# THE ABSORPTION OF RADIOACTIVE STRONTIUM BY CERTAIN CROP PLANTS AS INFLUENCED BY THE CHEMICAL PROPERTIES OF SOME ARIZONA SOILS

by

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## INTRODUCTION

The use of the atomic bomb at Nagasaki and Hiroshima has most vividly brought to mind the terrible effects of the use of atomic weapons. The subsequent explosion in the Bikini Islands has dramatically demonstrated the dangers of radioactive fall-out materials from these bombs. To date, very little is known about the effect of the fall-out material. These radioactive products have far reaching effects which have raised serious questions in the minds of scientists and laymen alike. The products of these explosions are generally known. Radioactive strontium, one of these products, is probably the most hazardous. The effect of radioactive strontium upon plant and animal life is not fully understood. The proposed use of atomic energy in industry also poses a problem of waste disposal. Radioactive strontium, for example, is a product from uranium fission that can be absorbed by living plants. Disposal or dispersal must be resolved in such a manner as to eliminate its hazard to man. Thus, with the advent of nuclear fission and the production of fission products, there exists a need for knowledge concerning the uptake of these products by crops.

Among the principal products of the nuclear fission of plutonium is radioactive strontium with a half life of 25 years. Jacobson and Overstreet(32)* report that yttrium, zirconium, columbium, ruthenium,

*Parentheses indicate the number of the reference, as listed in the bibliography.

tellurium, cesium, barium, lanthanum and cerium are included in the list of principal long-lived products of nuclear fission. While none of these elements have been proven to be essential to plant nutrition, some may be absorbed by plants either by chance or by substitution for some essential nutrient element. Barley and pea plants were found to take up the fission elements yttrium, cesium, tellurium and strontium, even when present in only trace amounts. Of these only strontium was found to be absorbed readily by the plant. Although it is a nonessential element, the plant can accumulate strontium. If it is absorbed from the soil in the radioactive state, and then concentrated in the edible parts of food plants, it could conceivably reach a point where the eating of such parts could be detrimental to the health of both human beings and livestock. Of the products studied by Jacobson and Overstreet, only strontium was taken up in quantities sufficiently large to be concentrated by the plant and thus to become a health hazard.

## Occurrence of Strontium Minerals

Since strontium occurs in the earth's surface naturally and is found in all soils, it might be well to mention something of its occurrence and behavior in the natural state. Strontium is a metal intermediate between calcium and barium in chemical characteristics but occurs less abundantly in nature than either of the two(13). It occurs quite regularly in both igneous and sedimentary rocks and in the mineral form chiefly as the sulfate, celestite or as the carbonate, strontianite. Clarke(13), and Washington(56) independently report the average composition of igneous rocks contain 0.022 percent strontium as strontium oxide, or 0.034 percent in the elemental form. McMurtrey and Robinson (41) report that the earth's crust down to a depth of approximately 10 miles contains 0.018 percent strontium compared with 3.65 percent calcium. This represents a natural Ca/Sr ratio of about 200. In the soil, these authors report strontium to be widely distributed but in small quantities of the order of magnitude of 0.05 percent, while plants contain about one-fifth as much. The figure, 0.022 percent, seems to be a good average value for the percentage of strontium present in the earth's crust. This figure is reported by Clarke in his average composition of the lithosphere and also in his table of the average composition of known terrestrial matter. Strontium occurs, on the average, in sedimentary rocks to a lesser degree than in igneous rocks.

In Clarke's analysis of Colorado river water he found it to contain from zero to 0.0023 percent strontium oxide. He found no strontium in the river waters of the St. Lawrence basin, Atlantic slope, or the eastern tributaries of the Gulf of Mexico. Neither the upper nor lower Mississippi River was found to contain strontium. From Clarke's analysis of the river waters of the North American continent, one could conclude that the presence of strontium is localized and its occurrence is chiefly in the Colorado basin.

Celestite, the sulfate of strontium, has been reported in the saline residues of the Strassfurt region and also in the Searles marsh section of California. In fact, celestite is found universally throughout the world, to a greater or lesser extent. For example, it has been found in large beds in Transylvania, Egypt, France and other parts of Europe. Celestite appears in many localities of western United States. Deposits have been reported in Arizona near Casa Grande(19). Celestite occurs chiefly in sedimentary rocks and is often associated with gypsum and sulfur. Kraus and Hunt(37) found celestite disseminated through dolomite in Michigan. The upper layer of the dolomite of Monroe County contained up to 14 percent celestite. Kraus also reported celestite disseminated through dolomitic limestone near Syracuse, New York. The limestone in some of the caverns at Put-in Bay, Lake Erie, contain celestite distributed as crystals.

The carbonate of strontium, strontianite, has been found in deposits of commercial importance near Barstow, California. It is thought to have been formed by the replacement of limestone through the agency of water carrying strontium in solution.

Both celestite and strontianite are only very slightly soluble in water. Celestite is the more soluble of the two minerals. The solubility of strontianite is increased when the concentration of carbon dioxide in the water is increased. This may account for much of the strontium in the soil solution. Strontium reacts similar to calcium and barium with the soil colloids. One might expect strontium to be absorbed rather energetically and thus displace some of the other bases which may be present in greater quantities on the clay colloids.

## Absorption of Strontium by Plants

Several investigations have been conducted to show the relationship of strontium to plants. Most of the investigators have used either pure nutrient solutions or a controlled nutrient environment. There seems to be a lack of study dealing with the relationship between strontium and calcium uptake by crops grown on different soils. Rediske and Selders(45) studied the absorption and translocation of strontium by five different crops which included the Red Kidney bush bean, Rutger tomato, White Russian wheat, Belsfort beardless barley and Russian thistle. These authors felt that while the final objective in studying the behavior of strontium should be its absorption from the soil, they could study its effects more precisely in nutrient solutions under controlled conditions. They found that the total amount of strontium which a trifoliate leaf would accumulate was directly proportional to the age of the leaf up to a maximum which depended upon the given nutrient conditions. They observed that the absorption of strontium was proportional to the concentration of the nutrient solution up to 100 p.p.m. Sr. This indicated to the authors that strontium had no deleterious effect on the plants at concentrations below 100 p.p.m. Sr.

Spooner(48) studied the uptake of radioactive $Sr^{89}$ and $Sr^{90}$ by marine algae. The algae were treated with sea water containing the radioisotopes and the uptake of strontium by the algae was determined. The brown alga, Fucus serratus, extracted strontium from the sea water. Spooner states that the process is probably one of ion exchange since the algal cells regularly contain many times as much strontium as is contained in the sea water. Fucus serratus had about 40 times as much strontium as the sea water, other algae contained lesser amounts but all concentrated strontium within their cells.

Jacobson and Overstreet(33) tried to pinpoint the actual mechanism of ion absorption by plant roots. Radioactive $Sr^{85}$ was included among other radioactive cations for study. They found that maximum uptake of cations occurred near the growing point of the root in the case of all ions. Strontium was absorbed from solutions at extremely low concentrations.

This work was later verified by Vlamis and Pearson(53) who used radioactive zirconium and columbium. The zirconium and columbium were absorbed by clay particles and once absorbed, they were held very tenaciously, resisting leaching by many different reagents. The leachings were evaporated and the activity was measured by the Geiger-Mueller counter. Vlamis and Pearson report that since no zirconium or columbium were present in the leachings, the carbon dioxide solution theory for soil solution was inadequate to explain the uptake of these radioactive ions by the plants. They explained the uptake by postulating a "contact theory" whereby the plant roots excreted organic acids from their growing tips which released the radioactive ions to the root.

The study of uptake of strontium by plants is not by any means new. In 1915 Voelcher(54) determined strontium absorption at the Woburn Pot-Culture Experiment Station. Strontium was supplied to plants in the forms of sulfate, nitrate, hydrate, chloride and carbonate salts at two different rates, namely, 0.05 and 0.10 percent. The experiments indicated that except for the chloride no other salt had a retarding effect on the germination of the seed at the concentrations chosen.

In the case of chloride only nine plants out of 12 germinated in the 0.10 percent treatment. They claim that the chloride salt therefore had a toxic effect at this level. The plants treated with the chloride were weaker and slower in developing. In the early stages of growth the plants had a weak appearance and bad color, this being more marked with the heavier dressing. The leaf tips also showed signs of injury. The nitrate salt gave the plants a slight lead in the early stages but the authors felt it was no more than could be expected from any other nitrogen fertilizer. The carbonate salt seemed to give a slight stimulus but it was hardly beyond experimental error. The sulfate, hydrate and carbonate forms were without measurable influence. The ill effect of the strontium chloride was more likely due to the anion than to the cation, since the toxic effect was present only when the chloride salt was used. Moreover the symptoms described were similar to those reported for chloride toxicity.

Collander(14) showed that strontium and calcium were displaced from and readsorbed by the base-exchange complex at similar rates in accordance with their exchange constants, although there was approximately 400 times as much calcium as strontium present. Hazelhoff(28) using both soil and culture solutions concluded that strontium is not injurious to plants and appears to take the place of calcium as a plant food when the latter is deficient.

## Interchange Between Calcium and Strontium in Plant Nutrition

Strontium is not considered to be essential to plant growth. However, many investigators have shown that in water culture experiments, strontium will replace calcium in the plant. McMurtrey and Robinson(41) state, for example, that strontium salts are not toxic to plant growth at relatively small concentrations. At high concentrations strontium salts were claimed to be toxic but not as toxic as barium.

Walsh(55) used a soil medium to determine the extent to which strontium would replace calcium in plants and result in possible strontium toxicity. The soil selected was acid with a pH value of 4.9 and had an exchangeable calcium content of 0.24 percent. The pots were filled with 7 kilograms of soil-sand mixture which was made up as 5 parts pure sand and 2 parts soil. One set of pots received 1.50 grams of calcium carbonate per pot, a second series received no calcium or strontium carbonate, and a third series received strontium carbonate at the rate of 1.01 grams per pot, i.e., an amount of strontium equivalent to the calcium in the first series. There were no striking differences between the effects of strontium and calcium, although there appeared to be a slight difference in favor of the strontium. Strontium can replace calcium in the growth of the plant, according to data presented by Walsh(55). Some evidence also was presented to indicate that in the presence of calcium some benefit was obtained by additions of strontium, though this benefit seemed hardly significant. Walsh found that strontium did not replace calcium to any great extent in the grain of cereals, and that it was restricted more to the vegetative parts of the plant. The results presented by Walsh and by other investigators reported in this discussion, seem to be in disagreement with those of McMurtrey and Robinson(41), i.e., that strontium except at very low concentration is toxic.

Collander(14), in his studies of selective absorption of ions by plants found that in nutrient solutions containing both calcium and strontium in various concentrations, each of these cations was absorbed in amounts directly proportional to the concentration of that ion in the solution. Plants growing in solutions containing 400 times more calcium than strontium contained almost the same ratio of calcium to strontium as the nutrient solution. This indicated to Collander that the absorptive power of a given plant species for strontium was proportional to the absorptive power of the same species for calcium. This does not mean that strontium will not replace calcium to some extent; it simply means that the plant cannot distinguish between calcium and strontium at the lower concentrations. Collander says, "The explanation is not quite clear, but perhaps it may be found in the assumption that the plants are unable to distinguish between potassium, rubidium and cesium and also between calcium and strontium." The cation absorption series presented by Collander, with some reservation for its limited validity, is:

$$\text{Rb, K, Cs} > \begin{matrix}\text{Mg}\\ \text{Ca, Sr}\end{matrix} > \begin{matrix}\text{Li}\\ \text{Na}\\ \text{Mn}\end{matrix}$$

Therefore, it might rightly be assumed that when both cations, calcium and strontium are present in equivalent concentrations, strontium will be absorbed as readily as calcium. Some investigators have stated that the high concentration of calcium, normally present in western soils, would have a diluting effect on the absorption of trace amounts of strontium(44). A suggested method to reduce the absorption of strontium by plants therefore, would be to supply the soil with lime. Such a practice is not incompatible with the findings of Collander and others. Further study on the effect of the absorption of strontium by plants in soils of varying amounts of calcium carbonate are required to prove the validity of this contention.

## Availability of Calcium to Plants

There appears to be no chemical method suggested for measuring the availability of native soil calcium to plants. Furthermore, there are no known biological methods that have been devised specifically for the determination of available calcium in soils. However, available calcium could be determined by the usual pot-culture method in the greenhouse involving the soils in question, or by comparing the total calcium content of a given crop with that obtained when grown in the field.

Even the pot methods would hardly seem adequate for measuring the available calcium in soils since the plant does not consume calcium in luxury amounts. The calcium content of the plant remains more or less constant regardless of the content in the soil. Calcium deficiency can not be easily detected by quantitative measurement of calcium in the plant. The percentage of calcium present in the soil can be determined by ultimate analysis. The total calcium in the plant can also be determined but this does not necessarily indicate the amount of calcium that is available to the plant. The exchangeable calcium, the water-soluble calcium, the very slightly soluble calcium carbonate, and the calcium in organic forms all have their effect on availability.

Fuller and McGeorge(25) used the Drouineau(18) method for determining what they called "active calcium" as distinguished from total carbonate calcium. Active calcium represented that amount of soil calcium which reacted with 0.2 N ammonium oxalate. This method has been used with some success by Drouineau on the calcareous soils of

France to measure the availability of calcium. When applied to Arizona soils, however, it has not been successful in characterizing the amount of calcium available to the plant(40).

Harris, et. al.(27) used radioactive $Ca^{45}$ in lysimeter studies to determine the mobility of calcium carbonate in the soil. They found that increased applications of calcium carbonate caused an increase in the calcium content of the leachings. The isotopic exchange between the added $Ca^{45}$ and native calcium was incomplete, according to their data. Borland and Reitemeier(6), however, obtained complete isotopic exchange of $Ca^{45}$ in a rather short period of time in the clays which they studied.

In an attempt to determine the availability of calcium to plants in the carbonate, phosphate and sulfate forms, Ririe and Toth(47) used the isotope $Ca^{45}$ in greenhouse pot experiments on Sassafras sandy loam. Radiocalcium was used at a rate of 47.3 millicuries per pot. When calcium in the form of calcium carbonate was applied with superphosphate, alfalfa absorbed more calcium from the carbonate form than from either the sulfate or phosphate forms. The distribution of calcium in the alfalfa varied widely but the lower leaves in most cases contained more calcium than did the upper leaves while the upper stems contained more than the lower stems. The stems always had less calcium, than did the leaves. The authors could not explain why the plants absorbed more calcium from the carbonate form than either the phosphate or sulfate forms. Fried and Peech(24) studied the absorption of calcium in the form of lime and gypsum by plants grown in acid soils and reported that plants absorbed more calcium from the soil treated with lime than from those treated with gypsum.

Menzel(42) studied the competitive uptake by plants of such elements as potassium, rubidium, cesium, calcium, strontium and barium from 42 soils. He showed that the uptake of calcium and strontium by the plant was proportional to their concentration in nutrient solution. In mathematical language the relationship takes on the form of an equation as:

$$\frac{\text{Sr in plant}}{\text{Ca in plant}} = k\,\frac{\text{Available Sr in soil}}{\text{Available Ca in soil}}$$

where k is the distribution factor. According to Menzel, k is considered to be an index of similarity in behavior of the element toward uptake by the plant.

In his greenhouse pot experiment, Menzel used radioisotopes which greatly simplified the experimental procedure. All crops were grown in the greenhouse under natural light or in a growth chamber with artificial light and controlled temperature. A constant volume of soil was used while the weight varied from 3 to 4 kilograms. All crops were fertilized with nitrogen and phosphorus and in the experiments with strontium and barium, potassium was also supplied. The soils selected were collected from many parts of the United States. The pH values ranged from 4.6 to 7.6 and available calcium content ranged from 0.7 to 48 m.e. per 100 gm. The uptake of strontium by cowpeas grown 49 days on the 42 soils was measured, and the ratio of strontium to calcium was plotted against the reciprocal of exchangeable calcium content of the soil. Menzel found the Sr/Ca ratio to be proportional to the content of exchangeable calcium, the correlation coefficient being 0.93.

## Use of Radiotracers in Plant Studies

The use of radioactive tracers in plant studies has increased tremendously since their manufacture became simplified by the use of the atomic pile. Prior to this, isotopes could be made only by bombarding the substance with high velocity particles accelerated in a cyclotron. It was a slow, tedious, and expensive process. The use of isotopes is justifiable only if it can be shown that the radiation given off by them does not affect the results of the experiment(15). Isotopes are used mainly because their quantitative identification is easily determined and because their movement can be traced throughout the life cycle of the plant. If, however, the results of the experiment are altered by the effects of radiation, the use of isotopes would be very limited in plant studies. Blume(4) and (5) studied the effect of radiation by $P^{32}$ in various concentrations on the plant. Plants receiving phosphorus at rates of 100, 500 and 2,500 microcuries of $P^{32}$ per gram $P^{31}$ did not vary significantly from one another. In a second series Blume found that only when concentrations of over 12,500 microcuries of $P^{32}$ were used did the plants differ significantly from those grown with the stable isotope of phosphorus. This range exceeds considerably that normally used in tracer work. The quantities of $P^{32}$ usually used for tracer purposes in experimental plant research is so small that the influence of the radiation is unimportant from a practical standpoint. Certainly none of the effects was of sufficient importance to eliminate the use of $P^{32}$ as a tracer in plant nutrition studies.

Radiophosphorus emits a beta ray with an energy of approximately

1.71 Mev. while the isotope of strontium, $Sr^{89}$ emits a beta ray of approximately 1.5 Mev.(38). The energies of the beta emission of both phosphorus and strontium are thus of the same order of magnitude.

Dion, et. al.(17) applied fertilizer at the rate of 12, 24 and 48 pounds of $P_2O_5$ per acre. Two dilutions of $P^{32}$ were used, one at 26 microcuries and the other at 260 microcuries per gram of phosphorus (both measured at planting time). They had information on identical fertilizer treatments, with and without $P^{32}$, at various stages of growth, and at two levels of $P^{32}$ activity. They felt that if injury due to radiation should occur, it would appear in the 48-pound-per-acre treatment since the absolute uptake of $P^{32}$ was highest for this treatment. They measured the total yield, total phosphorus uptake, and $P^{32}$ concentration. Their data show a small but statistically significant increase in phosphorus uptake as the result of the presence of $P^{32}$. However, they explained that this increase was due to uneven germination in their nonradio-fertilizer plots. They did not consider any real benefits to have resulted from the use of radioactive phosphorus but by the same token there were no detrimental effects. This confirmed the work of Hendricks and Dean(30) that there was a sufficient margin of tolerance to make the avoidance of injury from $P^{32}$ a relatively easy matter.

Bould, et. al.(9) were not completely satisfied with work done previously by Hendricks and Dean, Russel and other investigators in that these authors measured only the effect in the above ground part of the plant. Before using $P^{32}$ in plant nutrition studies, Bould and his colleagues determined the magnitude of radiation effects in tomatoes and barley, grown in soil. They used radiophosphorus having different specific activities, associated with two levels of carrier phosphate, respectively. Effects of radiation were found to occur at rather low concentrations but they were relatively small and were in no way sufficient to preclude the use of $P^{32}$ in plant nutrition studies.

Ririe and Toth(47) using $Ca^{45}$ in plant absorption studies report no damage from radiation to plants whether the plants were grown in solution, sand or soil cultures.

Immediately after the exploding of the atomic bomb in Japan, reports began to come from the bombed areas intimating that greatly increased crop yields had been obtained in the vicinity of the explosion due to radioactivity in the soil, and its influence on plant development. The United States Department of Agriculture in cooperation with 13 state agricultural experiment stations conducted very extensive studies on the use of radioactive materials as a plant stimulant with a large variety of crops. The results of these experiments were classified material until in May 1949 the Atomic Energy Commission made the information available in a Progress Report(2) through the Department of Agriculture. Leaders of the program included L. T. Alexander, S. B. Hendricks and R. Q. Parks. In a summary of this work published by Alexander,(1) he states, "No comment need be made with regard to individual experiments. The general conclusion to be drawn from the data is that no effect of the radioactive materials was found, either beneficial or harmful. There are a few cases of differences that reach the 5 percent level of significance but they are no more than would be expected in sampling from normal distributions."

It would seem therefore that from the results reported by many authors, working independently both in the United States and abroad, that the use of radioactive isotopes, in quantities much higher than normally available to the plant, would be justifiable and that the effects derived from radiation may be expected to be negligible(29), (34), (39) and (49).

Several systems of units are being used to measure the amount of radiation but probably the most universally one used is the unit expressed as a curie. The curie is defined as that amount of any radioactive element undergoing the same number of disintegrations in a given length of time as one gram of radium, excluding the disintegrations of its radioactive daughter products. In these units, one curie is numerically equivalent to $3.7 \times 10^{10}$ disintegrations.

The term "specific activity" has been very useful in biological studies and is used to indicate the activity of one gram of a substance. Specific activity is defined as the number of disintegrations per unit time per gram of radioactive element(35). This means, that the shorter the half-life the greater will be the specific activity of the emitter.

The basis on which biological experiments can be made using the concept of specific activity, therefore depends upon the change in specific activity of a radioactive element brought about by dilution of the radio element with nonradioactive element. For example, since the mass of the radio element $P^{32}$ is essentially the same as the mass of the nonradio element $P^{31}$, the plant cannot distinguish between them when absorbing phosphorus from the soil. The specific activity of the radiophosphorus when added to the soil and diluted by the native phosphorus already present will therefore decrease when the plant absorbs the mixture of the two forms of phosphorus. The percentage of the phosphorus absorbed by the plant derived from the radiophosphorus will be the specific activity of the total phosphorus absorbed, i.e., the diluted specific activity divided by the specific activity of the radiophosphorus added, multiplied by 100(31).

## Objectives of the Study

An attempt has been made in the introduction to bring out some of the factors of strontium and calcium uptake problems for which a complete understanding is lacking. Certain objectives consequently were chosen to fill in some of these gaps in our knowledge and to define more clearly the relationship between soil and plant with reference to calcium and strontium absorption. One objective was to evaluate the uptake of radiostrontium by various types of crops such as legumes, grains and forage from several soils as influenced by the concentration of native soil calcium, added calcium carbonate and added strontium. A second objective was to determine the amount of strontium concentrated in the edible parts of several economically important crops, which were grown on soils supplied with this element. The absorption, translocation and concentration of strontium added to leaves of plants as a spray were also studied as a third objective. The fourth objective was to determine the uptake of strontium of a crop residue added to soils by a succeeding crop. The answer to these questions would facilitate the answer to the over-all question as to the possibility of a threat to our food supply in the event of large scale explosions of atomic bombs or to the possible absorption of radiostrontium by plants from wastes of industries powered by atomic energy.

Another problem studied in this investigation was the use of radiostrontium as a tool for the precise determination of the availability of native-soil-calcium to plants.

## PREPARATION OF EXPERIMENTAL MATERIALS

Thirteen different soils obtained from the upper 6-inch layer, were selected for the study of strontium absorption of various crops. Soils from a calcareous desert area located in the Santa Cruz Valley near Tucson, Arizona included Pima clay loam, Gila sandy clay loam, Tubac sandy loam, Laveen sandy loam, and three Tucson sandy loams each with different calcium carbonate contents. The Mohave sandy clay loam and Laveen loamy sand soils were collected in the Salt River Valley near Gilbert, and Sunrise, Arizona, respectively. The Flagstaff sandy loam* came from an aspen forest on the San Francisco Peak near Flagstaff, Arizona. Clinton silt loam and Miami silt loam, were obtained from a deciduous forest area in the humid climatic zone near Ames, Iowa and Crawfordsville, Indiana, respectively.

The soils were brought into the laboratory, air-dried, rolled and screened through a 2 mm. screen. Calcium and strontium content of the different soils are shown in Tables 1 and 2, respectively. Other chemical characteristics are shown in Table 3.

<u>Preparation of soil mixtures of varying native calcium carbonate content.</u>

To obtain soils with different amounts of native calcium carbonate for greenhouse-pot research, soils containing various amounts of calcium carbonate were mixed in different proportions. Table 4 shows the soils used, the initial calcium carbonate, the proportion of each soil represented in the mix, and the final calcium carbonate content. The soils

*Uncorrelated soil type. This soil will be referred to throughout the manuscript as Flagstaff sandy loam.

