an Ephrata fine sandy loam soil are shown in table I. Absorption of strontium apparently is independent of the Sr^{90} administered to the soil in the range of 0.01

TABLE I

THE UPTAKE OF SR^{90} ABSORBED FROM EPHRATA FINE SANDY LOAM SOIL, CONTAINING ABOUT 10 P.P.M. STRONTIUM AT A pH OF 7.6 BY BARLEY PLANTS USING THE NEUBAUER SEEDLING TECHNIQUE. REPLICATE CULTURES WERE GROWN AS INDICATED.

Dose μc./gm. soil	Dry wt. Tops (gm.)	Conc. factor Dry wt. basis Conc. in tops / Conc. in soil	Per cent of dose absorbed
0.01	1.229	1.3	1.6
	1.269	1.4	1.9
0.05	1.311	.76	1.0
	1.152	1.4	1.7
0.10	1.117	1.6	1.8
	1.083	1.8	1.9
100 p.p.m. Sr added to soil:			
0.01	1.452	1.2	1.8
	1.300	2.0	2.6
	1.282	1.7	2.2
Soil adjusted to pH 4.0:			
0.01	1.245	1.4	1.7
	1.092	1.8	2.0

to 0.10 μc./gm. of soil. The maximum uptake of strontium, under the conditions of this experiment, is only about 1.7% of the total strontium within the root environment. A concentration in the tops is attained about 1.4 times greater than that in the soil as indicated by the average of six replicates. This is substantially in agreement with the work of Jacobson and Overstreet (6) using dwarf pea plants with a 3-month growth period.

Neubauer experiments were also performed with soil to which 100 p.p.m. of strontium was added and with soil adjusted with sulfuric acid to a pH of 4.0. Judging from the previously described nutrient culture results, both of these treatments should have increased the rate of strontium absorption. While the results (table I) do indicate a slightly increased uptake the difference is not significant, considering the limited number of determinations.

Discussion

Most of the emphasis in the study of the absorption of fission products by plants is on being able to estimate the degree of absorption of the element by a plant from its natural environment. This has been done by establishing the maximum uptake obtainable from soils using the Neubauer technique, and supplementing this knowledge with general information on the effect of variables obtained from nutrient culture experiments. The expression of the nutrient culture results in terms applicable to soil conditions is the greatest difficulty in this approach. This difficulty, we believe, has been met by use of the leaf : root ratio as a measure of absorptive efficiency.

In the present nutrient culture experiments with strontium, it was found that massive accumulations of strontium occurred on the roots. This accumulation was in no way connected with metabolic absorption, since it occurred on dead roots to nearly the same extent as on living roots. This adsorption can be associated with several mechanisms most of which would not apply to growth in soils. JACOBSON and OVERSTREET (**6**) have indicated that the ions of this element are simply adsorbed on the root surface, finding that the roots of barley plants could successfully compete with clay particles in removing adsorbed strontium to the roots by exchange. There also has been found in nutrient solutions containing one or more p.p.m. of iron a heavy accumulation of iron on the roots (**8**). The gelatinous ferric oxide matrix could constitute a second site of adsorption. There are sulfates, phosphates, and carbonates in the nutrient solution which undoubtedly precipitate a considerable amount of the strontium present, and this insoluble strontium could well form a heterogeneous accumulation with a ferric oxide on the roots. The concentration of soluble strontium remaining in solution is small in comparison with that adsorbed on the roots, and the significance of this soluble strontium is further reduced because the accumulation of material on the root tends to inhibit direct absorption from the solution (**2**).

It is felt, therefore, that the most significant evaluation of absorption can be obtained by considering the concentration of strontium on the roots as the nutrient strontium concentration affecting absorption. This is accomplished by expressing the data as leaf : root ratios, *i.e.*, the concentration of absorbed strontium found in the aerial portions, divided by the concentration of nutrient strontium associated with the roots. The efficacy of such a procedure is well illustrated in the treatment of the data on the effect of pH on strontium uptake (fig. 5). On a simple concentration basis, the greatest uptake occurs at a pH of 6.0. However, when the data are expressed as leaf : root ratios, the greatest uptake efficiency is seen to occur at a pH of 4.0 with a decreasing linear relationship maintained in the range of pH 4.0 to 7.0. This latter explanation is more consistent with the known effects of pH on solubility and root permeability.

Summary

1. There was found to be no significant redistribution of strontium within the leaf system of the bean plant grown at a pH of 6.0, even though favor-

able concentration gradients existed. The total amount of strontium which a trifoliate leaf will accumulate is proportional to the age of the leaf. However, each tissue appears to have a maximum total amount of strontium which it will accumulate for given nutrient conditions. This maximum accumulation is attained at some characteristic time before senescence, depending on the tissue.

2. It was shown that the absorption of strontium is proportional to the concentration in the nutrient solution up to 100 p.p.m. This indicates that there is no deleterious effect of strontium concentration on the uptake mechanism below 100 p.p.m.

3. The accumulation of strontium on the root decreases as the acidity is increased between pH 7.0 and 4.0. The ratio of leaf strontium concentration to root strontium concentration increases linearly as the pH decreases.

4. It was found that tomato will maintain a concentration of strontium in its leaves, which is 39% of that found on the roots. The percentage for the bean was 34; wheat, 28; and Russian thistle, 14.

5. In Neubauer seedling tests, barley was able to remove to its leaves only about 1.7 per cent. of carrier-free Sr^{90} incorporated in an Ephrata fine sandy loam soil, or to concentrate the strontium in its leaves about 1.4 times over the concentration present in the soil.

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LITERATURE CITED

1. Biddulph, O. Diurnal migration of injected radiophosphorus from bean leaves. Amer. Jour. Bot. **28**: 348–352. 1941.
2. Biddulph, O. Studies of chlorosis using radioiron and radiophosphorus. Proceedings of the Auburn Conference on the "Use of radioactive isotopes in agriculture research." Auburn, Alabama. 1948.
3. Collander, R. Selective absorption of cations by higher plants. Plant Physiol. **16**: 691–720. 1941.
4. Hurd-Karrer, Annie M. Rubidium and strontium toxicity to plants inhibited by potassium and calcium, respectively. Wash. Acad. of Sci. **27**: 351–353. 1937.
5. Hurd-Karrer, Annie M. Antagonism of certain elements essential to plants toward chemically related toxic elements. Plant Physiol. **14**: 9–29. 1939.
6. Jacobson, L. and Overstreet, R. The uptake by plants of plutonium and some products of nuclear fission adsorbed on soil colloids. Soil Sci. **65**: 129–134. 1948.
7. Jacobson, L. and Overstreet, R. A study of the mechanism of ion absorption by plant roots using radioactive elements. Amer. Jour. Bot. **34**: 415–420. 1947.

8. REDISKE, J. H. and BIDDULPH, O. The absorption and translocation of iron in plants. Plant Physiol. **28**: 576–593. 1953.
9. SPOONER, M. A. Observations on the absorption of radioactive strontium and yttrium by marine algae. Jour. Marine Biol. Assoc. **28**: 587–625. 1949.
10. VANDECAVEYE, S. C. Biological methods of determining nutrients in soils. In: Diagnostic techniques for soils and crops. The American Potash Institute, Washington, D. C. 1948.
11. WALSH, T. The effect on plant growth of substituting strontium for calcium in acid soils. Proc. Roy. Irish Acad. **50B**: 287–294. 1945.