THE ABSORPTION AND TRANSLOCATION OF RADIOSTRONTIUM BY THE LEAVES, FRUITS AND ROOTS OF CERTAIN VEGETABLE PLANTS

Thesis for the Degree of Ph. D.

MICHIGAN STATE COLLEGE

Dudley Carl Martin

1954

THESIS

This is to certify that the

thesis entitled

THE ABSORPTION AND TRANSLOCATION OF RADIOSTRONTIUM BY THE LEAVES, FRUITS AND ROOTS OF CERTAIN VEGETABLE PLANTS

presented by

Dudley Carl Martin

has been accepted towards fulfillment of the requirements for

Ph.D. degree in Horticulture

Sylvan H. Wittwer
Major professor

Date July 30, 1954

O-169

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A THESIS

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ACKNOWLEDGEMENTS

The author is deeply indebted to Dr. S. H. Wittwer, Professor of Horticulture, Michigan State College for his sincere interest, competent guidance, and personal friendliness in connection with the preparation of this thesis. Appreciation is also given to other members of the guidance committee: Professor C. D. Ball, Department of Chemistry; Dr. R. L. Carolus, Department of Horticulture; Dr. G. P. Steinbauer, Department of Botany and Plant Pathology; and Dr. L. M. Turk, Director of the Experiment Station.

All members of the Department of Horticulture are thanked for their friendliness and encouragement, particularly Dr. H. B. Tukey and Dr. A. L. Kenworthy.

Thanks are also given to Mr. O. N. Hinsvark for his assistance in all phases of the chemical analyses and to Mr. R. A. Bacon for performing the spectrographic analyses.

The author is indebted to the Biological and Medical Division of the United States Atomic Energy Commission for supplying the radioactive isotopes and providing the financial support (Contract AT-(11-1)-159) which made this study possible.

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AN ABSTRACT

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Approved by Sylvan H. Wittwer

The relatively large amount of strontium present in the products of uranium fission has stimulated new interest in the qualitative and quantitative aspects of strontium absorption and translocation by plants. From the standpoint of radioactive contamination of crop plants, the absorption by leaves and fruits becomes at least equal in importance to root absorption. In this investigation tomato, beet and bean plants were used in sand culture to study both root and foliage absorption of radiostrontium, radiocalcium and radiobarium. Both the spectrograph and the flame spectrophotometer were used to quantitatively analyze plant tissues for strontium, calcium, potassium, magnesium, phosphorus, boron, iron, manganese and copper. Autoradiography and radioactive sample counting were the important isotope techniques employed.

Strontium applied to the roots of tomato, beet and bean plants was absorbed by the roots and translocated to all above ground plant parts. Generally its absorption was proportional to its concentration in the nutrient solution, and also to its concentration relative to calcium, providing the treatment period was long enough for equilibrium to occur. Strontium can accumulate in tomato and beet tissues in amounts almost equivalent to the normal calcium content, but at such high concentrations it is toxic to both plants.

Beets can accumulate higher strontium concentrations in the plant tops and are less sensitive to strontium toxicity. Strontium and calcium in the same nutrient solution mutually favor the absorption of each other as compared to the same amount of strontium or calcium alone. The effect of high strontium and low calcium content of plant tissues upon the absorption of other nutrients is discussed.

Autoradiographic studies indicated that radiocalcium, radiostrontium and radiobarium are absorbed by tomato and beet roots and translocated to all above ground plant parts. The upward translocation of strontium is greater than that of barium but both elements tend to accumulate in the vascular tissues. Tomato fruits accumulate relatively little strontium, probably because of the low calcium requirement.

Tomato plants high in calcium always absorbed more strontium from a root application than those low in calcium when the applied strontium was in ionic form. However when the applied strontium was chelated, absorption was greater in tomato plants low in calcium. Plant calcium content had little effect on strontium absorption by beets.

In contrast to the free movement upwards and high accumulation of strontium from a root application, the movement of strontium from the site of a foliage or fruit

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application was very slight or completely lacking. Bean and beet plants showed a somewhat greater downward movement than tomato plants but in neither was the amount translocated more than a trace of that applied. This was likewise true of calcium and barium. Chelation of strontium did not increase translocation away from treated tomato leaves or fruits. By means of autoradiography it was demonstrated that radiostrontium can penetrate tne intact skin of a tomato fruit and accumulate in the inner tissues.

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I. INTRODUCTION

In plant nutrition most studies with strontium have been conducted from the standpoint of its chemical relationship to calcium. It was thought, and in some cases demonstrated, that strontium could partially of almost completely replace calcium in plant metabolism. Strontium is not considered an essential plant nutrient but is an element which plants will absorb and accumulate in rather large amounts if it is present.