TABLE 1. THE CALCIUM CONTENT OF VARIOUS SOILS AS DETERMINED BY DIFFERENT METHODS

| Soil | Carbonate calcium | Calcium | | | | |
|---|---|---|---|---|---|---|
| | | Soluble in water | Exchangeable | Soluble in 1:1 HCl | "Active" | Total* |
| | percent | percent | percent | percent | percent | percent |
| Clinton silt loam | None | Trace | 0.24 | 0.040 | .... | 1.00 |
| Miami silt loam | None | Trace | 0.17 | 0.040 | .... | 1.00 |
| Flagstaff sandy loam | None | Trace | 0.13 | 0.356 | 0.79 | 1.00 |
| Mohave sandy clay loam | 0.031 | 0.010 | 0.32 | 0.365 | 0.97 | 1.05 |
| Tucson sandy loam | 0.148 | 0.008 | 0.16 | 0.317 | 0.99 | 0.90 |
| Tubac sandy loam | 0.176 | 0.008 | 0.16 | 2.185 | 0.87 | 2.29 |
| Tucson sandy loam | 0.612 | 0.009 | 0.14 | 1.443 | 0.85 | 2.16 |
| Pima clay loam | 0.624 | 0.012 | 0.64 | 1.506 | 1.25 | 2.44 |
| Tucson sandy loam | 1.484 | 0.010 | 0.15 | 2.075 | 1.58 | 2.59 |
| Gila sandy clay loam | 3.416 | 0.013 | 0.36 | 3.756 | 2.16 | 4.00 |
| Laveen loamy sand | 4.138 | 0.023 | 0.13 | 3.858 | 1.80 | 4.59 |
| Laveen sandy loam | 4.556 | 0.010 | 0.08 | 3.953 | 1.73 | 4.44 |

*Determined by $Na_2CO_3$ fusion(51).

TABLE 2. THE STRONTIUM CONTENT OF VARIOUS SOILS AS DETERMINED BY DIFFERENT METHODS

| Soil | Strontium soluble in 1:1 HCl | Total* strontium |
|---|---|---|
| | percent | percent |
| Clinton silt loam | 0.0014 | 0.020 |
| Miami silt loam | 0.0014 | 0.025 |
| Flagstaff sandy loam | 0.0035 | 0.020 |
| Mohave sandy clay loam | 0.0042 | 0.024 |
| Tucson sandy loam | 0.0028 | 0.021 |
| Tubac sandy loam | 0.0028 | 0.019 |
| Tucson sandy loam | 0.0028 | 0.027 |
| Pima clay loam | 0.0035 | 0.024 |
| Tucson sandy loam | 0.0020 | 0.019 |
| Gila sandy clay loam | 0.0028 | 0.017 |
| Laveen loamy sand | 0.0028 | 0.039 |
| Laveen sandy loam | 0.0020 | 0.017 |

*Determined by $Na_2CO_3$ fusion(51).

No measureable amount of water-soluble or exchangeable strontium was present in any of the soils.

TABLE 3. CHEMICAL CHARACTERISTICS OF SOILS

| Soil type | Cation exchange capacity | Exchangeable cations | | | | Organic† carbon | Total nitrogen | $CO_2$-soluble†† phosphorus (P) | pH of paste |
|---|---|---|---|---|---|---|---|---|---|
| | | Ca* | Ca** | Na | K | | | | |
| | m.e./100 gm. | | m.e./100 gm. | | | percent | percent | p.p.m. | |
| Clinton silt loam | 12.3 | 11.8 | 11.7 | 0.4 | 0.2 | 0.90 | 0.111 | ... | 6.55 |
| Miami silt loam | 9.8 | 8.7 | 9.3 | 0.3 | 0.2 | 0.99 | 0.195 | ... | 6.70 |
| Flagstaff sandy loam | 24.3 | 6.7 | 22.2 | 0.5 | 1.6 | 5.90 | 0.347 | T | 6.33 |
| Mohave sandy clay loam | 18.5 | 16.0 | 15.4 | 1.3 | 1.8 | 0.95 | 0.091 | T | 7.29 |
| Tucson sandy loam | 8.2 | 8.2 | 6.8 | 0.5 | 0.8 | 0.63 | 0.047 | 1.8 | 8.06 |
| Tubac sandy loam | 8.7 | 8.1 | 8.0 | 0.5 | 0.2 | 0.53 | 0.041 | 3.2 | 8.14 |
| Tucson sandy loam | 8.4 | 6.9 | 7.5 | 0.4 | 0.5 | 0.64 | 0.055 | 1.5 | 8.22 |
| Pima clay loam | 40.5 | 31.9 | 30.0 | 4.8 | 5.7 | 1.37 | 0.339 | 8.5 | 7.40 |
| Tucson sandy loam | 9.7 | 7.3 | 8.4 | 0.6 | 0.7 | 0.57 | 0.039 | 1.5 | 8.23 |
| Gila sandy clay loam | 19.1 | 17.8 | 17.7 | 0.6 | 0.8 | 0.99 | 0.076 | 1.3 | 7.89 |
| Laveen loamy sand | 10.4 | 6.4 | 8.6 | 1.2 | 0.6 | 0.59 | 0.052 | 1.8 | 7.82 |
| Laveen sandy loam | 6.4 | 3.9 | 5.0 | 0.6 | 0.8 | 0.66 | 0.052 | 4.9 | 8.37 |

*Determined by direct analysis by Beckman DU Flame Photometer.
**Determined by difference.
†Determined by Aldrich, Parker, and Chapman Method(1).
††Determined by Dickman, Bray Method(16).

TABLE 4. COMPOSITION OF SOIL MIXTURES OF VARYING NATIVE CALCIUM CARBONATE CONTENT

| Soil | Initial calcium carbonate content | Approximate ratio mixed | Final calcium carbonate content |
|---|---|---|---|
| | percent | | percent |
| Clinton silt loam | 0.0 | | |
| Laveen loamy sand | 10.3 | 1:1 | 5.0 |
| Miami silt loam | 0.0 | | |
| Laveen loamy sand | 10.3 | 1:1 | 5.0 |
| Pima clay loam | 1.6 | | |
| Laveen loamy sand | 10.3 | 6:4 | 5.0 |
| Pima clay loam | 1.6 | | |
| Laveen loamy sand | 10.3 | 9:1 | 2.5 |
| Clinton silt loam | 0.0 | | |
| Pima clay loam | 1.6 | 1:1 | 0.8 |
| Miami silt loam | 0.0 | | |
| Pima clay loam | 1.6 | 1:1 | 0.8 |

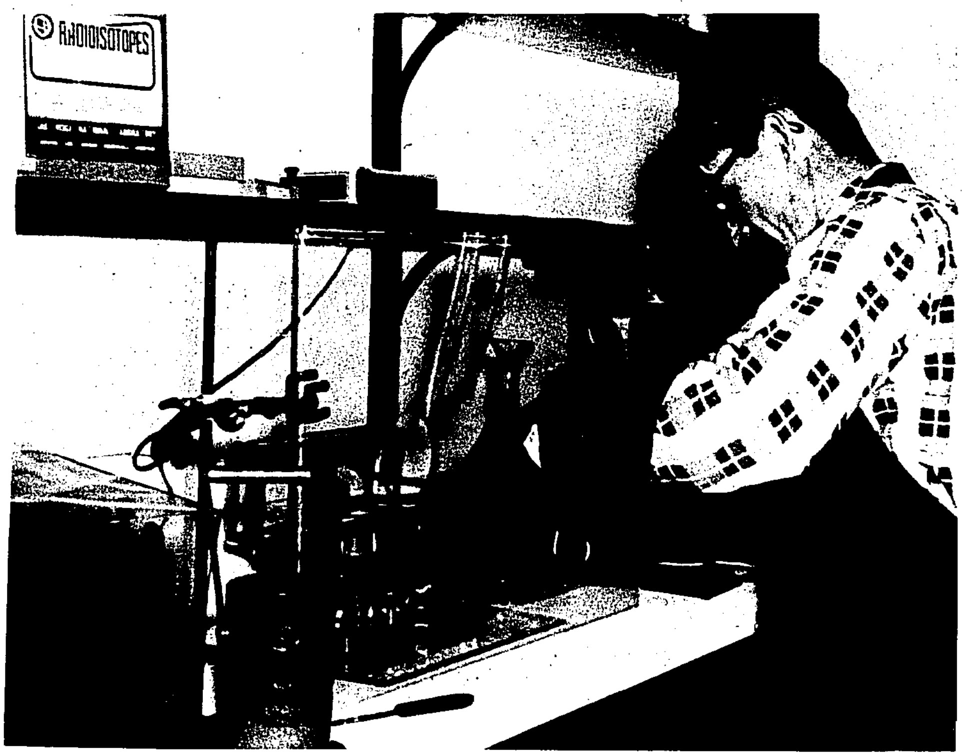



PLATE I WEIGHING RADIOSTRONTIUM.

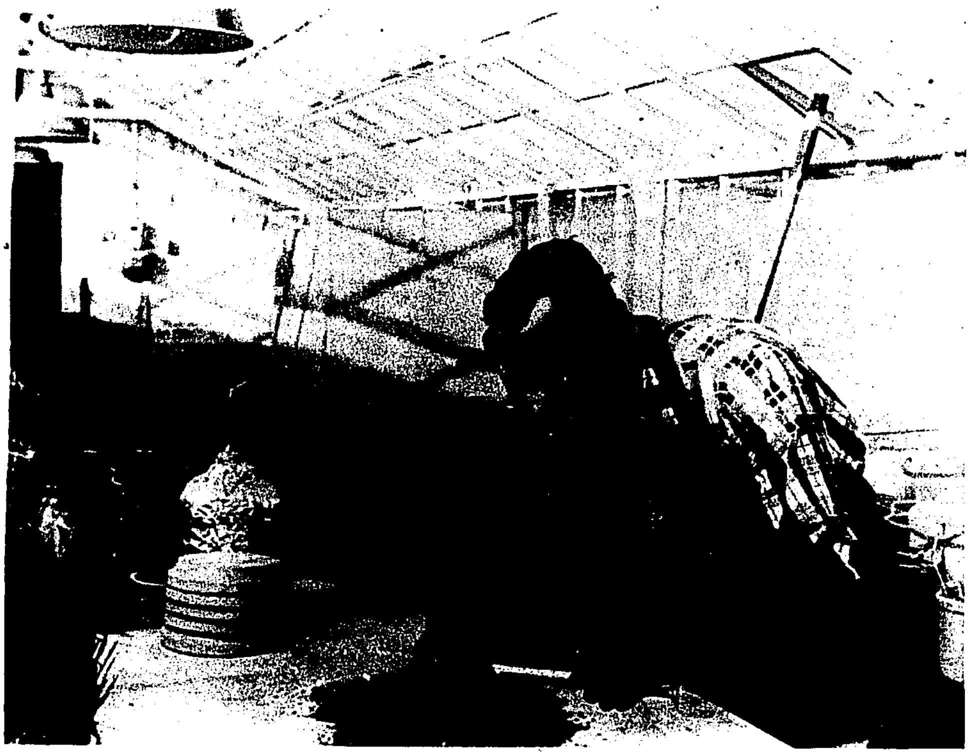


PLATE II ADDING RADIOSTRONTIUM TO SOIL FOR GREENHOUSE STUDY.

were thoroughly mixed to assure uniform distribution.

Preparation and application of strontium nitrate to lettuce leaves.

A study was undertaken to determine whether or not strontium in solution would be translocated within the plant when the solution was applied to the leaf. Cos Romaine lettuce was planted in glazed earthenware pots containing 1 kilogram of Pima sandy loam and allowed to grow for about six weeks. At this age radiostrontium was applied to the leaves. Five ml. of a radiostrontium nitrate solution containing 1.21 mgm. Sr was painted on the upper side of four leaves with a camel's-hair brush. Two sets, each of four leaves, one set being well matured the other one quite immature were chosen per plant for painting. The experiment was conducted in triplicate pots of lettuce of uniform size. A drop of detergent was added to the bottle containing the radiostrontium dose before application was made. The detergent increased the ability of the solution to wet the leaves. Applications were made several times allowing the solution to dry after each painting until the entire 5 ml. had been applied. When the bottle was emptied, 5 ml. of distilled water was added to the bottle three separate times, and each time painted on the leaves to be sure that all of the strontium had been washed out of the bottle and brush. This procedure was repeated in the same manner using three other pots of plants except that the solution was painted on the under side of the leaves. Tags were placed on the treated leaves giving the rate and position of the application.

Four additional lettuce plants were painted with strontium solution to determine the influence of place of application on absorption by the leaf. Two plants received the strontium solution on the upper side of the leaf and two on the under side. The plants were then allowed to complete growth until the head reached a prime-market-age. This required an additional two weeks. The plants were harvested, and the leaves separated into groups depending upon their original treatment. The leaves were dried at 50° C. and their radioactivity determined.

Preparation of labeled crop residues.

Various crops used as turn-under residues included Red Bush beans, Baart wheat, Marglobe tomatoes, Perennial rye grass, and Cos Romaine lettuce. The crops were grown in redwood flats approximately 24" x 14" x 6" containing a mixture of 10 kilograms each of silica sand and Pima clay loam. The soil mixture was treated with a water solution of radiostrontium nitrate of sufficient concentration so that the soil contained 360 p.p.m. Sr. The strontium was thoroughly rolled and mixed into the damp soil prior to seeding. The plants were cut at ground level, and the roots and tops harvested separately. Roots were washed thoroughly to remove the sand, soil and radiostrontium adhering to the surface of the root. Washings were made until they were free of any activity above background to insure complete removal of external strontium. The wheat was harvested in the boot stage, and lettuce at prime market stage. All material was washed, dried and ground.

The strontium content of the residues was found to be as follows:

| Crop | Part | Strontium mgm. Sr/gm. |
|---|---|---|
| Bean | Tops | 0.6580 |
| Bean | Roots | 0.2019 |
| Wheat | Tops | 0.2125 |
| Wheat | Roots | 0.1588 |
| Tomato | Tops | 0.8577 |
| Tomato | Roots | 0.5505 |
| Rye grass | Tops | 0.5292 |
| Rye grass | Roots | 0.5042 |
| Lettuce | Tops | 0.7371 |
| Lettuce | Roots | 0.3893 |

Preparation of an exchange resin.

It was felt that it would be desireable to study the absorption of strontium by rye grass if, instead of the strontium ion being added directly to the soil, it was adsorbed by an exchange resin that was placed in the soil. Strontium with calcium at different ratios was adsorbed on the exchange resins. A synthetic cation exchange resin known as Amberlite was prepared in the following manner(3). Strontium nitrate (2.32 gm.) containing $Sr^{89}$ was dissolved in distilled water, and diluted to give a final concentration of strontium ion of 0.64 gm. Sr per 800 ml. Eight hundred gm. of Amberlite was then added to this solution and allowed to stand two days. This mixture was stirred intermittently. At the end of two days, the mixture was filtered through a Buchner filter, the liquid poured back through the Amberlite several times. To determine the amount of strontium which was adsorbed by the Amberlite, 250 ml. of the liquid was evaporated to 10 ml. The concentrated solution was then washed into a 25 ml. volumetric flask and brought to volume. One ml. of this solution was placed into a planchet and evaporated to dryness, and tested for radioactivity. The solution count was essentially that of the background indicating that the Amberlite had virtually adsorbed all the strontium. This meant that the 0.64 gm. of strontium ion was adsorbed by the 800 gm. of Amberlite. The Amberlite, therefore, contained 0.08 gm. $Sr^{89}$ per 100 gm. of Amberlite. Fifty gm. of treated Amberlite was then diluted with 50 gm. of untreated Amberlite and the 100 gm. of the final mixture was placed in a layer in a pot containing 1 kilogram of soil. This gave an equivalent of 40 p.p.m. $Sr^{89}$ per pot.

Calcium nitrate tetra hydrate weighing 1.885 gm. was added to another 800 ml. of strontium nitrate solution containing 0.64 gm. $Sr^{89}$. The solution was added to 800 gm. of Amberlite and treated as described above. The amount of strontium adsorbed by the Amberlite was determined as described earlier. The amount of calcium adsorbed was determined by a Beckman DU Flame Photometer on the Amberlite filtrate. Both tests showed essentially complete adsorption. One hundred grams of the Amberlite was placed in a layer in a pot containing 1 kilogram of soil. Each pot therefore contained 40 p.p.m. $Sr^{89}$ and 40 p.p.m. calcium ions.

## EXPERIMENTAL METHODS

### Chemical and Physical Methods

#### Chemical analysis of soils studied.

An effort was made to characterize the calcium content of the soil. The gasometric method suggested by Erickson(20) was used to evaluate the total calcium carbonate content since magnesium carbonate was not found in appreciable quantities in the soils examined using the flame photometer. Water-soluble calcium and strontium were determined by leaching 20 gm. samples of each soil with a total of 300 ml. of neutral methyl alcohol. An extract was made of the residue using 300 ml. of 1.0 N ammonium acetate as the extracting agent to determine the amount of exchangeable calcium and strontium. The residue from this treatment was allowed to stand overnight in a 1:1 hydrochloric acid solution. This latter treatment indicated the amount of calcium and strontium soluble in HCl. An ultimate analysis for calcium and strontium was made on 2-gram samples by the usual fusion procedure with sodium carbonate(51). Each extract obtained from the above procedure was prepared for analysis of calcium and strontium by the Beckman DU Flame Photometer(26). Table 1 gives the percent calcium in each fraction together with the carbonate calcium determined. The percent strontium is reported in Table 2. An analysis for calcium was also made by the oxalate method(12) and (36) to verify the results secured by the flame photometer method. The results of the two methods were in close agreement.

The determination of the total soluble and total exchangeable sodium, potassium, calcium was made on the soils by the method suggested by Fields, et. al.(21) and modified for use in calcareous soils(8), (10) and (11).

The modified procedure was as follows: Ten grams of air-dried soil, which had been pulverized and passed through a 2 mm. screen was placed in a 150 ml. beaker. Thirty ml. of 1 N ammonium acetate solution (pH 7) was added. The mixture was allowed to stand overnight. The soil and extract was then washed into a funnel fitted with a 15 cm. Whatman No. 30 filter paper. Small portions of the ammonium acetate were used for washing after the first filtration was complete. This was continued until a total of 300 ml. had been used. The filtrate contained all of the exchange cations plus the water-soluble salts. The filtrate was evaporated to dryness without cover, very slowly to avoid spattering. Whenever an appreciable amount of organic matter was present, two or three drops of concentrated nitric acid were added to hasten oxidation. The filtrate was then evaporated to dryness and the residue ignited at 400-450° C. The residue was taken up in 25 ml. of 0.2 N HCl and filtered. The HCl solution was neutralized with 1.0 N ammonium hydroxide, using methyl red as an indicator, and 2-3 drops of $FeCl_3$ solution containing 100 mgm. ferric ions per ml. were added. The solution was kept slightly alkaline with small additions of ammonium hydroxide. When the removal of ferrous ions was required, a drop or two of bromine water was added to oxidize the iron to the ferric state before precipitating as ferric hydroxide. The precipitate was washed on a Whatman No. 30 filter paper, three times with a 2 percent ammonium hydroxide solution and the filtrate was taken slowly to dryness without cover. The residue of the filtrate was ignited at 400° C. for two to three hours to remove the ammonium chloride and again the residue was taken up in 25 ml. of 0.2 N HCl and filtered through a Whatman No. 30 paper to remove the silicates. The clear filtrate was collected in a 100 ml. volumetric flask and brought to volume with 0.2 N HCl.

To obtain the water soluble cations, 20 gm. of dried soil was placed in a 250 ml. beaker and 100 ml. of distilled water added. The mixture was allowed to stand for at least one hour, with occasional shaking. The soil solution was then filtered through a Whatman No. 30 filter paper. If the solution was cloudy because of colloids, neutral methyl alcohol was employed as the extracting reagent. The solution was taken to dryness, placed in a muffle and ignited at 400-500° C. The residue was again filtered and made up to 100 ml. volume with 0.2 N HCl solution. Since this solution contained only the soluble salts, and the first solution contained the soluble salts plus the total exchangeable salts, the exchange cations were determined by difference. The total exchange capacity and individual exchangeable cations were compared by the method described by Richards(46). Results obtained by the two methods are given in Table 5.

Concentration curves were used to calculate the content of the various cations from the transmission data secured with a Beckman DU Flame Photometer.

The pH determinations were made with a Beckman pH meter using a soil paste and a 1:5 soil-water solution.

Mechanical analysis was made by the Bouyoucos hydrometer method(7).

TABLE 5. COMPARISON OF CATION EXCHANGE CAPACITY OF SOILS BY TWO METHODS

| Soil | Na saturation | $NH_4$ distillation |
|---|---|---|
| | m.e./100 gm. | m.e./100 gm. |
| Clinton silt loam | 12.3 | 12.4 |
| Miami silt loam | 9.8 | 9.2 |
| Flagstaff sandy loam | 27.4 | 24.8 |
| Mohave sandy clay loam | 18.5 | 19.1 |
| Tucson sandy loam | 8.2 | 7.8 |
| Tubac sandy loam | 8.7 | 8.9 |
| Tucson sandy loam | 8.4 | 8.6 |
| Pima clay loam | 40.5 | 42.4 |
| Tucson sandy loam | 9.7 | 9.6 |
| Gila sandy loam | 19.1 | 19.9 |
| Laveen loamy sand | 10.4 | 8.2 |
| Laveen sandy loam | 6.4 | 8.6 |

Analysis of plant material.

The plant material from all experiments was dried at 50° C. and ground in a Wiley mill fitted with a 60-mesh screen. Total nitrogen determinations were made according to the standard Microkjeldahl procedure, using samples weighing 40 mgm.

Calcium, sodium and potassium were determined by the following method: Samples of finely ground plant material of one to two grams were weighed, placed in a 50 ml. beaker and ashed at 500° C. for two and one-half hours. The cooled samples were moistened with a few drops of concentrated $HNO_3$ or just enough to wet the ash. The $HNO_3$ was driven off slowly on a hot plate to avoid spattering. After evaporating to dryness the sample was returned to the oven and heated at 450 to 500° C. until it was completely ashed and white in appearance. Twenty-five ml. of 0.2 N HCl was added to the ashed material and the mixture allowed to stand for about thirty minutes before filtering through a Whatman No. 30 paper. If the sample was being analyzed for sodium or potassium only, it was made up to a volume of 100 ml. at this point. If it was to be analyzed for calcium also, the phosphates were precipitated since they interfere with the analysis for calcium(21).

To precipitate the phosphate, the filtrate from the above was neutralized with ammonium hydroxide using methyl-red as an indicator. One or two drops of ferric chloride solution containing 100 mgm. ferric ion per liter of solution were added. The solution was kept on the alkaline side. This solution was warmed on the hot plate and filtered through a Whatman No. 30 paper. The filtrate was evaporated to dryness on a hot plate, exercising care to avoid spattering and then the residue was ignited at 400° C. for one hour. (The precipitate should be white; a red or pinkish color indicates that all of the organic dye had not been ignited). The ash was dissolved in 25 ml. of 0.2 N HCl and filtered. After filtering the solution was made up to a volume of 100 ml. and analyzed by the flame photometer(50).

The results obtained by the flame photometer for calcium were compared with those obtained by the standard calcium oxalate-titrametric procedure(36). Table 6 shows that very good agreement was found between the two methods.

TABLE 6. CALCIUM IN RYE GRASS AS DETERMINED BY FLAME PHOTOMETER AND TITRAMETRIC METHODS

| Sample No. | Calcium | |
|---|---|---|
| | Flame analysis | Titrametric analysis |
| | percent | percent |
| 1 | 0.241 | 0.248 |
| 2 | 0.320 | 0.318 |
| 3 | 0.241 | 0.246 |
| 4 | 0.230 | 0.234 |
| 5 | 0.253 | 0.252 |
| 6 | 0.270 | 0.278 |
| 7 | 0.265 | 0.268 |
| 8 | 0.253 | 0.252 |
| 9 | 0.265 | 0.268 |
| 10 | 0.265 | 0.268 |
| 11 | 0.265 | 0.268 |
| 12 | 0.253 | 0.252 |
| 13 | 0.265 | 0.268 |
| 14 | 0.344 | 0.340 |
| 15 | 0.378 | 0.370 |

The advantage of the flame photometer was the speed with which the samples could be analyzed. This is particularly true for sodium and potassium.