Radiostrontium, as Sr^{89}, Sr^{90}, Sr^{91} and Sr^{92}, is a product of atomic nuclear fission, constituting about 15 percent of the fission products (51). Furthermore, radiostrontium is the one fission product that is easily absorbed, translocated and accumulated by plants. These facts coupled with the long half-life of Sr^{90} (25 years) make radiostrontium possibly the most serious radioactive contaminant of crop plants. This study was undertaken to determine by additional qualitative and quantitative evidence the magnitude of uptake of radiostrontium and factors influencing its absorption and distribution in certain selected horticultural plants. Because of the chemical similarities of calcium, strontium and barium, there is considerably emphasis on the comparative absorption, distribution and accumulation of the three elements including their radioactive forms in the pages which follow.

II. REVIEW OF LITERATURE

General

Strontium is an alkali earth metal located in Group IIA of Period 5 of the periodic table of the elements. Its nearness to calcium in the periodic table makes its chemical behavior similar to calcium. While not as common as some elements, strontium is world wide in distribution. The Handbook of Chemistry and Physics (26) lists it as eighteenth most common element comprising 0.018 percent of the earth's crust. Odum (41) found the average strontium content of sea water to be 8.10 milligrams per liter. He also worked out the world strontium cycle (42) and found it to be a fairly stable one. That is, the amount of strontium entering the ocean from the land is balanced by the amount being taken out of solution by ocean organisms, and the quantity incorporated into ocean sediments is balanced by sedimentary rocks raised above sea level. This strontium cycle is qualitatively similar to the calcium cycle but quantitatively the Sr:Ca ratio is about 1:500.

The metabolism of strontium in the animal organism is similar to calcium (52). It rapidly accumulates in the skeleton when taken into the body. It is one of the few products

of nuclear fission that is absorbed by the animal body from the digestive tract. The essentiality of strontium as a trace element in animal nutrition has not been established but its nearly universal presence in the skeletal tissues of higher animals has been demonstrated by a number of workers (52, 56, 62). Rygh (48) concluded that small amounts of strontium appear necessary in the nutrition of the rat and guinea pig. He found that strontium stimulates deposition of calcium in bones and teeth. Some lower forms of marine animals and plants contain large amounts of strontium in certain body or plant parts (41, 54).

Historical Review of Strontium Nutrition of Plants

Early workers claimed that strontium was not absorbed or translocated. According to Daubeny in 1835 (14) and again in 1861 (15) plants did not absorb strontium. He attributed this phenomena to the "vital" activity of the roots whereby needed nutrients were absorbed and unnecessary elements were excluded. Colin and Lavison (11) reported that only minute amounts of strontium could be detected in plants and that barium was excluded entirely. Later Brenchley (7) suggested that the chemical methods of Daubeny and Colin and Lavison may have been inadequate.

Nearly all other workers have agreed that strontium can be absorbed by plants to a greater or lesser degree but opinions

as to its value to the plant, and its relation to calcium nutrition vary considerably. Some investigators reported beneficial effects of strontium. Haselhoff in 1893 (22) concluded with barley, beans and corn that strontium was not toxic and that it will replace calcium when calcium is limited. According to Russell (47) Azotobacter, the non-symbiotic nitrogen fixing bacterium, requires either calcium or strontium. Osterhout (43) noted that either strontium or barium could perform the same function as calcium in the soil solution; that of counteracting the toxic effects of high concentrations of magnesium, sodium or potassium. He called this a balancing rather than a nutrient effect. McCool (34) also noted this effect while studying the antitoxic action of certain nutrient and non-nutrient elements. Barium and strontium alone were very toxic to peas and wheat, but in mixtures with other elements barium inhibited the toxicity of high concentrations of magnesium or potassium, and strontium reduced the toxicity of potassium, sodium or magnesium.

In the Hawaiian Islands Hance (20) found that sugar cane filter-press cake contained strontium along with several other non-essential elements. Poor sugar cane soils contained less strontium, chromium and zinc than soils which would support good crops. An excellent cane producing soil was characterized by the presence of strontium, barium, and lithium. Vlamis and Jenny (60) investigating a calcium

deficiency disease of romaine lettuce, reported that strontium alleviated the symptoms of the "disease", and suggested strontium could partially substitute for calcium in this crop. A peculiar chlorosis of Red Elberta peach trees in New Jersey studied by Wolf and Cesare (66) failed to respond to any of the normal plant nutrients applied either to soil or foliage. When they applied strontium chloride sprays to the leaves they obtained complete correction of the chlorosis within two weeks.