Strontium($Sr^{89}$) was measured by use of a Geiger-Mueller counter fitted with a thin mica window tube(22). The material was prepared as follows: A 0.5 gm. sample of dried plant material was accurately weighed on an analytical balance in tared metal planchets. The samples were ignited for three to four hours at 450° C. After cooling, 1 ml. of distilled water was placed in the planchets and gently swirled. This formed a slurry of plant ash. The samples were then dried slowly on a steam bath. A smooth and even deposition of the ashed material formed in the bottom of the planchet. Planchets containing the same kind of plant material but from check plants grown without radiostrontium treatments were also ignited and their radioactivity determined. The activity of the check planchets was subtracted from the planchets containing plant material receiving radiostrontium to correct for background radiation. Standards were prepared by adding 1 ml. of the same strontium nitrate solution of known concentration as that which had been added to the soil originally, to the planchets of ashed plant material not treated with radiostrontium. The standard planchets were evaporated to dryness and counted along with the checks and test materials. The counting of the checks, standards, and test planchets was done on the same day so that no error was introduced due to the natural decay of the $Sr^{89}$. From the data obtained by counting the checks, standards, and test planchets, the number of mgm. of $Sr^{89}$ in the sample was easily obtained. An example calculation is as follows: If the average count per second of four check planchets was 0.575, the average count per second of four standard planchets was 20.650, and the test planchet gave a count per second of 43.952. Then 43.957 - 0.575 = 43.382 counts per second for the 0.5 gm.

of plant material corrected for background radiation, and 20.650 - 0.575 = 20.075 counts per second corrected for background. Now if the standard contained 1 ml. of strontium nitrate solution containing 0.04344 mgm. $Sr^{89}$, then one count per second of the standard would be equivalent to 0.04344/20.075 or 0.002164 mgm. of $Sr^{89}$ and the 0.5 gm. sample would contain 0.002164 x 43.382 or 0.09387 mgm. $Sr^{89}$.

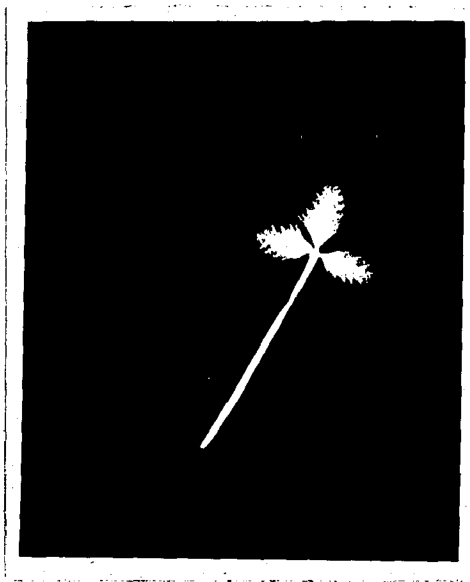
Radioautographs were prepared in this investigation by first pressing and drying the leaf of the plant to be studied. After the leaves were thoroughly dry they were placed against a piece of fine-grained photographic paper in the darkroom. X-ray film was used in some instances but better results were obtained by using Kodak Panchromatic daylight type film. A sheet of black paper was then placed over the leaf, then the layers of paper, film, leaf and paper were placed between two heavy glass plates and firmly pressed together using C-clamps to hold them in place. The plates were kept in absolute darkness during the entire procedure. After a period of time varying from a few days to a few weeks, depending upon the activity of the radioelements in the leaf, the film was removed in total darkness and developed.

## Greenhouse Methods

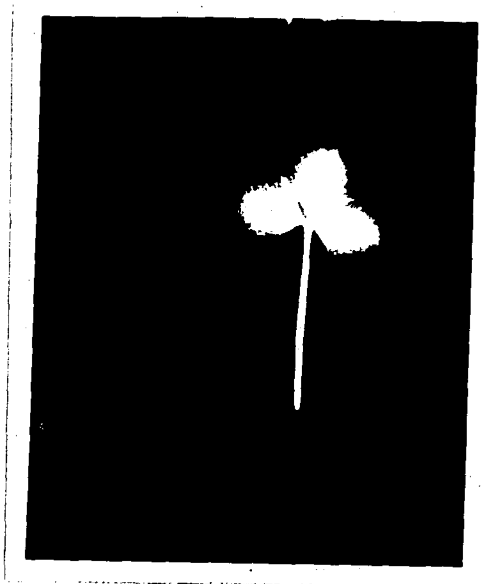
### Pot culture procedures.

In general, pots capable of holding about 1 kg. of soil were used in the greenhouse study. The radiostrontium solution of known concentration was introduced into the dampened soil in the desired quantity. The strontium was thoroughly mixed with the soil by rolling and tumbling. A sample of the strontium solution was saved and used to

PLATE III RADIOAUTOGRAPHS OF BEAN AND TOMATO LEAVES SHOWING DISTRIBUTION OF RADIOSTRONTIUM.



A



B

A. Strontium in soil 90 p.p.m.
B. Strontium in soil 360 p.p.m.

PLATE IV RADIOAUTOGRAPHS OF CLOVER LEAVES CONTAINING DIFFERENT CONCENTRATIONS OF RADIOSTRONTIUM.

prepare standards for radioactivity measurement. When the particular objective required the addition of some substance such as calcium carbonate, dried plant material and etc., this material was rolled into the soil in the dry state before the soil was placed in the pot. After the soils were mixed, they were placed in glazed earthenware pots over approximately one inch of washed gravel, and then seeded to their respective crops. Vermiculite was placed on the surface of the soil to a depth of about one-half inch. Nutrients were added in a water solution at the rate of 150 pounds of N and 200 pounds $P_2O_5$ per acre-six inches in the form of ammonium nitrate and potassium dihydrogen phosphate, respectively. Additional amounts of nitrogen were added after each cutting of rye grass at the rate of 100 pounds per acre in order to prevent any limitation to growth due to nitrogen deficiency.

The crops used throughout the research included Perennial rye grass, Cos Romaine lettuce, Arivat barley, Baart wheat, Marglobe tomatoes, White Dutch clover, Nobel Giant spinach, Crimson Giant radish, Burpee beans and Red kidney beans. The pots were thinned in the case of tomatoes and lettuce to one plant per pot and for beans to four plants per pot. The crops were harvested either at prime-market-stage or full maturity, depending upon the problem. In the case of rye grass, harvesting took place after intervals of four weeks, six weeks, and eight weeks for the first, second and third cutting, respectively. All plant material was dried in an oven at 50° C. for at least forty-eight hours and yield data obtained by weighing on an oven-dry basis. The plant material was then ground to pass through a 60-mesh screen before analysis.

# RESULTS

## The Absorption of Added Strontium by Plants from Soils as Influenced by Native Calcium

Strontium and calcium have been shown to be absorbed equally well by plants(42). In fact, plants do not appear to be able to distinguish between the two elements in this respect. Thus the amount and nature of calcium in soils might be expected to influence the adsorption of added strontium by plants. This relationship, between soil calcium and soluble strontium, was studied by adding strontium nitrate to soils having a wide range of native calcium and growing test crops on the treated soils. The amount of calcium and strontium absorbed from the various soils by the test crop was determined and the relationship between added strontium and soil calcium calculated from the data obtained.

The calcium in the soils used in this investigation was characterized as, (1) carbonate calcium, (2) water-soluble calcium, (3) calcium soluble in a 1:1 hydrochloric acid solution, (4) total calcium as determined by sodium carbonate fusion analysis, (5) "active" calcium and (6) exchangeable calcium as already shown in Table 1.

### Rye grass.

Rye grass grown on Laveen sandy loam, which had the highest calcium carbonate content, absorbed more strontium than any of the other soils, according to data in Table 7. On the other hand, rye grass grown on

TABLE 7. THE AMOUNT OF CALCIUM AND STRONTIUM ABSORBED BY RYE GRASS FROM TEN ARIZONA SOILS OF VARYING CONTENT OF NATIVE CALCIUM

| Soil | Yield per pot* | Strontium** in plant, Cuttings 1 | Strontium** in plant, Cuttings 2 | Strontium** in plant, Cuttings 3 | Ratio of Ca/Sr, Cuttings 1 | Ratio of Ca/Sr, Cuttings 2 | Ratio of Ca/Sr, Cuttings 3 | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|---|---|---|---|
| | gm. | µgm./gm. | µgm./gm. | µgm./gm. | | | | mgm. | percent |
| Flagstaff sandy loam | 25.0 | 129 | 108 | 78 | 12 | 21 | 19 | 2.511 | 1.67 |
| Mohave sandy clay loam | 19.5 | 153 | 130 | 118 | 9 | 16 | 18 | 2.513 | 1.66 |
| Tucson sandy loam | 18.0 | 245 | 164 | 174 | 4 | 6 | 10 | 3.367 | 2.24 |
| Tubac sandy loam | 15.5 | 242 | 197 | 184 | 5 | 8 | 9 | 3.013 | 2.01 |
| Tucson sandy loam | 16.0 | 266 | 206 | 185 | 5 | 7 | 8 | 3.308 | 2.21 |
| Pima clay loam | 29.6 | 45 | 40 | 34 | 14 | 54 | 57 | 1.137 | 0.76 |
| Tucson sandy loam | 14.5 | 200 | 176 | 158 | 6 | 9 | 9 | 2.448 | 1.63 |
| Gila sandy clay loam | 19.1 | 86 | 74 | 72 | 13 | 21 | 20 | 1.440 | 0.96 |
| Laveen loamy sand | 17.2 | 230 | 200 | 148 | 8 | 6 | 9 | 2.932 | 1.95 |
| Laveen sandy loam | 19.2 | 269 | 218 | 178 | 7 | 6 | 7 | 3.881 | 2.59 |

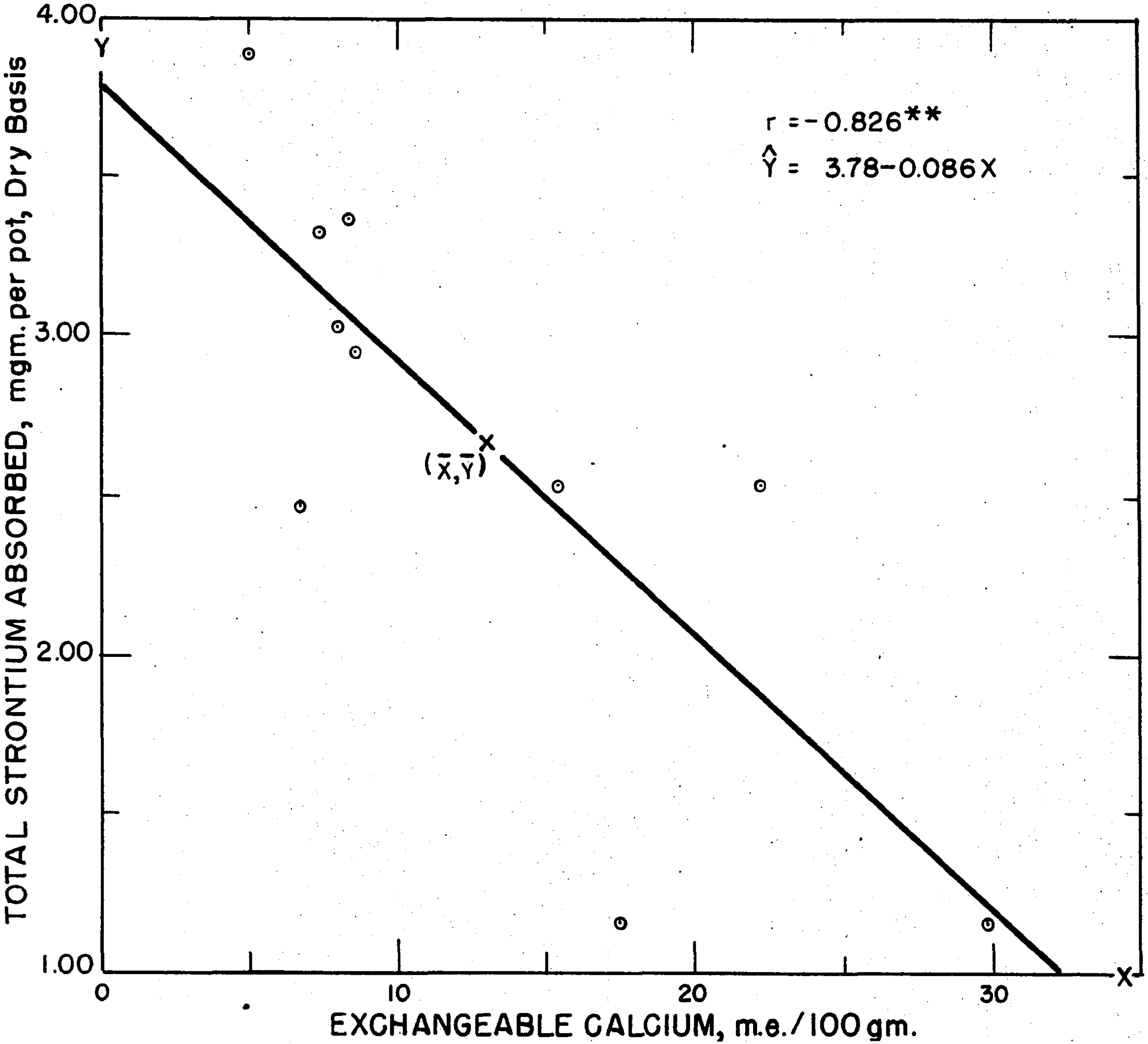
*Each figure represents a mean of 3 pots and is calculated on an oven-dry weight basis.
**Pots contained 3 kg. soil and received 50 p.p.m. Sr as $Sr(NO_3)_2$.

Pima clay loam, a soil intermediate in calcium carbonate content, absorbed the least amount of strontium. The total uptake of strontium by the Flagstaff sandy loam was almost identical with that of the Tucson sandy loam even though the former soil contained only trace amounts of calcium carbonate whereas the latter contained 3.7 percent calcium carbonate, Table 7. The correlation between amount of calcium carbonate in the soil and the strontium absorbed by rye grass was not significant even at the 5 percent level.

Strontium absorption by rye grass was also found to be independent of water-soluble, 1:1 hydrochloric acid soluble, total, and "active" calcium in these soils. The correlation coefficient fell below significance at the 5 percent level in all instances. Likewise, the ratio of calcium to strontium in the plant was not found to be significantly correlated with the above mentioned forms of calcium. It was observed that, in general, the Ca/Sr ratio increased with successive cuttings of rye grass, which was attributed to the fact that the uptake of strontium decreased with each cutting while the calcium content changed only slightly as compared to the decrease in strontium content, Table 7.

By comparing the total strontium absorbed by rye grass with the exchangeable calcium of the soil, a highly significant correlation coefficient was found. Figure 1 shows that as the amount of exchangeable calcium in soils increases, the total amount of strontium absorbed by the grass decreases. The correlation between the amount of strontium absorbed per gram of plant material and the exchangeable calcium was even more highly significant, Figure 2.

To further verify the fact that the native calcium carbonate content



TOTAL STRONTIUM ABSORBED, mgm. per pot, Dry Basis
4.00
3.00
2.00
1.00
Y
X
0
10
20
30
EXCHANGEABLE CALCIUM, m.e./100 gm.
r = -0.826**
Ŷ = 3.78-0.086X
(X̄, Ȳ)

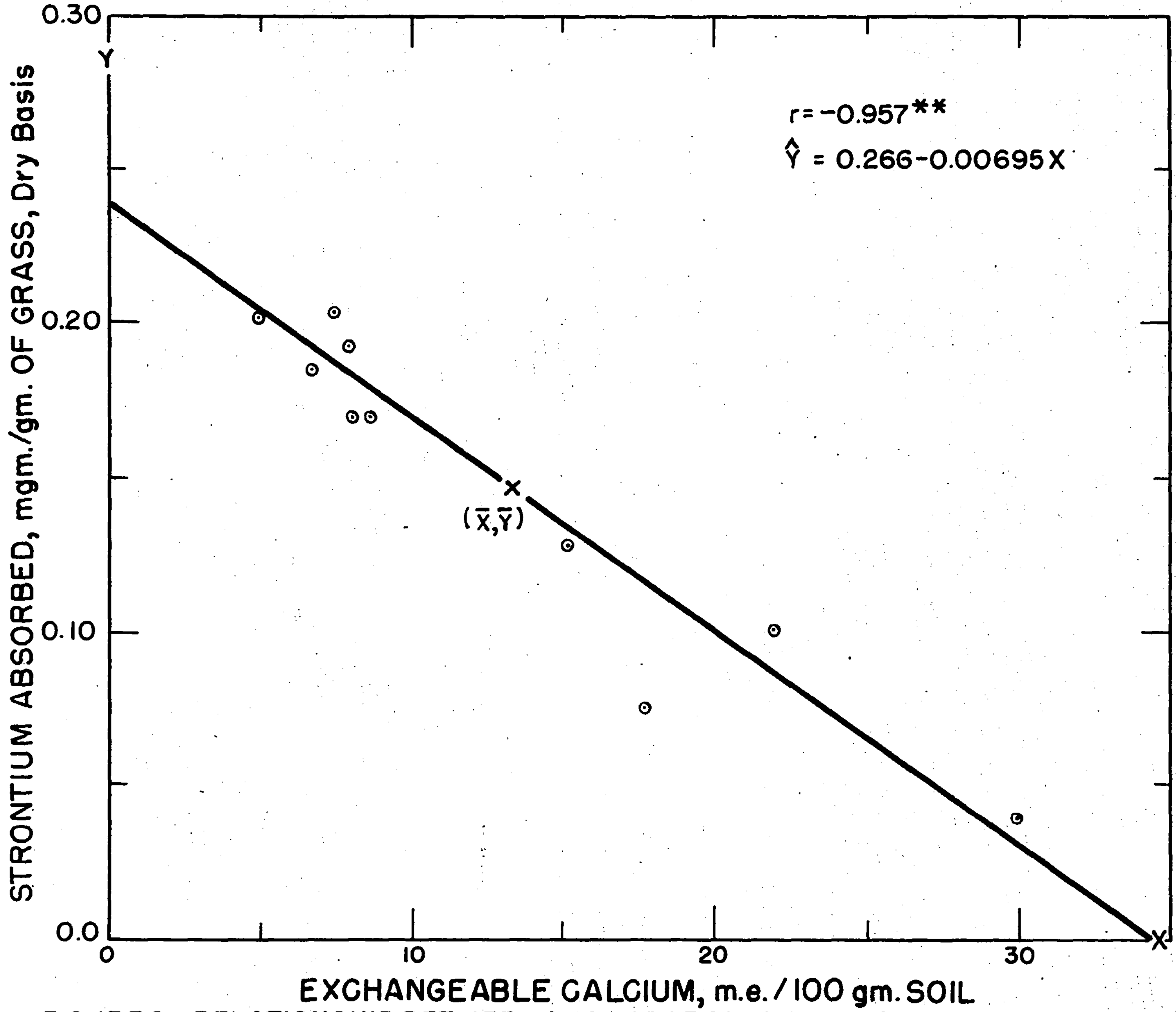



FIGURE 2.- RELATIONSHIP BETWEEN AMOUNT OF STRONTIUM ABSORBED PER UNIT DRY WEIGHT OF RYE GRASS AND EXCHANGEABLE CALCIUM CONTENT OF ARIZONA SOILS.

of the soil has little effect upon the absorption by plants of strontium when added in a soluble form, two noncalcareous acid forest soils from the humid Midwest were studied along with four calcareous soils of Arizona. Inspection of Tables 8, 9, and 10 shows that the absorption of strontium by the three test crops, rye grass, wheat, and lettuce, was as great or greater from the desert soils having an abundant supply of native calcium carbonate as from the noncalcareous forested soils from Iowa and Indiana. Again, there was no significant correlation between the native soil calcium carbonate and the strontium absorbed by the rye grass, Table 8. This was also true for the water-soluble, 1:1 HCl soluble, total and "active" calcium. The rye grass grown on Clinton silt loam and Miami silt loam absorbed strontium in amounts of the same order of magnitude as the highly calcareous Tucson sandy loam and Laveen loamy sand, Table 8. A high degree of correlation, significant at the 1 percent level, was found to exist for the six soils between the total strontium absorbed and the exchangeable calcium, Figure 3. The correlation coefficient had a value of - 0.963.

The Ca/Sr ratio of the plant again increased somewhat with successive cuttings.

The amount of strontium absorbed by three cuttings of rye grass calculated as percentage of the total added at the rate of 40 p.p.m., did not exceed 4 percent from any of the soils.

<u>Wheat</u>.

The results obtained by using wheat as the test crop were very similar to those for rye grass, Table 9. The native calcium carbonate

TABLE 8. THE AMOUNT OF STRONTIUM ABSORBED BY RYE GRASS FROM SIX DIFFERENT SOILS OF VARYING CONTENT OF NATIVE CALCIUM

| Soil | Yield per pot* | Strontium** in plant Cuttings | | | Ratio of Ca/Sr Cuttings | | | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 1 | 2 | 3 | | |
| | gm. | μgm./gm. | μgm./gm. | μgm./gm. | | | | mgm. | percent |
| Clinton silt loam | 18.1 | 129 | 69 | 57 | 13 | 27 | 37 | 1.280 | 3.2 |
| Miami silt loam | 14.9 | 174 | 137 | 133 | 14 | 19 | 22 | 1.386 | 3.5 |
| Mohave sandy clay loam | 9.6 | 89 | 93 | 90 | 18 | 19 | 21 | 0.864 | 2.2 |
| Pima clay loam | 13.0 | 32 | 43 | 38 | 40 | 67 | 70 | 0.488 | 1.2 |
| Tucson sandy loam | 10.1 | 116 | 149 | 201 | 19 | 22 | 18 | 1.614 | 4.0 |
| Laveen loamy sand | 7.5 | 139 | 189 | 218 | 20 | 12 | 10 | 1.334 | 3.3 |

*Each figure represents a mean of 3 pots and 3 cuttings and is calculated on an oven-dry weight basis.
**Pots contained 1 kg. soil and received 40 p.p.m. Sr as $Sr(No_3)_2$.

TABLE 9. THE AMOUNT OF STRONTIUM ABSORBED BY WHEAT FROM DIFFERENT SOILS OF VARYING CONTENT OF NATIVE CALCIUM

| Soil | Yield per pot+ | | Strontium in plant | | Ca/Sr ratio | | Total Sr absorbed per pot | | Sr absorbed per pot as percentage total added | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Straw | Grain | Straw | Grain | Straw | Grain | Straw | Grain | Straw | Grain |
| | gm. | gm. | µgm./gm. | µgm./gm. | | | mgm. | mgm. | percent | percent |
| Rate of application of $Sr(NO_3)_2$—40 p.p.m. Sr* | | | | | | | | | | |
| Flagstaff sandy loam | 57.8 | 8.6 | 79 | 7 | 12 | 17 | 4.55 | 0.057 | 2.63 | 0.048 |
| Mohave sandy clay loam | 59.5 | 6.3 | 84 | 8 | 11 | 12 | 5.01 | 0.047 | 2.98 | 0.030 |
| Tucson sandy loam | 51.7 | 2.8 | 173 | 10 | 6 | 8 | 8.95 | 0.029 | 4.63 | 0.008 |
| Tubac sandy loam | 44.9 | 6.3 | 235 | 11 | 5 | 13 | 10.52 | 0.072 | 4.72 | 0.045 |
| Tucson sandy loam | 54.2 | 6.3 | 179 | 12 | 8 | 13 | 9.71 | 0.074 | 5.26 | 0.047 |
| Pima clay loam | 74.2 | 11.0 | 36 | 3 | 20 | 36 | 2.67 | 0.037 | 1.98 | 0.041 |
| Tucson sandy loam | 48.5 | 7.2 | 211 | 15 | 7 | 6 | 10.24 | 0.109 | 4.97 | 0.078 |
| Gila sandy clay loam | 61.9 | 4.8 | 57 | 7 | 14 | 19 | 3.55 | 0.034 | 2.20 | 0.016 |
| Laveen loamy sand | 53.7 | 8.7 | 197 | 10 | 7 | 9 | 10.59 | 0.092 | 5.29 | 0.080 |
| Laveen sandy loam | 52.2 | 3.5 | 209 | 10 | 5 | 8 | 10.89 | 0.058 | 5.68 | 0.020 |
| Rate of application of $Sr(NO_3)_2$—50 p.p.m. Sr** | | | | | | | | | | |
| Clinton silt loam | 25.3 | 1.09 | 99 | 4 | 39 | 46 | 2.495 | 0.0048 | 6.2 | 0.012 |
| Miami silt loam | 25.8 | 0.76 | 123 | 4 | 30 | 37 | 3.168 | 0.0031 | 7.9 | 0.078 |
| Mohave sandy clay loam | 29.3 | 0.31 | 49 | 3 | 47 | 69 | 1.439 | 0.0008 | 3.6 | 0.002 |
| Pima clay loam | 36.6 | 0.60 | 25 | T | 93 | 225 | 0.908 | 0.0003 | 2.3 | 0.001 |
| Tucson sandy loam | 29.2 | 0.41 | 77 | 2 | 37 | 44 | 2.237 | 0.0007 | 5.6 | 0.002 |
| Laveen loamy sand | 28.3 | 0.64 | 83 | 3 | 33 | 24 | 2.360 | 0.0021 | 5.9 | 0.005 |

*Pots contained 1 kg. soil.
**Pots contained 3 kg. soil.
+Each figure represents a mean of 3 pots and is calculated on an oven-dry weight basis.

TABLE 10. THE AMOUNT OF STRONTIUM ABSORBED BY LETTUCE FROM SIX DIFFERENT SOILS OF VARYING CONTENT OF NATIVE CALCIUM

| Soil | Yield per pot* | Strontium** in plant | Ratio of Ca/Sr | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|
| | gm. | µgm./gm. | | mgm. | percent |
| Clinton silt loam | 10.3 | 169 | 58 | 1.741 | 4.4 |
| Miami silt loam | 4.8 | 206 | 41 | 0.989 | 2.5 |
| Mohave sandy clay loam | 8.3 | 111 | 84 | 0.921 | 2.3 |
| Pima clay loam | 9.4 | 47 | 124 | 0.442 | 1.1 |
| Tucson sandy loam | 0.3 | 252 | 69 | 0.076 | 0.2 |
| Laveen loamy sand | 0.7 | 432 | 69 | 0.302 | 0.8 |

*Each figure represents a mean of 3 pots and is calculated on an oven-dry weight basis.
**Pots contained 1 kg. soil and received 40 p.p.m. Sr as $Sr(NO_3)_2$.

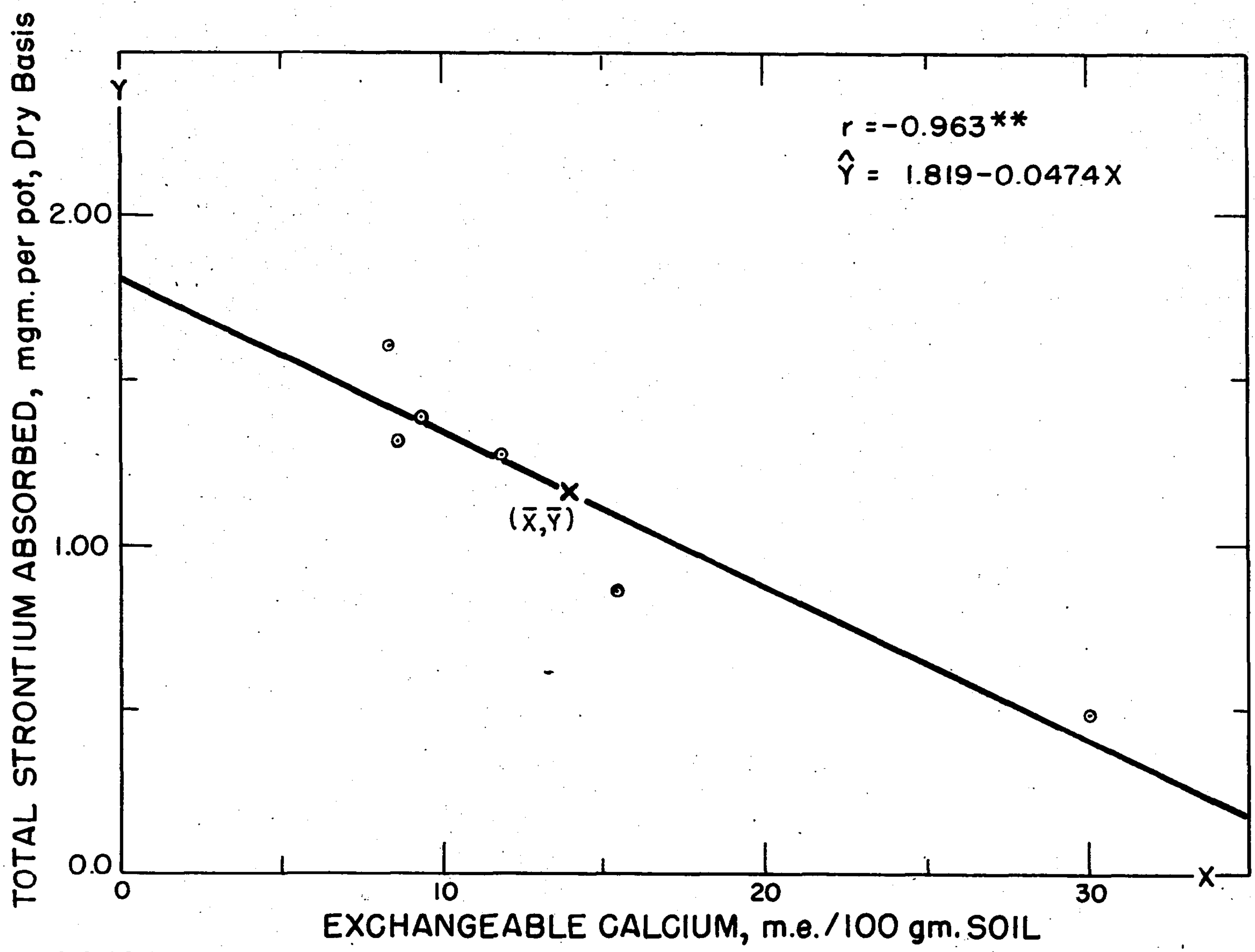
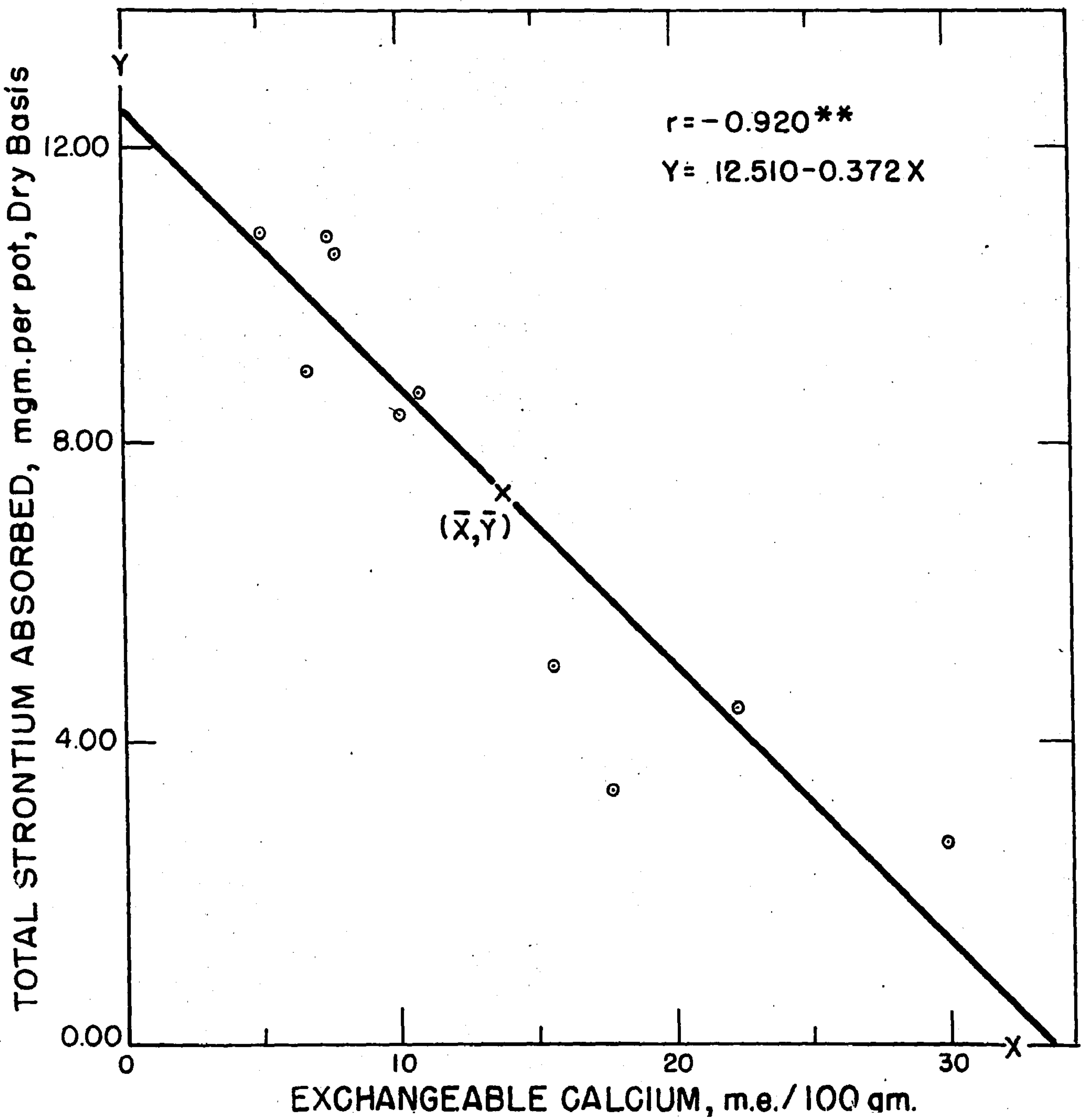
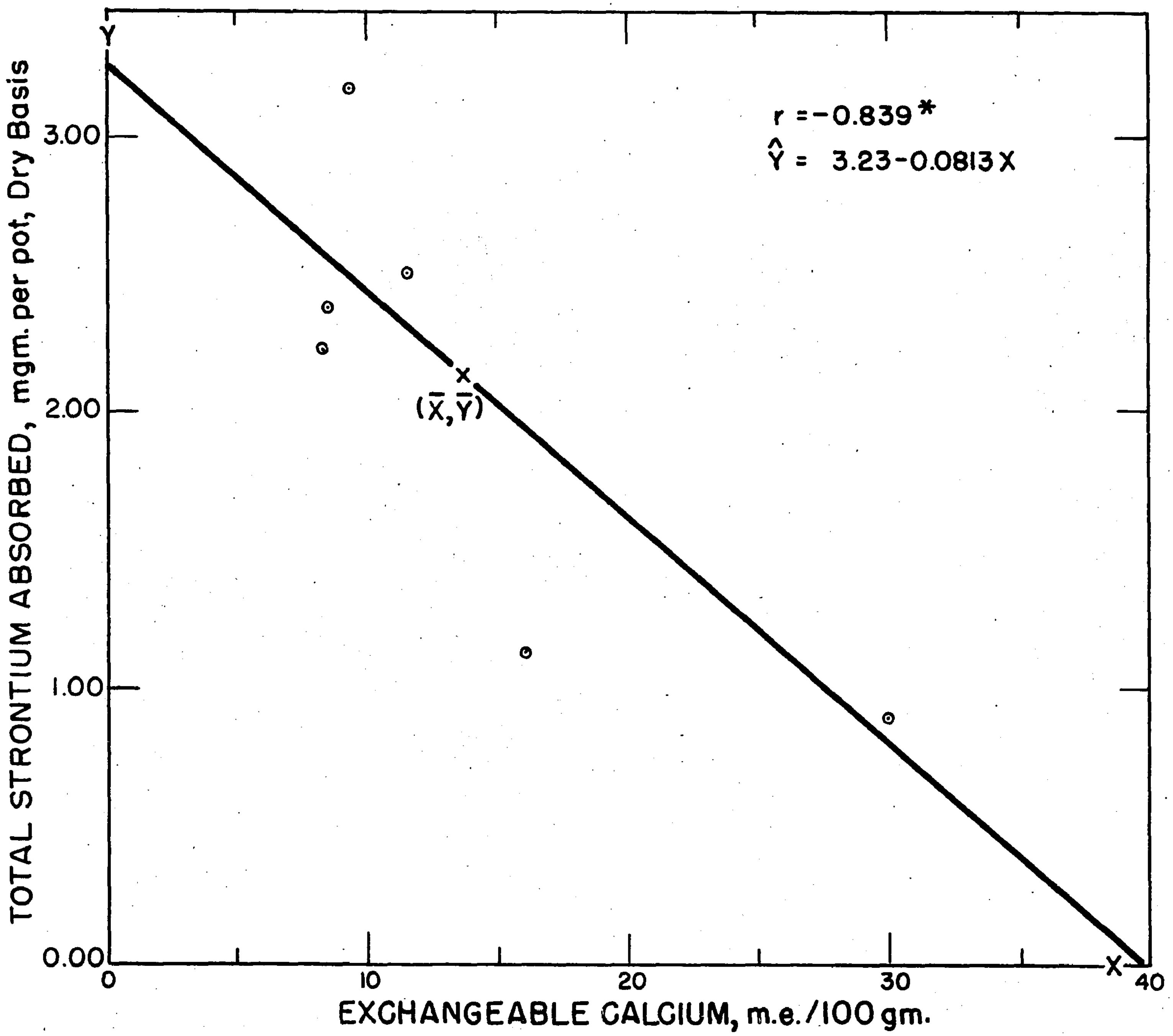



FIGURE 3.-RELATIONSHIP BETWEEN TOTAL AMOUNT OF STRONTIUM ABSORBED BY RYE GRASS AND EXCHANGEABLE CALCIUM CONTENT OF DIFFERENT SOILS.

of the soil had little, if any, effect on the strontium absorbed by wheat. Table 9 shows that the wheat grown in the noncalcareous Flagstaff sandy loam and the highly calcareous Laveen sandy loam took up almost identical amounts of strontium. The wheat grown on Tubac sandy loam, Tucson sandy loam, Laveen loamy sand, and Laveen sandy loam, all absorbed practically the same amount of strontium in the straw despite the fact that these soils contained calcium carbonate in widely different amounts, Table 9. A comparison of strontium uptake by wheat from all ten soils also indicated that there was no significant correlation between strontium absorption and the other forms of calcium, i.e. water-soluble, 1:1 hydrochloric acid soluble, total, and "active" calcium. On the other hand, strontium absorption by wheat was significantly correlated with the amount of exchangeable calcium of the soils. The correlation coefficient of − 0.920 exceeded the value for significance at the 1 percent level, Figure 4.

A similar experiment, using four of the soils reported above and two noncalcareous Midwest soils with wheat as the test crop was conducted. The results again indicated that there was no significant correlation between strontium absorption and the various forms of calcium except exchangeable calcium. The correlation between total strontium absorbed and exchangeable calcium was significant at the 5 percent level, Figure 5. Almost negligible quantities of strontium were found in the seed, Table 9. The wheat grain contained very little of the added strontium, as compared with the amount contained in the straw and roots. Almost negligible amounts were found in the grain harvested from Pima clay loam, Table 9.


TOTAL STRONTIUM ABSORBED, mgm. per pot, Dry Basis
EXCHANGEABLE CALCIUM, m.e./100 gm.
r = -0.920**
Y = 12.510-0.372 X
(X̄, Ȳ)
Y
X
0.00
4.00
8.00
12.00
0
10
20
30



TOTAL STRONTIUM ABSORBED, mgm. per pot, Dry Basis
0.00
1.00
2.00
3.00
Y
r =-0.839*
$\hat{Y}$ = 3.23-0.0813X
X
$(\bar{X},\bar{Y})$
0
10
20
30
40
X
EXCHANGEABLE CALCIUM, m.e./100 gm.

Lettuce.

Cos Romaine lettuce was used as a test crop for the absorption of strontium on the same six soils as those seeded to rye grass and wheat. Although the total strontium absorbed decreased somewhat with increasing calcium carbonate content of the soil, the correlation coefficient between these two values was far below the minimum value required for significance at the 5 percent level, being - 0.610. No significant correlation was found between strontium uptake and the amounts of the various forms of soil calcium. However, the correlation coefficient for absorbed strontium and exchangeable calcium was - 0.734, which is only slightly below the minimum value of - 0.754 for significance for six observations. Table 10 shows that the yield per pot of the lettuce was extremely low. The plants developed chlorosis and failed to grow properly in the soils highest in calcium carbonate. Chlorosis was particularly noticeable on Laveen loamy sand. Chlorosis of lettuce in the field is frequently associated with soils having high amounts of calcium carbonate and caliche. When the results for the highly calcareous Laveen loamy sand were disregarded and the correlation for the remaining five soils determined, the correlation coefficient was - 0.921. This is significant at the 5 percent level for five observations, Figure 6.

## The Absorption of Added Strontium by Plants from Mixed Soils of Different Native Calcium Carbonate Content

To gain further information on the effect of native soil calcium on strontium absorption by plants, the two noncalcareous forest soils from the Midwest were mixed in varying proportions with the calcareous

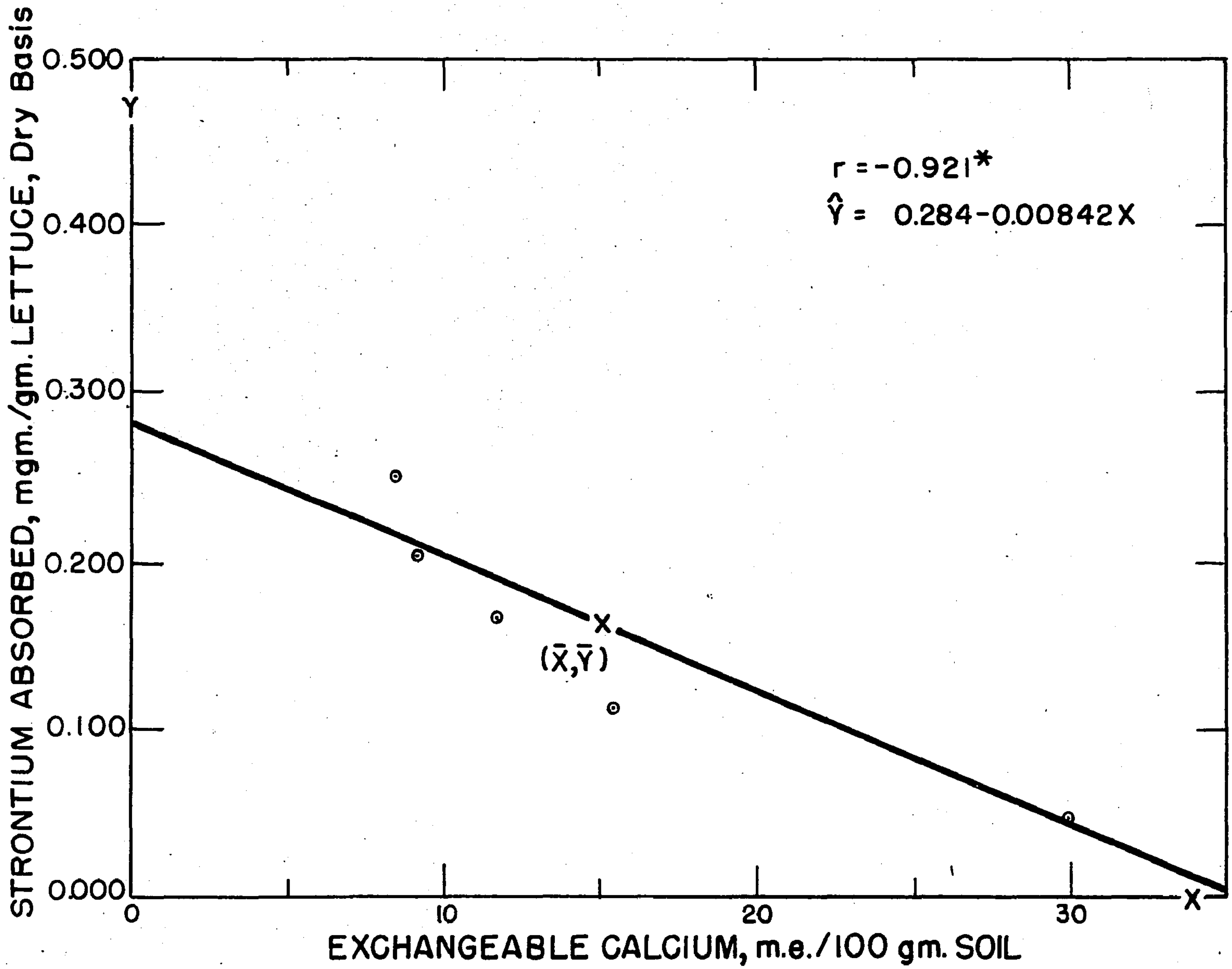



FIGURE 6.- RELATIONSHIP BETWEEN TOTAL AMOUNT OF STRONTIUM ABSORBED BY LETTUCE AND EXCHANGEABLE CALCIUM CONTENT OF DIFFERENT SOILS.

soils of Arizona, treated with radiostrontium and planted to rye grass, Table 11. Rye grass grown on soil, made by mixing equal parts of Laveen loamy sand and Clinton silt loam to give a final $CaCO_3$ content of 5 percent, had a strontium content about the same as that grown on the noncalcareous Clinton silt loam alone. This amount was considerably lower than that of rye grass grown on Laveen loamy sand alone. Compare data in Tables 11 and 8. Grass harvested from a mixture of Laveen loamy sand and Miami silt loam, contained less strontium than rye grass from either soil alone. However, there was no significant difference between the final calcium carbonate content of the mixed soils and the amount of strontium absorbed. The correlation coefficient was found to be - 0.676. Thus, again the calcium carbonate content of soil was shown to have little effect upon strontium absorption by the plant. The exchangeable calcium content of the mixed soils was calculated from known weights of each soil used in the mixture in order to evaluate the effect of this factor on strontium absorption, Table 12. The correlation between this value for the exchangeable calcium of the different soil mixtures and the total strontium absorbed by the rye grass gave a correlation coefficient of - 0.897, Figure 7. The value is significant at the 5 percent level. It can easily be seen from Table 11 that the Pima clay loam had a dominant effect on the absorption of strontium in all soil mixtures. The over-all effect of mixing Pima clay loam with either calcareous or noncalcareous soils in various proportions was to keep the absorption of strontium at a level such that the plant material growing on these mixtures had a final concentration of strontium very similar to that of material grown on Pima clay loam alone and not of

TABLE 11. THE AMOUNT OF STRONTIUM ABSORBED BY RYE GRASS FROM MIXTURES OF SOILS OF DIFFERENT NATIVE CALCIUM CONTENT

| Soils mixed | Final $CaCO_3$ content | Yield per pot* | Strontium** in plant, Cuttings 1 | Strontium** in plant, Cuttings 2 | Strontium** in plant, Cuttings 3 | Ratio of Ca/Sr, Cuttings 1 | Ratio of Ca/Sr, Cuttings 2 | Ratio of Ca/Sr, Cuttings 3 | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|---|---|---|---|---|
| | percent | gm. | µgm./gm. | µgm./gm. | µgm./gm. | | | | mgm. | percent |
| Clinton silt loam and Laveen loamy sand | 5.0 | 8.7 | 105 | 66 | 50 | 29 | 44 | 47 | 0.612 | 1.53 |
| Miami silt loam and Laveen loamy sand | 5.0 | 9.7 | 117 | 78 | 57 | 26 | 49 | 47 | 0.766 | 1.91 |
| Pima clay loam and Laveen loamy sand | 5.0 | 10.1 | 35 | 40 | 28 | 69 | 67 | 95 | 0.340 | 0.85 |
| Pima clay loam and Laveen loamy sand | 2.5 | 12.9 | 28 | 30 | 23 | 70 | 81 | 113 | 0.341 | 0.85 |
| Clinton silt loam and Pima clay loam | 0.8 | 11.7 | 37 | 28 | 21 | 36 | 89 | 98 | 0.329 | 0.82 |
| Miami silt loam and Pima clay loam | 0.8 | 11.9 | 40 | 37 | 26 | 35 | 66 | 89 | 0.318 | 0.80 |

*Each figure represents a mean of 3 pots and is calculated on an oven-dry weight basis.
**Pots contained 1 kg. soil and received 40 p.p.m. Sr as $Sr(NO_3)_2$.

TABLE 12. EXCHANGEABLE CALCIUM CONTENT OF MIXED SOILS

| Soils mixed | Initial exchangeable calcium | Approximate ratio mixed | Weight of soil | Final exchangeable calcium |
|---|---|---|---|---|
| | m.e./100 gm. | | gm. | m.e./100 gm. |
| Clinton silt loam and | 11.7 | | 500 | |
| Laveen loamy sand | 8.6 | 1:1 | 500 | 10.1 |
| Miami silt loam and | 9.3 | | 500 | |
| Laveen loamy sand | 8.6 | 1:1 | 500 | 9.0 |
| Pima clay loam and | 30.0 | | 609 | |
| Laveen loamy sand | 8.6 | 6:4 | 390 | 22.6 |
| Pima clay loam and | 30.0 | | 896 | |
| Laveen loamy sand | 8.6 | 9:1 | 103 | 24.8 |
| Clinton silt loam and | 11.7 | | 500 | |
| Pima clay loam | 30.0 | 1:1 | 500 | 20.9 |
| Miami silt loam and | 9.3 | | 500 | |
| Pima clay loam | 30.0 | 1:1 | 500 | 19.7 |

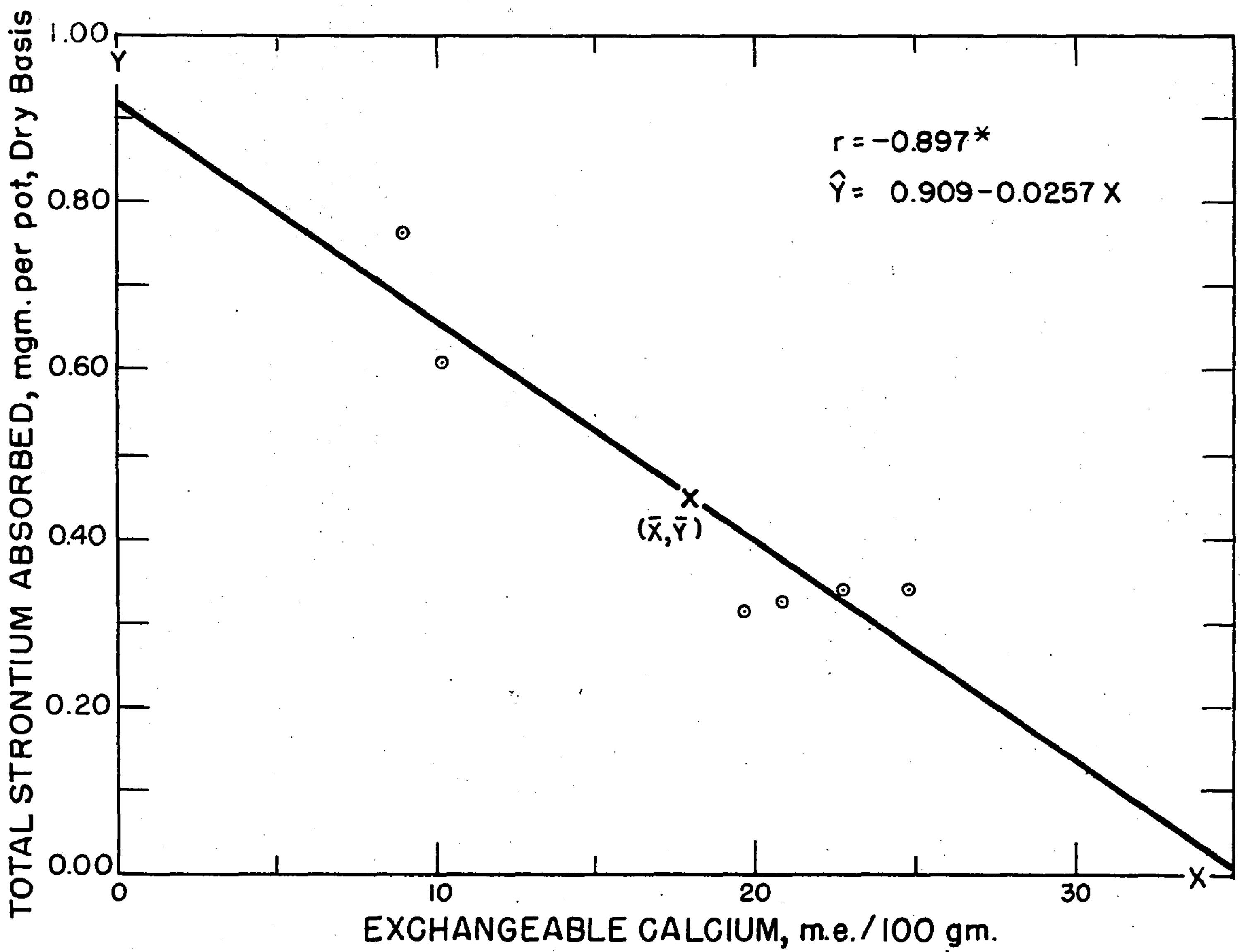



FIGURE 7.- RELATIONSHIP BETWEEN TOTAL AMOUNT OF STRONTIUM ABSORBED BY RYE GRASS AND EXCHANGEABLE CALCIUM CONTENT OF SOILS MIXED TO OBTAIN PREDETERMINED LEVELS OF CALCIUM CARBONATE.

that of the other soils. The factor in the Pima clay loam which appears to influence profoundly the absorption of soluble strontium is the high exchangeable calcium content.

## The Absorption of Added Strontium by Plants from Soils as Influenced by Addition of Calcium Carbonate

### Rye grass.

Since calcium and strontium have been found to be competitive in plant nutrition, liming a soil presumably would reduce the absorption of strontium by plants. Thus, a method for the partial control of the industrial waste of uranium fission, radiostrontium could be realized. Addition of precipitated $CaCO_3$ at the rate of two tons per acre (approximately 800 p.p.m.) to two noncalcareous soils, Clinton and Miami silt loams, reduced the absorption of strontium approximately 12 percent and 17 percent, respectively, Table 13. In another study using calcareous Mohave sandy clay loam, calcium carbonate was introduced into the soil at extremely high concentrations, 0, 5, 10 and 20 percent of the soil on an air-dry weight basis. Table 14 shows that the addition of calcium carbonate to this soil had no significant effect on strontium absorption. In fact, grass grown in pots containing 20 percent added calcium carbonate showed practically as much absorbed strontium as that grown without additions of calcium carbonate. The ratio of Ca to Sr in the plant also showed no relationship between strontium uptake and calcium carbonate content.

### Barley.

In another experiment, barley was grown as the test crop on Mohave

TABLE 13. THE AMOUNT OF STRONTIUM ABSORBED BY RYE GRASS FROM CLINTON AND MIAMI SILT LOAM AS INFLUENCED BY ADDITION OF CALCIUM CARBONATE

| Soil | $CaCO_3$ added | Yield per pot* | Strontium** in plant Cuttings 1 | 2 | 3 | Ratio of Ca/Sr Cuttings 1 | 2 | 3 | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|---|---|---|---|---|
| | tons/A | gm. | μgm./gm. | μgm./gm. | μgm./gm. | | | | mgm. | percent |
| Clinton silt loam | 0 | 9.4 | 107 | 69 | 57 | 13 | 27 | 37 | 0.683 | 1.7 |
| Clinton silt loam | 2 | 10.0 | 89 | 55 | 44 | 19 | 50 | 58 | 0.598 | 1.6 |
| Miami silt loam | 0 | 9.0 | 174 | 137 | 133 | 14 | 19 | 22 | 1.336 | 3.3 |
| Miami silt loam | 2 | 9.2 | 168 | 129 | 83 | 21 | 38 | 41 | 1.115 | 2.9 |

*Each figure represents a mean of 2 pots and is calculated on an oven-dry weight basis.
**Pots contained 1 kg. of soil and received 40 p.p.m. Sr as $Sr(NO_3)_2$.

TABLE 14. THE AMOUNT OF STRONTIUM ABSORBED BY RYE GRASS FROM MOHAVE SANDY CLAY LOAM AS INFLUENCED BY ADDITION OF CALCIUM CARBONATE

| $CaCO_3$ added | Yield per pot* | Strontium** in plant | | | Ratio of Ca/Sr | | | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|---|---|---|---|
| | | Cuttings | | | Cuttings | | | | |
| | | 1 | 2 | 3 | 1 | 2 | 3 | | |
| percent | gm. | µgm./gm. | µgm./gm. | µgm./gm. | | | | mgm. | percent |
| 0 | 18.3 | 153 | 234 | 118 | 20 | 23 | 16 | 2.648 | 3.3 |
| 5 | 24.6 | 90 | 169 | 90 | 33 | 32 | 29 | 1.517 | 1.9 |
| 10 | 28.0 | 107 | 156 | 123 | 25 | 62 | 24 | 1.847 | 2.3 |
| 20 | 16.9 | 128 | 209 | 117 | 23 | 50 | 34 | 2.260 | 2.8 |

*Each figure represents a mean of 2 pots and is calculated on an oven-dry weight basis.
**Pots contained 4 kg. of soil and received 20 p.p.m. Sr as $Sr(NO_3)_2$.

sandy clay loam. The results were similar to those of rye grass, Table 15. There was no significant correlation between the amount of strontium absorbed and the added calcium carbonate. In the grain the total amount of strontium absorbed was almost constant; in the chaff, which consisted of the awns and hulls from the threshed grain, absorption varied; in the straw, the strontium concentration decresed as the amount of added calcium carbonate was increased. This tendency was also observed in the roots. When the total amount of strontium absorbed by the entire plant was summed up, there was a reduction in amount strontium absorbed as the amount of calcium carbonate added to soil was increased beyond 5 percent, Figure 8.

**Radish, tomato and lettuce.**

Further study on the effect of addition of calcium carbonate to soils on strontium absorption was made using two calcareous soils, Mohave sandy clay loam and Pima sandy loam with the vegetable crops Crimson Giant radish, Marglobe tomatoes and Cos Romain lettuce as the test crops.

In general, addition of calcium carbonate reduced the total amount of strontium absorbed by each of the crops grown on both soils, Tables 16, 17 and 18. This result was probably due more to the reduced yield rather than any dilution effect on strontium due to the calcium carbonate. The amount of strontium absorbed per unit weight of plant material was not significantly influenced by the addition of $CaCO_3$. The yield of crops grown on the Pima sandy loam was less affected by the $CaCO_3$ than those grown on Mohave sandy loam, Tables 16, 17 and 18. Applications of $CaCO_3$ considerably reduced the yield of the crops grown

TABLE 15. THE AMOUNT OF STRONTIUM ABSORBED BY BARLEY FROM MOHAVE SANDY CLAY LOAM TREATED WITH RADIOSTRONTIUM AS INFLUENCED BY ADDITION OF CALCIUM CARBONATE AT DIFFERENT RATES

| $CaCO_3$ added | Yield per pot* | | | | Strontium** in plant | | | |
|---|---|---|---|---|---|---|---|---|
| | Grain | Chaff | Straw | Roots | Grain | Chaff | Straw | Roots |
| percent | gm. | gm. | gm. | gm. | µgm./gm. | µgm./gm. | µgm./gm. | µgm./gm. |
| 0 | 6.8 | 10.9 | 37.9 | 12.5 | 16 | 38 | 112 | 97 |
| 5 | 7.0 | 9.6 | 36.2 | 10.9 | 18 | 52 | 117 | 107 |
| 10 | 6.6 | 10.5 | 36.3 | 9.9 | 20 | 49 | 96 | 97 |
| 20 | 7.8 | 12.4 | 45.5 | 13.9 | 16 | 38 | 71 | 50 |

| $CaCO_3$ added | Total Sr absorbed per pot | | | | | Sr absorbed per pot as percentage total added | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Grain | Chaff | Straw | Roots | Sum | Grain | Chaff | Straw | Roots | Sum |
| percent | mgm. | mgm. | mgm. | mgm. | mgm. | percent | percent | percent | percent | percent |
| 0 | 0.111 | 0.420 | 4.245 | 0.972 | 5.748 | 0.14 | 0.53 | 5.31 | 1.23 | 7.19 |
| 5 | 0.127 | 0.495 | 4.246 | 1.071 | 5.939 | 0.16 | 0.62 | 5.31 | 1.34 | 7.42 |
| 10 | 0.130 | 0.517 | 3.485 | 0.944 | 5.076 | 0.16 | 0.65 | 4.36 | 1.18 | 6.35 |
| 20 | 0.128 | 0.477 | 3.237 | 0.502 | 4.344 | 0.16 | 0.60 | 4.05 | 0.63 | 5.43 |

*Each figure represents a mean of 2 pots and is calculated on an oven-dry weight basis.

**Pots contained 4 kg. soil and received 20 p.p.m. Sr as $Sr(NO_3)_2$.

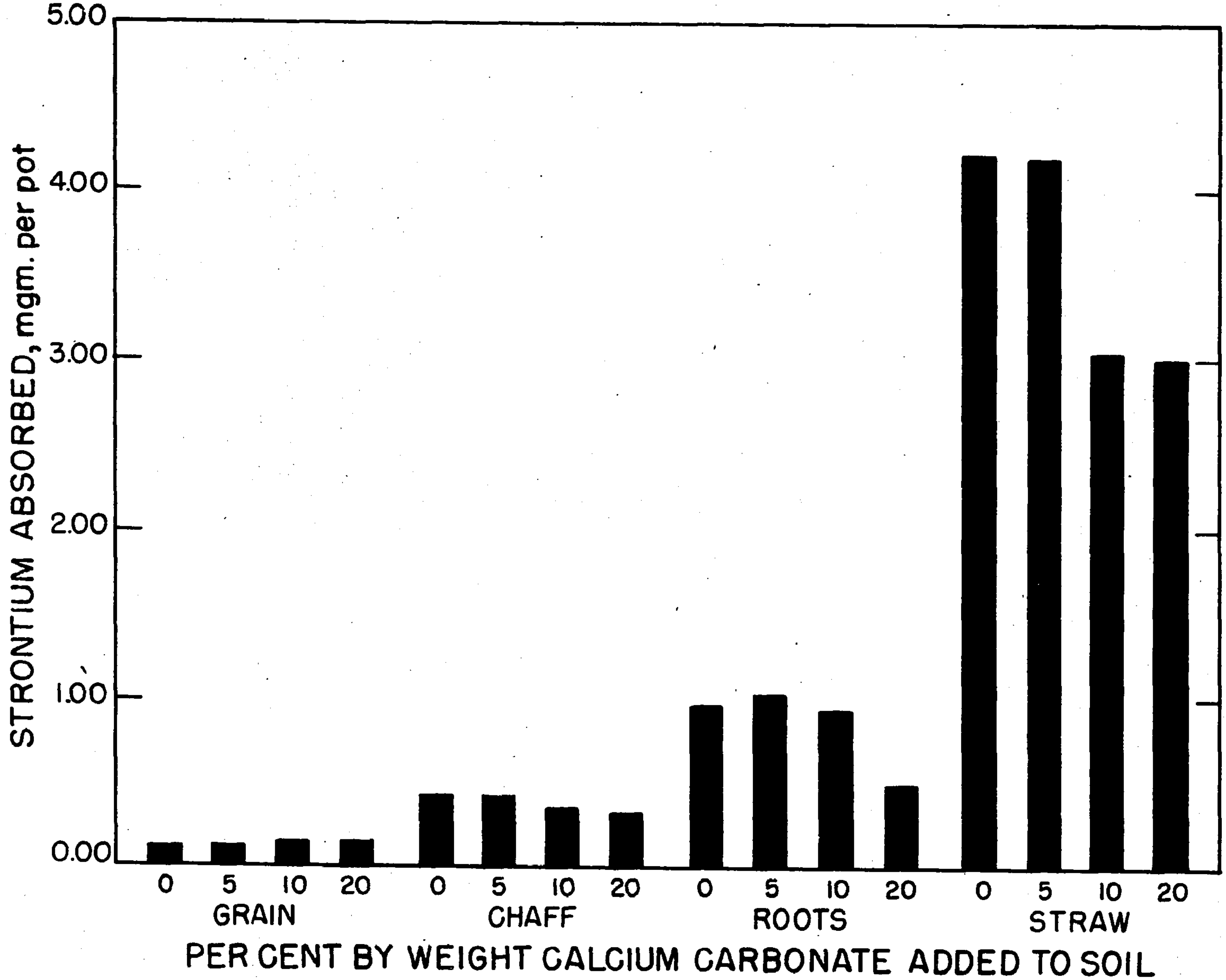



FIGURE 8.- INFLUENCE OF ADDED CALCIUM CARBONATE ON ABSORPTION OF STRONTIUM BY BARLEY GROWN ON MOHAVE SANDY CLAY LOAM.

TABLE 16. THE AMOUNT OF STRONTIUM ABSORBED BY RADISHES GROWN ON MOHAVE SANDY CLAY LOAM AND PIMA SANDY LOAM AS INFLUENCED BY ADDITION OF CALCIUM CARBONATE

| $CaCO_3$ added | Yield per pot* | | Strontium in plant** | | Ratio of Ca/Sr | | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added | |
|---|---|---|---|---|---|---|---|---|---|
| | Tops | Roots | Tops | Roots | Tops | Roots | | Tops | Roots |
| percent | gm. | gm. | µgm./gm. | µgm./gm. | | | mgm. | percent | |
| | | | | Mohave sandy clay loam | | | | | |
| 0 | 2.60 | 3.38 | 124 | 34 | 242 | 93 | 0.437 | 1.6 | 0.6 |
| 5 | 0.63 | 1.08 | 155 | 42 | 238 | 101 | 0.143 | 0.5 | 0.2 |
| 10 | 1.12 | 1.59 | 87 | 49 | 298 | 133 | 0.175 | 0.5 | 0.4 |
| 20 | 0.67 | 0.79 | 209 | 48 | 196 | 160 | 0.178 | 0.7 | 0.2 |
| | | | | Pima sandy loam | | | | | |
| 0 | 1.49 | 2.27 | 248 | 71 | 108 | 26 | 0.531 | 1.8 | 0.8 |
| 5 | 1.26 | 1.41 | 182 | 64 | 146 | 43 | 0.319 | 1.1 | 0.5 |
| 10 | 0.98 | 1.26 | 182 | 54 | 209 | 97 | 0.146 | 0.9 | 0.3 |
| 20 | 1.09 | 1.53 | 174 | 58 | 258 | 124 | 0.279 | 0.9 | 0.4 |

*Each figure represents a mean of duplicate pots and is calculated on an oven-dry weight basis.
**Pots contained 1 kg. soil and received 20 p.p.m. Sr as $Sr(NO_3)_2$.

TABLE 17. THE AMOUNT OF STRONTIUM ABSORBED BY TOMATOES GROWN ON MOHAVE SANDY CLAY LOAM AND PIMA SANDY LOAM AS INFLUENCED BY ADDITION OF CALCIUM CARBONATE

| $CaCO_3$ added | Yield per pot* | Strontium** in plant | Ratio of Ca/Sr | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|
| percent | gm. | μgm./gm. | | mgm. | percent |
| | | Mohave sandy clay loam | | | |
| 0 | 16.43 | 145 | 86 | 2.382 | 11.9 |
| 5 | 14.11 | 127 | 86 | 1.792 | 9.0 |
| 10 | 7.75 | 147 | 73 | 1.139 | 5.7 |
| 20 | 6.62 | 145 | 81 | 0.960 | 4.8 |
| | | Pima sandy loam | | | |
| 0 | 15.02 | 57 | 159 | 0.856 | 4.3 |
| 5 | 8.57 | 52 | 194 | 0.446 | 2.2 |
| 10 | 6.29 | 58 | 242 | 0.365 | 1.8 |
| 20 | 8.28 | 53 | 263 | 0.439 | 2.2 |

*Each figure represents a mean of 2 pots and is calculated on an oven-dry weight basis.
**Pots contained 1 kg. soil and received 20 p.p.m. Sr as $Sr(NO_3)_2$.

TABLE 18. THE AMOUNT OF STRONTIUM ABSORBED BY LETTUCE GROWN ON MOHAVE SANDY CLAY LOAM AND PIMA SANDY LOAM AS INFLUENCED BY ADDITION OF CALCIUM CARBONATE

| $CaCO_3$ added | Yield per pot* | Strontium** in plant | Ratio of Ca/Sr | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|
| percent | gm. | µgm./gm. | | mgm. | percent |
| | | Mohave sandy clay loam | | | |
| 0 | 13.08 | 73 | 23 | 0.955 | 4.8 |
| 5 | 10.32 | 71 | 19 | 0.733 | 3.7 |
| 10 | 6.74 | 87 | 21 | 0.586 | 2.9 |
| 20 | 5.31 | 112 | 32 | 0.595 | 3.0 |
| | | Pima sandy loam | | | |
| 0 | 9.15 | 53 | 32 | 0.485 | 2.4 |
| 5 | 8.23 | 50 | 32 | 0.412 | 2.1 |
| 10 | 9.08 | 40 | 25 | 0.323 | 1.6 |
| 20 | 7.16 | 56 | 45 | 0.401 | 2.0 |

*Each figure represents a mean of duplicate pots and is calculated on an oven-dry weight basis.

**Pots contained 1 kg. soil and received 20 p.p.m. Sr as $Sr(NO_3)_2$.

on the Mohave sandy clay loam. Radish roots grown on both soils absorbed considerably less strontium than did the tops. Less strontium was absorbed by Lettuce and tomato from the Pima than the Mohave soil.

## The Absorption of Strontium by Various Crops from Soils as Influenced by Additions of Strontium at Different Concentrations

### Tubac soil.

The purpose of this experiment was to ascertain whether the amount of strontium absorbed by plants was in direct proportion to the amount of strontium added to soil. Two experiments were conducted, one in which Tubac soil was treated with strontium nitrate at a rate ranging from 0 - 320 p.p.m. Sr and another in which the Pima soil was supplied strontium at a concentration ranging from 0 - 80 p.p.m. Tubac sandy loam was selected as one test soil because of its low exchangeable calcium content, and comparatively high calcium carbonate content.

Rye grass and wheat absorbed strontium in roughly the same proportion as was present in the soil, Tables 19 and 20. The yield of the crop was not affected significantly by Sr addition even at the highest concentration of strontium. It was noted that in the first cutting of rye grass the percentage of strontium exceeded the percentage of calcium as shown by the Ca/Sr ratio. The grain of the wheat absorbed much less strontium than the straw. The Ca/Sr ratios of both crops decreased with increasing strontium concentration showing that the strontium was substituting for the calcium in the plant.

### Pima soil.

A second experiment was performed using Pima sandy loam because it

TABLE 19. THE AMOUNT OF STRONTIUM ABSORBED BY RYE GRASS FROM TUBAC SANDY LOAM AS INFLUENCED BY ADDITION OF STRONTIUM AT VARIOUS CONCENTRATIONS

| Strontium added* | Yield per pot** | Strontium in plant Cuttings | | | Ratio of Ca/Sr Cuttings | | | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 1 | 2 | 3 | | |
| p.p.m. | gm. | μgm./gm. | μgm./gm. | μgm./gm. | | | | mgm. | percent |
| 0 | 13.66 | .... | .... | ... | ... | .... | .... | ...... | .... |
| 40 | 14.27 | 195 | 138 | 96 | 4.6 | 14.1 | 14.4 | 1.976 | 4.94 |
| 80 | 14.02 | 336 | 254 | 175 | 1.2 | 6.6 | 6.6 | 3.427 | 4.28 |
| 160 | 11.09 | 695 | 544 | 441 | 0.3 | 3.3 | 3.3 | 6.059 | 3.79 |
| 320 | 13.53 | 1429 | 1147 | 834 | 0.1 | 1.6 | 1.6 | 13.336 | 4.16 |

*Strontium added as $Sr(NO_3)_2$.

**Each figure represents an average of 2 pots containing 1 kg. soil and is calculated on an oven-dry weight basis.

TABLE 20. THE AMOUNT OF STRONTIUM ABSORBED BY WHEAT FROM TUBAC SANDY LOAM AS INFLUENCED BY ADDITION OF STRONTIUM AT VARIOUS CONCENTRATIONS

| Strontium added* | Yield per pot** | | Strontium in plant | | Ratio of Ca/Sr | | Total Sr absorbed per pot | | Sr absorbed per pot as percentage total added | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Straw | Grain | Straw | Grain | Straw | Grain | Straw | Grain | Straw | Grain |
| p.p.m. | gm. | gm. | µgm./gm. | µgm./gm. | | | mgm. | mgm. | percent | percent |
| 0 | 36.0 | 2.0 | ... | .. | .... | .... | ..... | ...... | .... | ..... |
| 40 | 34.7 | 3.9 | 101 | 8 | 13.5 | 29.5 | 3.51 | 0.0301 | 8.48 | 0.073 |
| 80 | 32.0 | 2.8 | 234 | 19 | 6.1 | 9.1 | 7.49 | 0.0546 | 9.04 | 0.066 |
| 160 | 33.0 | 2.5 | 400 | 29 | 3.3 | 5.2 | 13.18 | 0.0716 | 7.96 | 0.043 |
| 320 | 33.8 | 3.4 | 723 | 49 | 1.6 | 3.1 | 29.44 | 0.1664 | 7.38 | 0.050 |

*Strontium added as $Sr(NO_3)_2$.

**Each figure represents an average of 2 pots containing 1 kg. soil and is calculated on an oven-dry weight basis.

was high in exchangeable calcium and low in calcium carbonate content. Rye grass, tomato, radish and barley were used as the test crops. The rate at which the strontium was added was reduced to 0, 20, 40 and 80 p.p.m. It was felt that the concentration of industrial waste of strontium which could contaminate the soil might be more nearly represented by the lower rather than by the higher rate of application. The results at the lower range of Sr concentration were almost identical with those obtained at the higher range. Each crop absorbed strontium from the soil in approximately the same proportion as it was added, Tables 21, 22, 23 and 24.

## The Absorption and Concentration of Strontium in the Edible Parts of Six Crops

The absorption of strontium by six crops from a noncalcareous forest soil, Flagstaff sandy loam, and a calcareous desert soil, Pima clay loam, is shown to vary considerably depending upon the crop, Table 25. The concentration of strontium in the aerial parts of the crop varied from 289 to 1615 µgm./gm. for radish and lettuce, respectively, grown on Flagstaff sandy loam treated with 190 p.p.m. strontium. The concentration of strontium in the same plants grown on Pima clay loam was roughly half as great. The order of decreasing concentration of strontium in the aerial parts of the crops were arranged as: radish, bean, clover, tomato, spinach, and lettuce which were grown on Flagstaff sandy loam. The order was the same for the crops grown on Pima clay loam except that the clover and tomatoes exchanged places.

The order of decreasing concentration of strontium in the edible

TABLE 21. THE AMOUNT OF STRONTIUM ABSORBED BY RYE GRASS FROM PIMA SANDY LOAM AS INFLUENCED BY ADDITION OF STRONTIUM AT VARIOUS CONCENTRATIONS

| Strontium added* | Yield per pot** | Strontium in plant Cuttings 1 | 2 | 3 | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|---|
| p.p.m. | gm. | µgm./gm. | µgm./gm. | µgm./gm. | mgm. | percent |
| 0 | 16.76 | ... | ... | ... | .... | ... |
| 20 | 15.88 | 247 | 218 | 160 | 3.19 | 5.3 |
| 40 | 17.05 | 303 | 308 | 244 | 4.76 | 4.0 |
| 80 | 18.04 | 584 | 509 | 403 | 8.38 | 3.5 |

*Strontium added as $Sr(NO_3)_2$.

**Each figure represents an average of 2 pots containing 3 kg. soil and is calculated on an oven-dry weight basis.

TABLE 22. THE AMOUNT OF STRONTIUM ABSORBED BY TOMATOES FROM PIMA SANDY LOAM AS INFLUENCED BY ADDITION OF STRONTIUM AT VARIOUS CONCENTRATIONS

| Strontium added* | Yield per pot** | Strontium in plant | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|
| p.p.m. | gm. | μgm./gm. | mgm. | percent |
| 0 | 20.50 | ... | ..... | .... |
| 20 | 16.49 | 138 | 2.28 | 11.4 |
| 40 | 16.87 | 307 | 5.18 | 13.0 |
| 80 | 24.20 | 520 | 12.58 | 15.7 |

*Strontium added as $Sr(NO_3)_2$.
**Each figure represents an average of 2 pots containing 1 kg. soil and is calculated on an oven-dry weight basis.

TABLE 23. THE AMOUNT OF STRONTIUM ABSORBED BY RADISH FROM PIMA SANDY LOAM AS INFLUENCED BY ADDITION OF STRONTIUM AT VARIOUS CONCENTRATIONS

| Strontium added* | Yield per tray** | | Strontium in plant | | Total Sr absorbed per tray | | Sr absorbed per tray as percentage total added | |
|---|---|---|---|---|---|---|---|---|
| | Top | Root | Top | Root | Top | Root | Top | Root |
| p.p.m. | gm. | gm. | µgm./gm. | µgm./gm. | mgm. | mgm. | percent | percent |
| 0 | 5.70 | 1.35 | .... | ... | ..... | .... | ... | ... |
| 20 | 11.00 | 7.80 | 295 | 147 | 3.25 | 1.15 | 0.7 | 0.2 |
| 40 | 11.05 | 8.20 | 645 | 379 | 7.13 | 3.11 | 0.7 | 0.3 |
| 80 | 11.55 | 10.17 | 1012 | 397 | 11.69 | 4.04 | 0.6 | 0.2 |

*Strontium added as $Sr(NO_3)_2$.

**Each figure represents the total weight of crop from a flat of 25 kg. soil and is calculated on an oven-dry weight basis.

TABLE 24. THE AMOUNT OF STRONTIUM ABSORBED BY BARLEY FROM PIMA SANDY LOAM AS INFLUENCED BY ADDITION OF STRONTIUM AT VARIOUS CONCENTRATIONS

| Strontium added* | Yield per pot** | | | | Strontium in plant | | | |
|---|---|---|---|---|---|---|---|---|
| | Grain | Chaff | Straw | Roots | Grain | Chaff | Straw | Roots |
| p.p.m. | gm. | gm. | gm. | gm. | µgm./gm. | µgm./gm. | µgm./gm. | µgm./gm. |
| 0 | 2.87 | 2.99 | 27.71 | 9.09 | .. | .. | ... | ... |
| 20 | 2.67 | 3.22 | 28.67 | 10.06 | 4 | 17 | 54 | 58 |
| 40 | 2.69 | 2.96 | 32.72 | 8.84 | 7 | 29 | 121 | 167 |
| 80 | 2.37 | 3.44 | 29.12 | 8.15 | 14 | 67 | 204 | 267 |

| Strontium added* | Total Sr absorbed per pot | | | | Strontium absorbed per pot as percentage total added | | | |
|---|---|---|---|---|---|---|---|---|
| | Grain | Chaff | Straw | Roots | Grain | Chaff | Straw | Roots |
| p.p.m. | mgm. | mgm. | mgm. | mgm. | percent | percent | percent | percent |
| 0 | ...... | ...... | ..... | ..... | ..... | ..... | ..... | ..... |
| 20 | 0.0096 | 0.0547 | 1.556 | 0.579 | 0.016 | 0.091 | 2.590 | 0.965 |
| 40 | 0.0197 | 0.0860 | 3.341 | 0.942 | 0.016 | 0.072 | 2.780 | 0.785 |
| 80 | 0.0335 | 0.2312 | 5.952 | 2.177 | 0.014 | 0.096 | 2.480 | 0.907 |

*Strontium added as $Sr(NO_3)_2$.

**Each figure represents an average of 2 pots containing 4 kg. soil and is calculated on an oven-dry weight basis.

TABLE 25. AMOUNT OF ABSORBED STRONTIUM IN EDIBLE PARTS OF SIX CROPS FROM TWO SOILS

| Crop | Plant part | Yield per pot* | Strontium in plant** | Ratio of Ca/Sr | Sr absorbed as percentage of amount added |
|---|---|---|---|---|---|
| | | gm. | µgm./gm. | | percent |
| | | | Flagstaff sandy loam | | |
| Radish | Top | 4.7 | 1615 | 11 | 4.0 |
| Radish | Roots | 6.4 | 266 | 3 | 0.9 |
| Bean | Top | 11.1 | 1106 | 12 | 6.5 |
| Bean | Pod | 2.5 | 479 | 12 | 0.6 |
| Clover | Leaf | 6.7 | 1043 | 13 | 5.7 |
| Tomato | Top | 25.2 | 938 | 17 | 12.4 |
| Tomato | Fruit | 12.4 | 41 | 5 | 0.3 |
| Spinach | Leaf | 6.8 | 818 | 8 | 2.1 |
| Lettuce | Leaf | 4.8 | 289 | 11 | 0.7 |
| | | | Pima clay loam | | |
| Radish | Top | 5.8 | 696 | 26 | 2.1 |
| Radish | Roots | 4.9 | 130 | 5 | 0.3 |
| Bean | Top | 13.1 | 662 | 20 | 4.6 |
| Bean | Pod | 3.6 | 269 | 17 | 0.5 |
| Clover | Leaf | 4.1 | 334 | 27 | 1.2 |
| Tomato | Top | 28.4 | 474 | 30 | 7.1 |
| Tomato | Fruit | 14.0 | 20 | 11 | 0.2 |
| Spinach | Leaf | 6.5 | 230 | 28 | 0.8 |
| Lettuce | Leaf | 9.0 | 179 | 17 | 0.8 |

*Mean of 4 pots containing 1 kg. of air-dry soil. All data are calculated on an oven-dry weight basis.

**Strontium added as $Sr(NO_3)_2$ at a rate of 190 p.p.m.

parts of these crops were arranged as: spinach, string beans, lettuce, radish and tomato when grown on Flagstaff sandy loam, Table 25. Spinach and string beans exchanged places when the crops were grown in Pima clay loam. The edible parts of radish, beans, and tomatoes contained far less strontium per unit dry weight than the leaves and stems. Tomato fruit, for example, contained less than 5 percent of that of the leaves and stems.

The Ca/Sr ratio of the crops grown in Flagstaff sandy loam ranged between a low of three in radish to 17 in tomato tops and was in general about two times as great as that in crops grown on Pima clay loam. This again indicates the greater availability of the calcium of Pima clay loam than that of Flagstaff sandy loam.

The fraction of the added strontium absorbed by the different crops was small, as shown by Table 25. Less than 1 percent of the total strontium added to both soils was recovered in edible parts of the five crops.

## The Absorption of Strontium from Strontium Nitrate Solution Added Directly to Leaves

Lettuce was planted in pots containing 1 kg. of Pima sandy loam and allowed to grow until they were six to eight weeks old. A solution of radiostrontium nitrate was prepared and applied as mentioned in an earlier section of this text, pages 24 and 25.

Strontium was not translocated from the treated to untreated leaves or to the roots of any of the plants. Since all plants were alike in this respect, the analyses of only the lettuce leaves is presented in Table 26. The leaves that received strontium retained as much as 14-16 percent of the amount applied. The percentage of the total added strontium which was retained was the same regardless of side of the leaf to which it was applied. Neither water alone nor water solutions containing detergents would remove all the added strontium from the treated leaves. The depth of penetration of the strontium into the leaf was not determined. The physiological function of the strontium in the leaves is not known.

### The Absorption of Strontium by Rye Grass Grown on Soils from Various Crop Residues Containing Radiostrontium

In an endeavor to evaluate the absorption of strontium from crop residues which had been contaminated by radiostrontium an experiment was designed in which bush beans, wheat, tomatoes, rye grass and lettuce were grown in a sand-soil culture in which strontium added as strontium nitrate was present at a concentration of 360 p.p.m. The residues from these crops were added at rates of 4 and 10 tons per acre to Clinton silt loam, Clinton silt loam with $CaCO_3$ added, Mohave clay loam, Pima clay loam and Laveen loamy sand.

In general, it was found that the rate of strontium absorption depended upon the exchangeable calcium content of the soils, Figures 9 and 10. When the amount of strontium absorbed from all five crops turned under was averaged, it was found that the amount of strontium absorbed from the residues varied inversely with the exchangeable calcium of the four soils. This was true with both the 4 ton and 10 ton rates of application. The correlation coefficient derived for the

TABLE 26. THE AMOUNT OF STRONTIUM ABSORBED BY LETTUCE FROM A SOLUTION OF STRONTIUM NITRATE APPLIED TO LEAVES

| Strontium applications | Part of leaf treated* | Concentration of Sr in leaves** | | | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|
| | | Treated | Old | New | |
| | | µgm./gm. | µgm./gm. | µgm./gm. | percent |
| 4 leaves per | Upper side | 113 | T | None | 14 |
| plant received | Upper side | 127 | T | None | 15 |
| Sr at the rate | Under side | 94 | T | None | 15 |
| of 303 ugm./leaf | Under side | 104 | T | None | 16 |
| 6 leaves per | Upper side | 104 | T | None | 7 |
| plant received | Upper side | 90 | T | None | 7 |
| Sr at the rate | Under side | 48 | T | None | 6 |
| of 202 ugm./leaf | Under side | 59 | T | None | 6 |

*One plant per pot containing 1 kg. of Pima sandy loam.

**Strontium was not found to be translocated to new leaves or roots. Radiostrontium was found in old leaves not receiving applications of this material but the translocation was erratic and in only trace amounts.

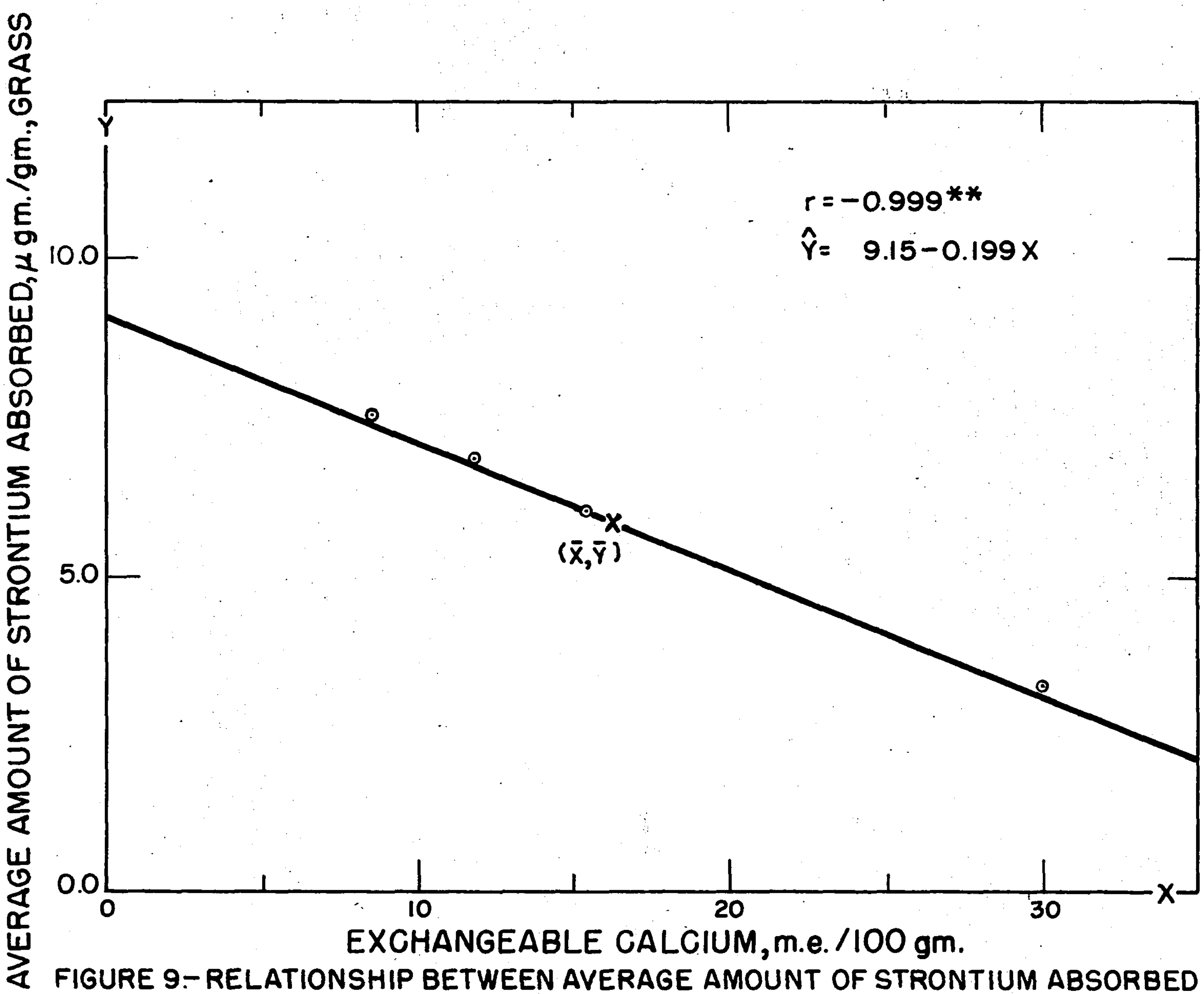



FIGURE 9.– RELATIONSHIP BETWEEN AVERAGE AMOUNT OF STRONTIUM ABSORBED PER UNIT DRY WEIGHT FROM CROP RESIDUES OF FIVE DIFFERENT CROPS TURNED UNDER AT RATE OF FOUR TONS PER ACRE AND EXCHANGEABLE CALCIUM CONTENT OF 4 DIFFERENT SOILS.

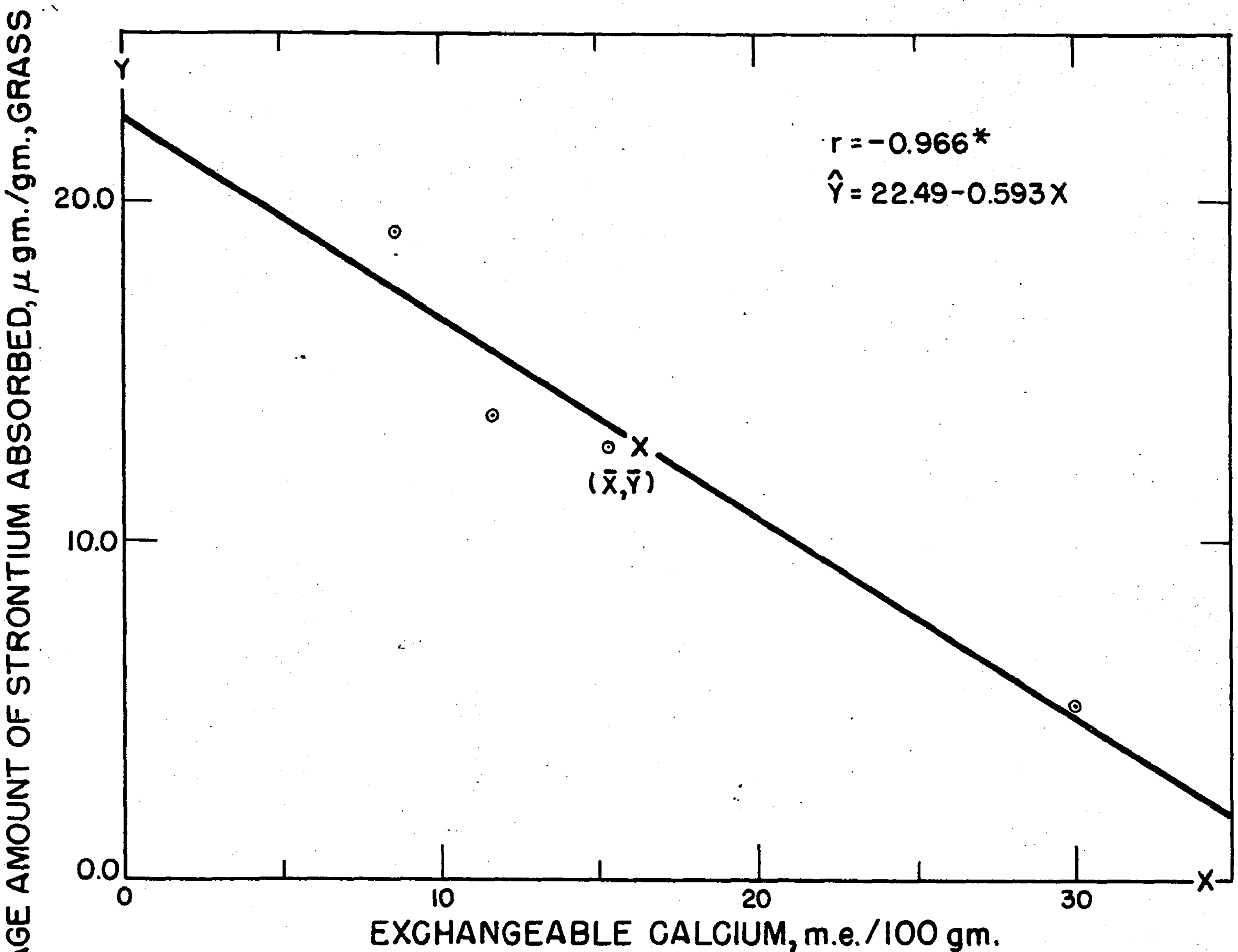



FIGURE 10.– RELATIONSHIP BETWEEN AVERAGE AMOUNT OF STRONTIUM ABSORBED PER UNIT DRY WEIGHT FROM CROP RESIDUES OF FIVE DIFFERENT CROPS TURNED UNDER AT RATE OF TEN TONS PER ACRE AND EXCHANGEABLE CALCIUM CONTENT OF 4 DIFFERENT SOILS.

4 ton per acre application was - 0.999, which was significant at the 1 percent level. The correlation coefficient for the 10 ton per acre rate was - 0.966, significant at the 5 percent level, Figures 9 and 10. It should also be pointed out that the addition of $CaCO_3$ at a rate of 2 ton per acre to Clinton silt loam, depressed the absorption of strontium, Table 27. This was also shown in a previous experiment using strontium as the pure salt, strontium nitrate, added to Mohave sandy clay loam and Pima sandy loam, Table 18.

Bean residue.

The absorption of strontium by rye grass from decomposing bean residue was less when grown on Pima clay than when grown on Mohave clay loam, Table 28. At both the 4 and 10-ton rates the absorption of strontium was inversely proportional to the exchangeable calcium in the soils. Rye grass grown on Pima clay loam absorbed the least amount of strontium while on Laveen loamy sand the greatest amount was absorbed. The strontium absorbed per gram of plant material was roughly proportional to the amount of residue added, being approximately two and one-half times as great at the 10-ton rate as that at the 4-ton rate. The Ca/Sr ratio tended to vary directly with the exchangeable calcium of the soils. For example, rye grass grown on Pima clay loam receiving 10 tons of residue had the highest ratio whereas Laveen loamy sand had the lowest.

Wheat straw.

The results for absorption of strontium from wheat straw are shown in Table 29. The total absorption of strontium from wheat straw was very low. It had been shown in a previous experiment that wheat does

TABLE 27. THE AMOUNT OF STRONTIUM ABSORBED BY RYE GRASS FROM CROP RESIDUES GROWN ON DIFFERENT SOILS

| Soil | Strontium absorbed by plant | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Bean | Wheat | Tomato Cuttings | | Rye grass Cuttings | | Lettuce Cuttings | | Average |
| | | | 1 | 2 | 1 | 2 | 1 | 2 | |
| | µgm./gm. | µgm./gm. | µgm./gm. | µgm./gm. | µgm./gm. | µgm./gm. | µgm./gm. | µgm./gm. | µgm./gm. |
| **Crop residue applied at rate of 4 T/A** | | | | | | | | | |
| Clinton silt loam | 4.5 | 0.6 | 10.7 | 15.3 | 5.3 | 4.0 | 8.0 | 5.7 | 6.8 |
| Clinton silt loam + 2 T $CaCO_3$/A | 6.8 | 0.4 | 8.5 | 8.1 | 5.5 | 3.5 | 7.1 | 5.0 | 5.6 |
| Mohave clay loam | 9.1 | 0.8 | 8.5 | 7.4 | 6.2 | 3.3 | 6.4 | 6.3 | 6.0 |
| Pima clay loam | 2.4 | 0.4 | 8.7 | 6.3 | 1.6 | 1.2 | 2.3 | 2.4 | 3.2 |
| Laveen loamy sand | 4.7 | 3.3 | 14.0 | 10.6 | 6.6 | 4.0 | 8.3 | 8.1 | 7.5 |
| **Crop residue applied at rate of 10 T/A** | | | | | | | | | |
| Clinton silt loam | 12.1 | 1.7 | 20.9 | 21.8 | 14.0 | 9.8 | 17.8 | 12.2 | 13.8 |
| Clinton silt loam + 2 T $CaCO_3$/A | 9.6 | 1.8 | 21.3 | 18.9 | 12.3 | 9.2 | 17.4 | 13.2 | 13.0 |
| Mohave clay loam | 7.6 | 3.2 | 17.7 | 17.5 | 11.6 | 11.0 | 11.3 | 23.1 | 12.9 |
| Pima clay loam | 5.2 | 0.9 | 9.4 | 8.9 | 3.4 | 2.8 | 5.6 | 4.8 | 5.1 |
| Laveen loamy sand | 17.1 | 3.4 | 22.7 | 20.6 | 19.9 | 16.1 | 24.0 | 29.5 | 19.2 |

TABLE 28. THE AMOUNT OF STRONTIUM ABSORBED BY RYE GRASS FROM ADDED BEAN RESIDUE

| Soil | Yield per pot* | Sr in plant derived from residue | Ratio of Ca/Sr | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|
| | gm. | µgm./gm. | | mgm. | percent |
| Bean residue applied at rate of 4 T/A** | | | | | |
| Clinton silt loam | 3.03 | 4.5 | 700 | 0.014 | 1.0 |
| Clinton silt loam + 2 T $CaCO_3$/A | 2.94 | 6.8 | 488 | 0.020 | 1.5 |
| Mohave clay loam | 3.34 | 9.1 | 353 | 0.031 | 2.2 |
| Pima clay loam | 4.59 | 2.4 | 1150 | 0.011 | 0.8 |
| Laveen loamy sand | 2.76 | 4.7 | 681 | 0.013 | 0.9 |
| Bean residue applied at rate of 10 T/A** | | | | | |
| Clinton silt loam | 4.24 | 12.1 | 274 | 0.051 | 0.8 |
| Clinton silt loam + 2 T $CaCO_3$/A | 3.26 | 9.6 | 382 | 0.031 | 0.5 |
| Mohave clay loam | 3.77 | 7.6 | 420 | 0.029 | 0.4 |
| Pima clay loam | 3.56 | 5.2 | 575 | 0.019 | 0.3 |
| Laveen loamy sand | 2.96 | 17.1 | 215 | 0.051 | 0.7 |

*Each figure represents a mean of 2 pots and is calculated on an oven-dry weight basis. Each pot contained 1 kg. of soil.

**Bean residue contained 0.6858 mgm. strontium per gm. of plant material.

TABLE 29. THE AMOUNT OF STRONTIUM ABSORBED BY RYE GRASS FROM ADDED WHEAT STRAW

| Soil | Yield per pot* | Sr in plant derived from residue | Ratio of Ca/Sr | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|
| | gm. | µgm./gm. | | mgm. | percent |
| Wheat straw applied at rate of 4 T/A** | | | | | |
| Clinton silt loam | 3.26 | 0.6 | 4216 | 0.002 | 0.2 |
| Clinton silt loam + 2 T $CaCO_3$/A | 2.79 | 0.4 | 6875 | 0.001 | 0.1 |
| Mohave clay loam | 2.56 | 6.8 | 4722 | 0.002 | 0.2 |
| Pima clay loam | 4.32 | 0.4 | 2678 | 0.002 | 0.2 |
| Laveen loamy sand | 2.88 | 3.3 | 4000 | 0.003 | 0.3 |
| Wheat straw applied at rate of 10 T/A** | | | | | |
| Clinton silt loam | 3.37 | 1.7 | 1618 | 0.006 | 0.3 |
| Clinton silt loam + 2 T $CaCO_3$/A | 2.72 | 1.8 | 1911 | 0.005 | 0.2 |
| Mohave clay loam | 1.27 | 3.2 | 1181 | 0.010 | 0.5 |
| Pima clay loam | 4.60 | 0.9 | 2678 | 0.004 | 0.2 |
| Laveen loamy sand | 2.21 | 3.4 | 1444 | 0.007 | 0.3 |

*Each figure represents a mean of 2 pots and is calculated on an oven-dry weight basis. Each pot contained 1 kg. of soil.

**Wheat straw contained 0.2125 mgm. strontium per gm. of plant material.

not absorb strontium to the same extent as other crops. The rate of decomposition of wheat straw was rather slow as compared with other crop residues which partly accounted for the low recovery of strontium. This might play an important role in the rate at which the various soils can yield their strontium to a succeeding crop. The absorption of strontium by rye grass from added wheat straw was related to the amount of exchangeable calcium in the soils used. The amount of strontium absorbed from wheat residue was less from Clinton silt loam treated with $CaCO_3$ than from the untreated soil.

Tomato residue.

The tomato residue contained the highest concentration of strontium of the crops tested, 0.8577 mgm. per gm. of straw. Rye grass also absorbed, on the average, a higher percentage of the total strontium added from the tomato residue than from the other crop residues. The tendency for rye grass to absorb strontium inversely to the amount of exchangeable calcium of the soil was again demonstrated although in certain instances discrepancies occurred, Table 30. For example, the first cutting of rye grass absorbed slightly more strontium from the residue when added to Pima clay loam than to Mohave clay loam at the 4-ton rate although absorption at the 10-ton rate was found to be better correlated with the exchangeable calcium. Variations in the ability of the soil microflora of different soils to decompose the added residues at different rates, and the various decomposition products formed, would tend to govern the rate at which the strontium was released to the succeeding crop. This might be used to explain the discrepancies. Clinton

TABLE 30. THE AMOUNT OF STRONTIUM ABSORBED BY RYE GRASS FROM ADDED TOMATO RESIDUE

| Soil | Yield per pot* | Sr in plant derived from residue, Cuttings 1 | Sr in plant derived from residue, Cuttings 2 | Ca/Sr ratio, Cuttings 1 | Ca/Sr ratio, Cuttings 2 | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|---|---|
| | gm. | μgm./gm. | μgm./gm. | | | mgm. | percent |
| **Tomato residue applied at rate of 4 T/A**** | | | | | | | |
| Clinton silt loam | 10.01 | 10.7 | 15.3 | 310 | 165 | 0.130 | 3.8 |
| Clinton silt loam + 2 T $CaCO_3$/A | 9.38 | 8.5 | 8.1 | 445 | 340 | 0.078 | 2.3 |
| Mohave clay loam | 7.39 | 8.5 | 7.4 | 499 | 496 | 0.059 | 1.7 |
| Pima clay loam | 12.10 | 8.7 | 6.3 | 351 | 402 | 0.092 | 2.7 |
| Laveen loamy sand | 7.74 | 14.0 | 10.6 | 307 | 292 | 0.099 | 2.9 |
| **Tomato residue applied at rate of 10 T/A**** | | | | | | | |
| Clinton silt loam | 11.33 | 20.9 | 21.8 | 159 | 122 | 0.241 | 2.8 |
| Clinton silt loam + 2 T $CaCO_3$/A | 9.43 | 21.3 | 18.9 | 130 | 152 | 0.216 | 2.5 |
| Mohave clay loam | 5.52 | 17.7 | 17.5 | 233 | 249 | 0.097 | 1.1 |
| Pima clay loam | 11.91 | 9.4 | 8.9 | 318 | 284 | 0.109 | 1.3 |
| Laveen loamy sand | 7.69 | 22.7 | 20.6 | 162 | 139 | 0.167 | 2.0 |

*Each figure represents a mean of 2 pots and is calculated on an oven-dry weight basis. Each pot contained 1 kg. soil.

**Tomato residue contained 0.8577 mgm. strontium per gm. of plant material.

silt loam absorbed the greater amount of strontium in the second cutting at both rates of application.

Rye grass.

The absorption of strontium from rye grass straw by a succeeding crop of rye grass was inversely proportional to the exchangeable calcium content of the soils, whether applied at the 4-ton or the 10-ton per acre rates, Table 31.

Lettuce residue.

Lettuce ranked next to tomatoes in its ability to absorb strontium from the soil, and being rather easily decomposed released a high percentage of its strontium to the succeeding crop, Table 32. The absorption of strontium by rye grass from decomposing lettuce was highest in soils having the lowest amount of exchangeable calcium and vice versa. Rye grass grown on Pima clay loam absorbed less strontium in both cuttings and at both rates of application of lettuce straw. The grass grown on the Laveen loamy sand absorbed the highest amount of strontium. The amount of strontium recovered was roughly proportional to the rate of application of the residue.

## The Absorption of Strontium from Various Crops Grown in Perlite

It was mentioned in the previous section that the ability of a succeeding crop to absorb strontium from a decomposing residue depended not only upon the exchangeable calcium of the soil but also upon other factors, such as (1) the rate at which the crop residue would decompose to yield the strontium to the succeeding crop, (2) the effect the soil

TABLE 31. THE AMOUNT OF STRONTIUM ABSORBED BY RYE GRASS FROM RYE GRASS ADDED TO SOIL

| Soil | Yield per pot* | Sr in plant derived from residue Cuttings 1 | Sr in plant derived from residue Cuttings 2 | Ca/Sr ratio Cuttings 1 | Ca/Sr ratio Cuttings 2 | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|---|---|
| | gm. | μgm./gm. | μgm./gm. | | | mgm. | percent |
| Rye grass applied at rate of 4 T/A** | | | | | | | |
| Clinton silt loam | 8.22 | 5.3 | 4.0 | 494 | 448 | 0.038 | 1.8 |
| Clinton silt loam + 2 T $CaCO_3$/A | 6.57 | 5.5 | 3.5 | 564 | 609 | 0.029 | 1.4 |
| Mohave clay loam | 4.18 | 6.2 | 3.3 | 637 | 870 | 0.019 | 0.9 |
| Pima clay loam | 11.30 | 1.6 | 1.2 | 1525 | 1992 | 0.016 | 0.8 |
| Laveen loamy sand | 4.52 | 6.6 | 4.0 | 573 | 705 | 0.023 | 1.1 |
| Rye grass applied at rate of 10 T/A** | | | | | | | |
| Clinton silt loam | 9.03 | 14.0 | 9.8 | 209 | 199 | 0.106 | 2.0 |
| Clinton silt loam + 2 T $CaCO_3$/A | 7.84 | 12.3 | 9.2 | 260 | 237 | 0.085 | 1.6 |
| Mohave clay loam | 5.37 | 11.6 | 11.0 | 311 | 323 | 0.060 | 1.1 |
| Pima clay loam | 11.90 | 3.4 | 2.8 | 744 | 843 | 0.037 | 0.7 |
| Laveen loamy sand | 4.30 | 19.9 | 16.1 | 184 | 228 | 0.076 | 1.4 |

*Each figure represents a mean of 2 pots and is calculated on an oven-dry weight basis. Each pot contained 1 kg. soil.
**Rye grass contained 0.5292 mgm. strontium per gm. of plant material.

TABLE 32. THE AMOUNT OF STRONTIUM ABSORBED BY RYE GRASS FROM ADDED LETTUCE RESIDUE

| Soil | Yield per pot* | Sr in plant derived from residue, Cuttings 1 | Sr in plant derived from residue, Cuttings 2 | Ca/Sr ratio, Cuttings 1 | Ca/Sr ratio, Cuttings 2 | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|---|---|
| | gm. | µgm./gm. | µgm./gm. | | | mgm. | percent |
| **Lettuce residue applied at rate of 4 T/A**** | | | | | | | |
| Clinton silt loam | 7.42 | 8.0 | 5.7 | 374 | 474 | 0.054 | 1.8 |
| Clinton silt loam + 2 T $CaCO_3$/A | 7.38 | 7.1 | 5.0 | 461 | 598 | 0.048 | 1.6 |
| Mohave clay loam | 6.55 | 6.4 | 6.3 | 520 | 583 | 0.042 | 1.4 |
| Pima clay loam | 10.74 | 2.3 | 2.4 | 1148 | 1292 | 0.025 | 0.9 |
| Laveen loamy sand | 6.69 | 8.3 | 8.1 | 428 | 467 | 0.055 | 1.9 |
| **Lettuce residue applied at rate of 10 T/A**** | | | | | | | |
| Clinton silt loam | 8.32 | 17.8 | 12.2 | 142 | 235 | 0.134 | 1.8 |
| Clinton silt loam + 2 T $CaCO_3$/A | 9.89 | 17.4 | 13.2 | 178 | 235 | 0.152 | 2.1 |
| Mohave clay loam | 6.33 | 11.3 | 23.1 | 325 | 198 | 0.101 | 1.4 |
| Pima clay loam | 9.59 | 5.6 | 4.8 | 452 | 552 | 0.051 | 0.7 |
| Laveen loamy sand | 5.64 | 24.0 | 29.5 | 129 | 181 | 0.169 | 2.0 |

*Each figure represents a mean of 2 pots and is calculated on an oven-dry weight basis. Each pot contained 1 kg. soil.

**Lettuce residue contained 0.7371 mgm. strontium per gm. of plant material.

would have upon the decomposition of the organic residue and (3) the products of decomposition of the different crops. To study the absorption of strontium from a decomposing crop residue without the complicating effect of the exchangeable calcium in the soil, an experiment was designed using Perlite*.

Table 33 shows that tomato tops and roots applied at the rate of 4 ton per acre yielded more strontium to the succeeding crop than any of the five crop residues used. Rye grass however, yielded the greatest amount of strontium at the 10-ton per acre rate. Wheat straw, as pointed out before in the soil cultures, yielded the least amount of strontium to the following crop regardless of the rate applied or the plant part used. The greater amount of strontium was absorbed by the first cutting of rye grass in every case, indicating that the organic residues decomposed rather quickly and that the strontium was made available for plant use rapidly. In general the greater percentage of the strontium was located in the aerial parts of the residues. A larger percentage of the strontium was also recovered from the top than from the root residues. The percentage of strontium recovered from Perlite was much greater than that from the soils. This was due to the fact that the crops were grown under conditions of limited calcium supply. The only calcium available was that in the decomposing residue. Strontium therefore replaced more of the calcium in the plant

*Perlite is a volcanic igneous rock which had cooled so rapidly that it is wholly or in part made up of glassy material in which the different elements have not had the opportunity to group themselves as minerals. It is composed chiefly of $SiO_2$ and prepared by heating at high temperature which cause the glassy particles to explode into a white fluffy material, ideal for plant culture studies.

TABLE 33. THE AMOUNT OF STRONTIUM ABSORBED BY RYE GRASS FROM VARIOUS TYPE CROP-RESIDUES GROWN IN PERLITE

| Crop residue added | Yield per pot* | Strontium in plant** Cuttings 1 | Strontium in plant** Cuttings 2 | Ratio of Ca/Sr Cuttings 1 | Ratio of Ca/Sr Cuttings 2 | Total Sr absorbed per pot | Sr absorbed per pot as percentage total added |
|---|---|---|---|---|---|---|---|
| | gm. | µgm./gm. | µgm./gm. | | | mgm. | percent |
| **Top residue added at rate of 4 T/A+** | | | | | | | |
| Bean | 5.16 | 35.6 | 19.3 | 98 | 184 | 0.144 | 10.5 |
| Wheat | 6.70 | 18.8 | 8.1 | 177 | 256 | 0.086 | 10.1 |
| Tomato | 7.32 | 76.8 | 61.3 | 25 | 38 | 0.508 | 14.8 |
| Rye grass | 6.10 | 88.0 | 31.4 | 27 | 60 | 0.364 | 17.2 |
| Lettuce | 6.91 | 107.3 | 33.5 | 23 | 82 | 0.470 | 15.9 |
| **Top residue added at rate of 10 T/A+** | | | | | | | |
| Bean | 6.84 | 95.8 | 51.7 | 29 | 56 | 0.537 | 7.6 |
| Wheat | 5.61 | 48.1 | 19.5 | 60 | 88 | 0.180 | 8.5 |
| Tomato | 5.74 | 112.8 | 86.7 | 17 | 21 | 0.565 | 6.6 |
| Rye grass | 8.63 | 132.6 | 78.6 | 16 | 22 | 0.925 | 17.5 |
| Lettuce | 7.91 | 142.7 | 89.5 | 14 | 27 | 0.937 | 12.7 |
| **Root residue added at rate of 4 T/A+** | | | | | | | |
| Bean | 4.82 | 21.1 | 13.9 | 157 | 223 | 0.086 | 10.6 |
| Wheat | 5.46 | 13.0 | 10.9 | 239 | 211 | 0.065 | 10.1 |
| Tomato | 7.31 | 54.1 | 53.2 | 36 | 43 | 0.392 | 17.8 |
| Rye grass | 5.00 | 133.8 | 44.0 | 26 | 44 | 0.390 | 19.3 |
| Lettuce | 5.62 | 53.8 | 17.8 | 45 | 168 | 0.193 | 12.4 |
| **Root residue added at rate of 10 T/A+** | | | | | | | |
| Bean | 6.10 | 64.5 | 39.4 | 45 | 67 | 0.327 | 16.2 |
| Wheat | 4.87 | 38.2 | 26.2 | 69 | 66 | 0.149 | 9.4 |
| Tomato | 6.03 | 98.8 | 61.6 | 20 | 28 | 0.478 | 8.1 |
| Rye grass | 5.42 | 209.5 | 88.4 | 13 | 20 | 0.680 | 13.5 |
| Lettuce | 5.27 | 86.0 | 42.1 | 27 | 65 | 0.340 | 8.7 |

*Each figure represents a mean of 2 pots and is calculated on an oven-dry weight basis.

**Pots contained 1 kg. soil and contained strontium derived from crop residues at given rates.

+The crop residues are those used in preceding experiment. The strontium content of each residue is listed at the bottom of Tables 28, 29, 30, 31 and 32.

tissues than when the same residues were added to soils.

## The Availability of Native Soil Calcium to Plants

The term "availability" of soil calcium used in this work was derived from the definition proposed by Fried and Dean(23). The definition of "available nutrient in the soil" implies that when two sources of a given nutrient are present in the soil, the plant will absorb the nutrient from both sources in proportion to the amount present in the respective sources. A further treatment of the term will be found in the discussion. It has been conclusively shown by the experiments presented so far that the exchangeable calcium of a soil tends to reduce the absorption of strontium by a crop. Since this is true, it follows that the exchangeable calcium in the soil is the form which is most available to the plant. The use of radiostrontium might be justified as a method for determining the "availability" of the calcium in a soil to plants, if a high degree of correlation were obtained between the "A" value and the exchangeable calcium of the soil.

### Rye grass.

The derived "A" values of calcium for 12 soils varying from 5 m.e./100 gm. to 30 m.e./100 gm. of exchangeable calcium are shown in Table 34. The soils with the highest amount of exchangeable calcium also had the highest "A" value. A correlation coefficient was determined between the exchangeable calcium of the soil and the derived "A" values for rye grass and was found to be 0.959 which was highly significant even at the 1 percent level, Figure 11.

TABLE 34. THE "AVAILABILITY" OF CALCIUM TO RYE GRASS FROM TWELVE SOILS AS CALCULATED BY THE "A" VALUE METHOD

| Soil* | Exchangeable calcium in soil | Calcium in plant** | Strontium in plant** | Total strontium and calcium | y† | (1 - y) | "A" value |
|---|---|---|---|---|---|---|---|
| | m.e./100 gm. | mgm. | mgm. | mgm. | | | p.p.m. |
| Clinton silt loam | 11.7 | 34.22 | 1.33 | 35.55 | 0.0374 | 0.9626 | 1030 |
| Miami silt loam | 9.3 | 39.63 | 2.19 | 41.81 | 0.0526 | 0.9474 | 720 |
| Flagstaff sandy loam | [illegible] | 42.09 | 2.51 | 44.60 | 0.0563 | 0.9437 | 1391 |
| Mohave clay loam | 15.4 | 37.32 | 2.51 | 39.83 | 0.0630 | 0.9370 | 817 |
| Tucson sandy loam | 6.8 | 25.85 | 3.37 | 29.22 | 0.1153 | 0.8847 | 422 |
| Tubac sandy loam | 8.0 | 23.95 | 3.02 | 26.98 | 0.1119 | 0.8881 | 547 |
| Tucson sandy loam | 7.5 | 24.22 | 3.31 | 27.53 | 0.1202 | 0.8798 | 403 |
| Pima clay loam | 30.0 | 48.66 | 1.14 | 49.80 | 0.0229 | 0.9771 | 2347 |
| Tucson sandy loam | 8.4 | 20.49 | 2.45 | 22.94 | 0.1068 | 0.8932 | 560 |
| Gila silt loam | 17.7 | 26.00 | 1.44 | 27.44 | 0.0525 | 0.9975 | 993 |
| Laveen loamy sand | 8.6 | 23.83 | 2.93 | 26.76 | 0.1095 | 0.8905 | 447 |
| Laveen sandy loam | 5.0 | 27.48 | 3.88 | 31.36 | 0.1237 | 0.8763 | 390 |

*All soils received 55 p.p.m. strontium as $Sr(NO_3)_2$ except Flagstaff sandy loam received 83 p.p.m., Clinton and Miami silt loams received 40 p.p.m. strontium.

**Sum of three cuttings represented by mean of duplicate pots.

†The proportion of the nutrient in the plant which came from the strontium and is calculated from the equation

$$y = \frac{\text{Sr in plant}}{(\text{Ca} + \text{Sr}) \text{ in plant}}.$$

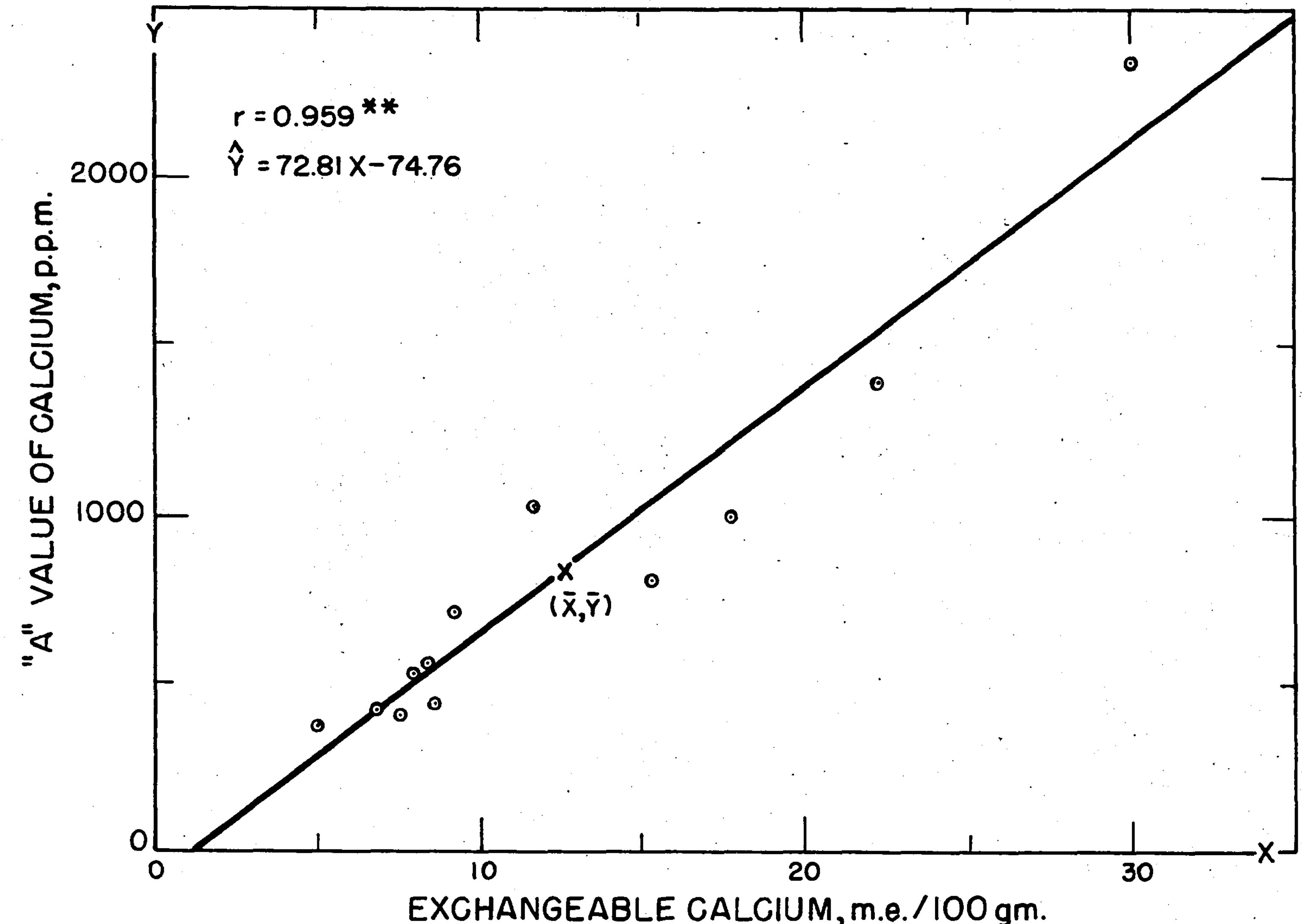



FIGURE 11.– RELATIONSHIP BETWEEN "A" VALUE FOR CALCIUM FROM SUMMATION OF THREE CUTTINGS RYE GRASS AND EXCHANGEABLE CALCIUM OF 12 DIFFERENT SOILS.

Wheat.

To further verify this method for determining availability of calcium to plants another experiment was performed, using ten soils with wheat as the test crop. Again the results showed that the derived "A" values were high for soils having high amounts of exchangeable calcium and vice versa, Table 35. This was true when either straw alone, or grain alone or the sum of grain and straw was considered. The correlation coefficient derived for the exchangeable calcium and the "A" values was found to be 0.968, which was highly significant at the 1 percent level, Figure 12.

Lettuce.

To determine whether the results could be repeated by using a vegetable crop, an experiment was performed with six soils seeded to lettuce. The results were similar to those obtained for the grass and grain crops, Table 36. The "A" values varied for the same soil with a different crop, but this could be expected due to the variations in feeding ability of the crops. The correlation coefficient for the lettuce crop between exchangeable calcium and "A" values was 0.974 which required a value of only 0.917 to be significant at the 1 percent level, Figure 13.

TABLE 35. THE "AVAILABILITY" OF CALCIUM TO WHEAT FROM TEN ARIZONA SOILS AS CALCULATED BY THE "A" VALUE METHOD

| Soil* | Exchangeable calcium in soil | Calcium in plant** | Strontium in plant** | Total strontium and calcium | y† | (1 - y) | "A" value |
|---|---|---|---|---|---|---|---|
| | m.e./100 gm. | mgm. | mgm. | mgm. | | | p.p.m. |
| Flagstaff sandy loam | [illegible] | 57.38 | 4.60 | 61.98 | 0.0743 | 0.9257 | 1034 |
| Mohave clay loam | 15.4 | 53.83 | 5.06 | 58.89 | 0.0859 | 0.9141 | 585 |
| Tucson sandy loam | 6.8 | 50.62 | 8.98 | 59.60 | 0.1507 | 0.8493 | 310 |
| Tubac sandy loam | 8.0 | 48.63 | 10.60 | 59.23 | 0.1789 | 0.8211 | 252 |
| Tucson sandy loam | 7.5 | 75.52 | 9.78 | 85.30 | 0.1147 | 0.8853 | 425 |
| Pima clay loam | 30.0 | 39.94 | 2.71 | 42.64 | 0.0635 | 0.9365 | 1669 |
| Tucson sandy loam | 8.4 | 70.34 | 10.35 | 80.69 | 0.1283 | 0.8717 | 374 |
| Gila silt loam | 17.7 | 71.94 | 3.59 | 75.53 | 0.0475 | 0.9525 | 1103 |
| Laveen loamy sand | 8.6 | 74.92 | 10.69 | 85.61 | 0.1248 | 0.8752 | 386 |
| Laveen sandy loam | 5.0 | 57.37 | 10.95 | 68.32 | 0.1603 | 0.8397 | 288 |

*All soils received 55 p.p.m. strontium as $Sr(NO_3)_2$ except Flagstaff sandy loam received 83 p.p.m.

**Includes both straw and grain and is a mean of duplicate pots.

†The proportion of the nutrient in the plant which came from the strontium and is calculated from the equation

$$y = \frac{\text{Sr in plant}}{(\text{Ca} + \text{Sr}) \text{ in plant}}.$$

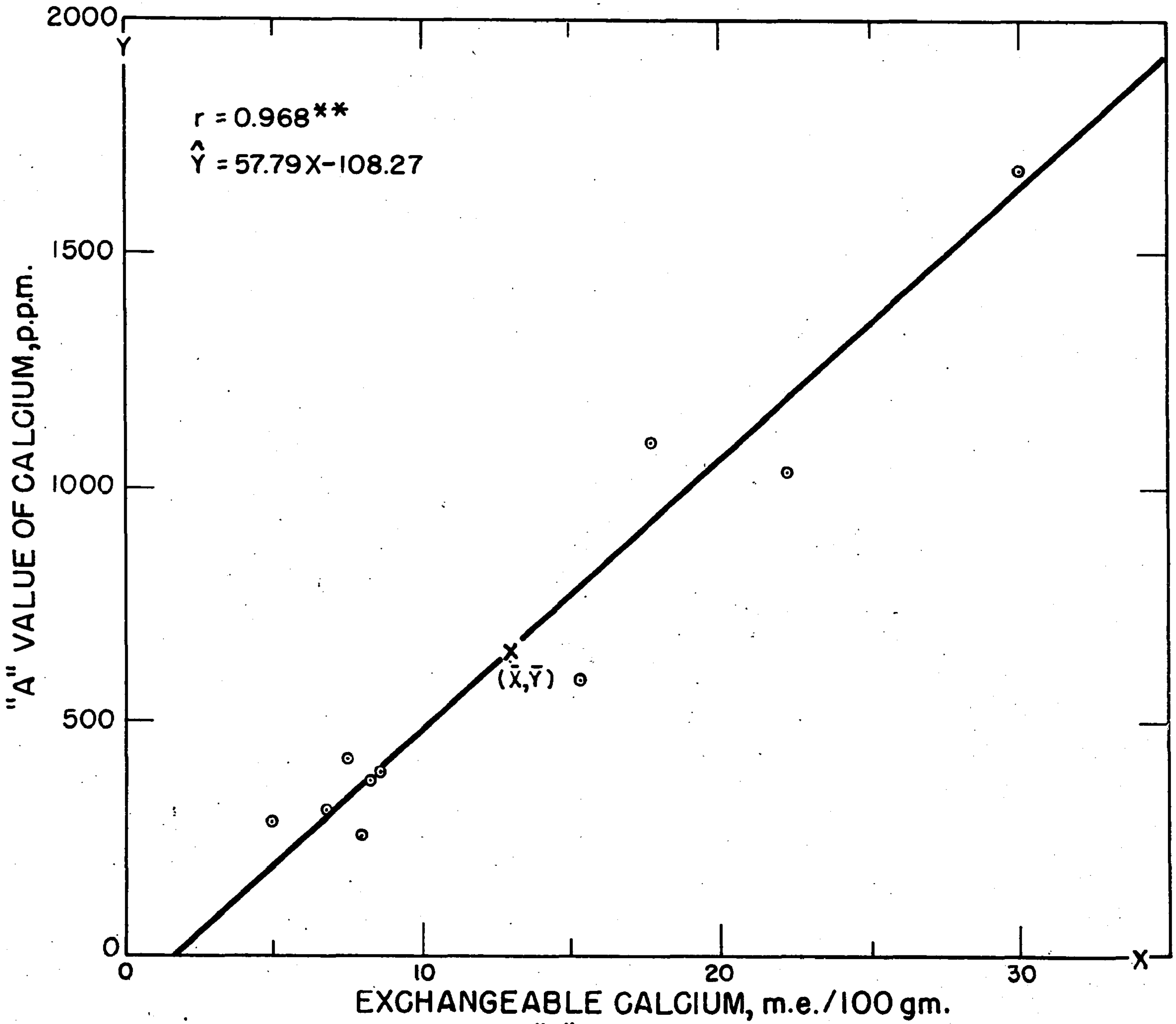



FIGURE 12.-RELATIONSHIP BETWEEN "A" VALUE FOR CALCIUM FROM WHEAT AND STRAW

TABLE 36. THE "AVAILABILITY" OF CALCIUM TO LETTUCE FROM SIX DIFFERENT SOILS AS CALCULATED BY THE "A" VALUE METHOD

| Soil* | Exchangeable calcium in soil | Calcium in plant** | Strontium in plant** | Total strontium and calcium | y✝ | (1 - y) | "A" value |
|---|---|---|---|---|---|---|---|
| | m.e./100 gm. | mgm. | mgm. | mgm. | | | p.p.m. |
| Clinton silt loam | 11.7 | 100.22 | 1.74 | 101.96 | 0.0170 | 0.9830 | 2544 |
| Miami silt loam | 9.3 | 40.49 | 1.00 | 41.49 | 0.0240 | 0.9760 | 1789 |
| Mohave clay loam | 15.4 | 76.84 | 0.92 | 77.76 | 0.0119 | 0.9881 | 3653 |
| Pima clay loam | 30.0 | 54.60 | 0.44 | 55.04 | 0.0080 | 0.9920 | 5456 |
| Tucson sandy loam | 8.4 | 2.42 | 0.07 | 2.49 | 0.0305 | 0.9695 | 1399 |
| Laveen loamy sand | 8.6 | 12.54 | 0.32 | 12.86 | 0.0251 | 0.9749 | 1709 |

*Soils received 44 p.p.m. strontium as $Sr(NO_3)_2$.

**Mean of duplicate pots containing 1 kg. soil each.

✝The proportion of nutrient in the plant which came from the strontium and is calculated from the equation

$$y = \frac{\text{Sr in plant}}{(\text{Ca} + \text{Sr}) \text{ in plant}}.$$

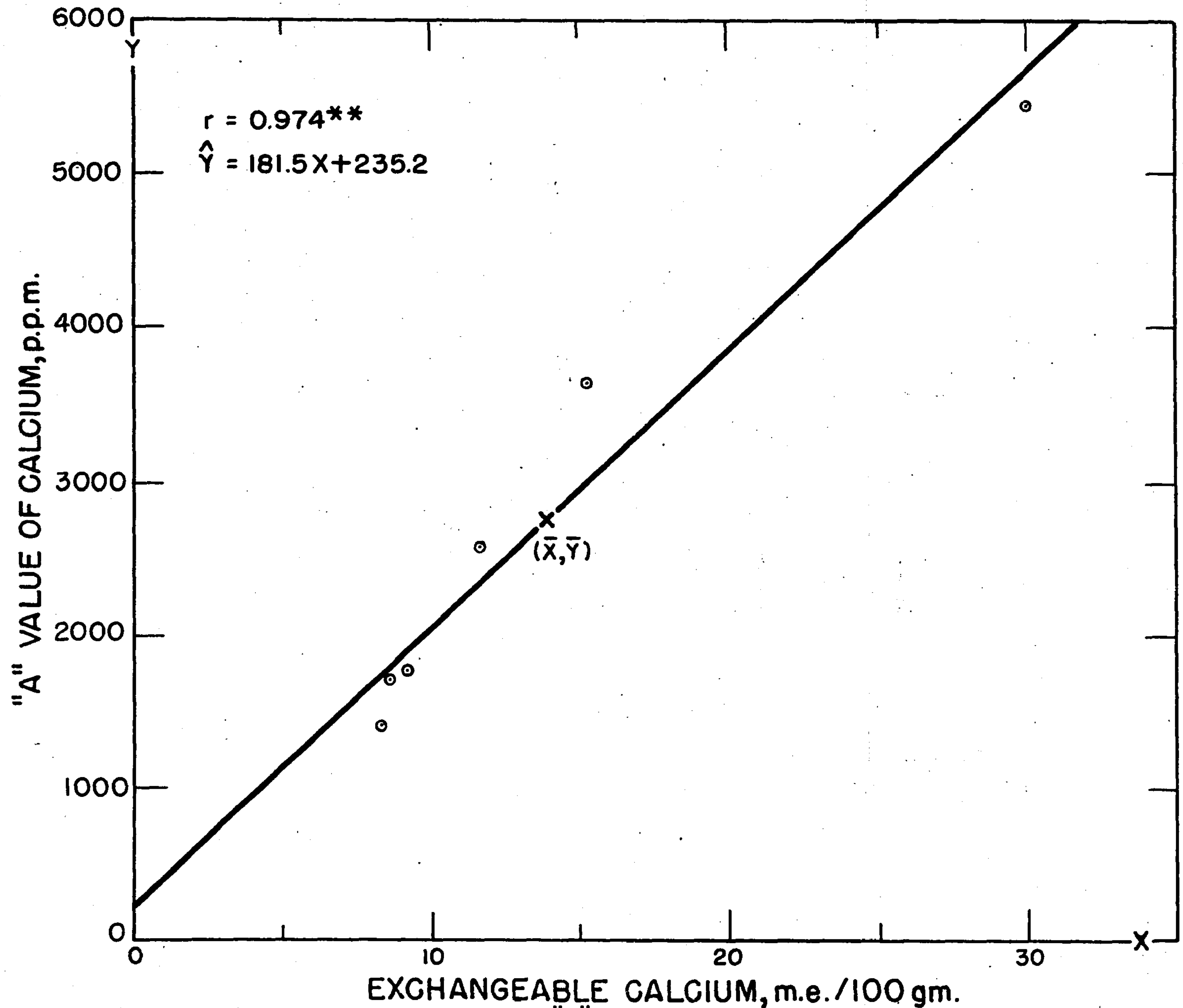



FIGURE 13.- RELATIONSHIP BETWEEN "A" VALUE FOR CALCIUM FROM LETTUCE AND EXCHANGEABLE CALCIUM OF 6 DIFFERENT SOILS

## DISCUSSION

Strontium was found to be readily absorbed from the soil by plants. This was not unexpected since there is an abundance of evidence indicating that plants grown in nutrient solutions will absorb strontium and calcium equally well and that they seem to be unable to distinguish between the two elements. At the time that this project was undertaken in 1950, there was little information regarding the absorption of strontium from calcareous soils or the effect of addition of calcium carbonate to soils on strontium absorption. There was a general belief, however, that only small amounts of strontium would be absorbed from calcareous soils because of competition between the strontium and the soil calcium.

Data presented in this manuscript not only show that strontium was absorbed by a wide variety of different crops but that a single plant species absorbed different amounts of strontium from different calcareous soils. For example, rye grass grown on Pima clay loam recovered only 0.76 percent of the added strontium while on Tucson sandy loam it recovered 2.24 percent. The extent of strontium absorption was surprising at the outset of the investigation since it was believed that the abundance of calcium carbonate in these soils would suppress the absorption of strontium. The amount of carbonate-calcium, however, had little influence upon the extent of strontium absorption by plants. Plants grown in noncalcareous soils from forested areas contained less added strontium than those from many calcareous soils. Moreover, addition of chemically-pure precipitated calcium carbonate to calcareous soils had little influence on the absorption of soluble strontium from the soil by plants. A comparison of strontium absorption by plants from different soils with the various forms in which calcium exists, such as, (1) water-soluble, (2) soluble in 1:1 HCl solution, (3) carbonate, (4) "active", (5) exchangeable, and (6) total calcium, showed that strontium absorption was inversely proportional only to the amount of exchangeable calcium of the soil. Crops grown on the soil that had the highest amount of exchangeable calcium, Pima clay loam, absorbed the least amount of strontium; whereas, on the soil with lowest amount of exchangeable calcium but the highest amount of calcium carbonate, the greatest amount of strontium was absorbed. Comparisons between amount of strontium absorbed and the other forms of calcium showed little correlation.

No significant relationship existed between the amount of calcium carbonate present and strontium absorbed even when Midwestern soils were mixed with calcareous and noncalcareous desert soils in varying ratios. The strontium absorbed by crops, however, was in all cases found to be inversely proportional to the exchangeable calcium content of the soil mixtures. The results clearly showed that the exchangeable calcium of the soils and not the calcium carbonate played the predominent role in strontium absorption. A minor role of calcium carbonate in calcareous soils as a source of calcium to plants is shown by the fact that applications of calcium carbonate had no pronounced diluting effect on strontium absorption, even though the calcium was added in far greater quantity than the strontium. Calcium carbonate appears to be much more available to plants in acid forest soils, however, than in calcareous soils of arid and semiarid regions.

There is an abundance of evidence showing that plants absorb strontium and calcium equally well when added to the soil in a soluble form and do not appear to distinguish between them(14), (27), (33), (42), (47) and (55). Under the conditions of this study where the ratio of calcium to strontium in the soil was high, such an assumption of calcium-strontium interchange may be even more valid. If the assumption is made that strontium and calcium are interchangeable in plant nutrition the results of this investigation assume additional practical significance for characterizing the behavior of calcium in the soil. For example, the percentage of strontium in the plant added as radiostrontium may be used as a basis by which "available" calcium in different soils can be compared. The radioisotope of strontium is very well suited for biological studies because its half-life is approximately 54 days. By use of the radiotracer technique it is possible to distinguish between the added and native sources of a nutrient element that a plant may absorb from a soil. In the experiment in which radiostrontium nitrate was added to the soils, it was assumed that there were two sources of the same nutrient available to plants; one being the native soil calcium and the other the added radiostrontium.

Fried and Dean(23) suggested a method for the quantitative study of the absorption of nutrients from the soil when the nutrient was derived from two sources. In their work they assumed that the nutrient from both sources is equally available. Their results have been applied quite extensively in phosphorus uptake studies. By using the same principles and assumptions made by Fried and Dean, the relationships for phosphorus availability may be applied to calcium availability. If a soil contains two sources of the same plant nutrient, the relationship between the two, since both are equally available to the plant, would be:

$$\frac{(Ca)_s}{(Sr)_s} = \frac{(Ca)_p}{(Sr)_p} \qquad (1).$$

where $(Ca)_s$ and $(Sr)_s$ represent the amount of calcium and strontium in the soil, respectively. $(Ca)_p$ and $(Sr)_p$ represent the amount of calcium and strontium in the plant, respectively. This relationship gives a basis for comparing the available nutrient in the soil with that of a standard and the amount taken up by the plant. In this example calcium is the nutrient in the soil while strontium is the standard which can be introduced into the soil. Since the calcium in the soil and the added strontium is the only source for the nutrient, the proportion of the nutrient absorbed by the plant equals:

$$(Ca)_p + (Sr)_p = 1$$

If we let:

$$y = \frac{(Sr)_p}{(Ca)_p + (Sr)_p} \qquad (2).$$

this will be the proportion of the nutrient in the plant which came from the standard, since $(Ca)_s$ is the amount of the calcium available in the soil and $(Sr)_s$ is the amount of the strontium added as a standard. Solving equation (2) for $(Sr)_p$:

$$(Sr)_p = \frac{(Ca)_p\, y}{1 - y} \qquad (3).$$

then substituting equation (3) into equation (1):

$$(Ca)_s = \frac{(Sr)_s(1 - y)}{y} \qquad (4).$$

Since the equation now is independent of the nutrients in the plant, i.e. $(Ca)_p$ and $(Sr)_p$, the subscripts on equation (4) can be eliminated remembering that:

Ca = represents amount of calcium available in the soil.

Sr = represents the amount of the strontium added to soil.

y = proportion of the strontium in the plant derived from the added nutrient.

The availability of the calcium occurring naturally in the soil can be determined by use of this equation if the amount of strontium added to the soil and the proportion of the strontium added that was taken up by the plant is known. This value is known as the "A" value. If this method for the use of radiostrontium is valid for measuring the availability of soil calcium there should be a relationship between the calculated "A" value and some form of soil calcium. The amount of exchangeable calcium of the soil was found to control the absorption of calcium by plants, Figures 1 through 7, 9 and 10. The results show a high degree of correlation between the exchangeable soil calcium and the "A" value. Hence, the method proposed by Fried and Dean for evaluation of nutrients can be applied to calcium availability. The availability of calcium to a particular crop was found to vary with the type of soil, depending upon the exchangeable calcium content of the particular soil studied.

The outstanding finding of the "A" value test was that the amount of calcium available to plants was greater in the two acid soils from the humid Midwest than in most of the ten calcareous soils of Arizona. Furthermore, the noncalcareous forest soil of northern Arizona provided more calcium, available to plants, than most desert soils of Arizona including one which contained 13 percent calcium carbonate. The data clearly indicate that the calcium carbonate of desert soils is much less available than is commonly believed. This finding no doubt explains why many plants can grow quite normally on caliche knolls and in soils high in calcium carbonate(52). Certainly the effects of calcium carbonate or lime in alkaline desert soils are not the same as in acid soils of humid regions. The solubility of calcium carbonate in alkaline desert soils, of course, is less than in acid soils. This was shown by the data on strontium absorption by plants grown in acid and alkaline soils and in mixed soils of high calcium carbonate with acid soils, Tables 7, 8, 9 and 11. The plants grown on acid soils absorbed less strontium when calcium carbonate was added than those on unlimed soils. On the other hand, the plants grown on alkaline desert soils treated with the same amount of carbonate absorbed about the same amount of strontium as the untreated soils.

## SUMMARY

1. The absorption of applied radiostrontium by various crops was studied as influenced by (1) the kind and quantity of native soil calcium, (2) liming of soil, and (3) the amount of radiostrontium added to soil. The concentration of strontium in the edible parts of plants of the above type crops was determined. The intake of strontium by plants from solutions of strontium nitrate added to the aerial parts and from soils receiving crop residues containing radiostrontium was also studied. The availability of the native soil calcium was measured by the "A" value procedure.

2. Twelve soils, ranging in calcium carbonate content from 0 to 13 percent, obtained from noncalcareous forest areas of the Midwest and calcareous areas from the desert of Arizona were used. The investigation was carried out under greenhouse conditions using $Sr^{89}(NO_3)_2$ for tracing purposes.

3. The concentration of strontium found in plants grown on the twelve soils treated with soluble strontium did not correlate with the calcium carbonate content of the soils.

4. Addition of precipitated calcium carbonate to soils, to give concentrations up to 20 percent by weight, did not affect appreciably the absorption of strontium by plants.

5. Addition of calcium carbonate to two acid Midwestern soils reduced the absorption of strontium by rye grass by about 15 percent.

6. The amount of strontium absorbed by different crops was not found to be correlated with the water-soluble, hydrochloric acid-soluble, "active", carbonate calcium, or total calcium content of the soils used.

7. A highly significant correlation was observed between the strontium absorbed by various crops and the exchangeable calcium content of the soils tested.

8. The "available" calcium in the soils varied for each soil tested and for each individual crop. There was a definite relationship, however, between the exchangeable calcium content of the soil and the derived "A" values for the soil. "Available" calcium was determined by using the "A" value formula derived by Fried and Dean, based on the assumption that the plant cannot distinguish between Ca and Sr.

9. The amount of strontium absorbed by rye grass, tomatoes, radishes, and barley from Pima clay loam and Tubac sandy loam increased in direct proportion to the amount of added strontium.

10. The absorption and concentration of strontium by six crops from two soils varied with the crop. The concentration of strontium in leaves and stems of the crops was, in decreasing order, radish, bean, clover, tomato, spinach, and lettuce, when grown on Flagstaff sandy loam. The order was the same for the crops when grown on Pima clay loam except that tomatoes and clover exchanged places. The order of decreasing concentration in the edible parts of the crop were arranged as: spinach, string beans, lettuce, radish, and tomato. The strontium concentrated in the edible parts of the crops ranged from 41 ugm. per gm. of tomatoes to 479 ugm. per gm. of string beans when grown on Flagstaff sandy loam. When grown on Pima clay loam the uptake of strontium

varied from 20 ugm. to 269 ugm. per gm. of the same two crops, respectively.

11. The strontium absorbed by rye grass as a percentage of the total added varied with the soil used from 2.59 percent for Laveen sandy loam to 0.76 percent for Pima clay loam when applied at rate of 50 p.p.m. The percentage strontium absorbed from a single soil varied with different crops. For example, tomatoes absorbed as much as 12.4 percent of the strontium added to Flagstaff soil whereas spinach absorbed 2.1 percent.

12. Translocation of the strontium from painted lettuce leaves to new or old leaves does not occur to a measureable degree.

13. The amount of strontium absorbed by rye grass from different crop residues containing radiostrontium was inversely proportional to the exchangeable calcium content of the soil used. The strontium absorbed by rye grass as a percentage of the total added ranged from 3.8 percent from tomato straw applied at 4 tons per acre to Clinton silt loam to 0.1 percent from wheat straw applied at rate of 4 tons per acre to Clinton silt loam treated with 2 tons $CaCO_3$ per acre.

14. This study has shown that radiostrontium is not concentrated in the edible parts of such common food plants as beans, tomatoes, wheat, radishes, lettuce and spinach in amounts sufficient to be dangerous to health, the amount being of the order of 41 to 479 micrograms per gram of dry material, or 41 to 479 pounds per 500 tons dry material.

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