Additional cases where strontium has produced favorable growth responses have been reported by McHargue (36), Scharrer and Schropp (49) and Walsh (63) using small grains and legumes as test plants. In all of these reports the increased yields were produced only when adequate calcium was also present in the culture medium. They all found a definite toxicity and yield depression at strontium concentrations above those causing favorable responses.

On the other hand, other early investigators obtained no favorable plant responses to strontium at any concentration. Loew in 1898 (32) and 1903 (33) stressed the importance of calcium in the "calcium-protein compounds in the organized particles from which the nucleus and the chlorophyll bodies are built up", and concluded from his experimental data that no other element could replace calcium in this function. He stated that the abnormal symptoms developed by his plants were not just the effects of insufficient calcium but an actual

toxicity of strontium. Suzuki in 1900 (58) came to this same conclusion. Voelcker (61) added strontium in several forms to a "light unproductive soil". Additions of up to one-tenth percent strontium sulfate, hydroxide or carbonate had no effect upon germination or yield of wheat but the chloride at one-tenth percent was distinctly toxic. Strontium nitrate produced an increase in yield but this was not attributed to strontium.

McCool (34, 35) and Stiles (55) as well as Loew and Suzuki mentioned above discussed the effect of calcium on strontium toxicity in solution culture. They noted that strontium in the absence of other nutrient elements is toxic to many plants at very low concentrations. Much higher concentrations of strontium must be used to produce toxicity symptoms when the substrate is a complete nutrient solution or a soil. They attributed this primarily to the presence of calcium. Their work indicates that plants have considerable tolerance to strontium providing there is adequate calcium present. McCool (34) found that potassium, sodium and magnesium are also able to decrease strontium toxicity symptoms to a certain extent. Hurd-Karrer (27), working with pairs of chemically related elements, one essential the other toxic, discussed the calcium-strontium relationship to some length. Following is her discussion (in part):

> "The basic concept of what may be termed 'mass antagonism' is simply that of a mass effect of an essential element on the proportionate intake, and

> utilization in organic synthesis, of a toxic element sufficiently similar chemically as to preclude any considerable selectivity. The total intake of the two related elements, the one essential, the other toxic, is presumably determined by the gradient established by the plants metabolism of the essential one; and the intake of the toxic element decreases, in consequence, with increasing availability of the non-toxic one."

Ion differences or root membrane selectivity were not refuted but it was suggested that control was not good enough to distinguish between members of close pairs such as calcium-strontium, potassium-rubidium, phosphorus-arsenic and sulfur-selenium. Thus it would appear that the damage produced by a toxic element is in proportion to its concentration relative to the chemically similar nutrient rather than to its absolute concentration. The report by Collander (12) tends to support this contention. He experimented with twenty species of higher plants that had a wide range of calcium requirements. His results showed that plants with high calcium requirements were able to absorb and accumulate more strontium. A characteristic common to all plants was that the strontium:calcium ratio in the plant tissue was of the same magnitude as the strontium:calcium ratio in the nutrient solution. His explanation was that plants are unable to distinguish between the two and that absorption is proportional to quantities present.

Strontium Nutrition Studies Using Radioactive Isotopes

Jacobson and Overstreet (29) noted that the principal long-lived products of fission (Sr, Y, Zr, Cb, Ru, Te, Cs, Ba, La and Ce) were not essential to plant life and therefore have been studied very little. In their investigation they found plant roots could successfully compete with soil colloids for many fission products. However, most of the elements apparently remain adsorbed on the roots, or, if absorbed into the roots, are only sparingly translocated to the above-ground plant parts. The single exception is strontium which is easily absorbed and translocated to the stems and leaves in relatively large quantities. With the dwarf pea they found that strontium content in the root was ten times greater than the surrounding soil. The leaves and stem were slightly less radioactive than the roots while seeds showed very little strontium accumulation. Autoradiograms of pea leaves showed the highest concentration of strontium in the veins.

Jacobson and Overstreet studied the effect of radiation injury on plants and found that activity levels of one tenth microcurie per gram of soil were sufficient to cause pronounced radiation injury over a three-month period. Spinks, Cumming, Irwin and Arnason (53) also studied radiation injury. They reported the lethal dose of either Sr^{90} or P^{32} for wheat, barley and sunflower seeds was approximately 1.4 microcuries

per seed. Blume (6) was unable to demonstrate distinct radiation injury from P^{32} at levels as high as three-tenths microcurie per gram of soil. Of interest along this line, Biddulph and Cory (4) suggest fission product radioactivity causes calcium deficiency. Purslane, Portulaca oleracea, in revegetating the denuded areas of Eniwetok Atoll, showed a striking inverse relationship between total calcium content and fission product radioactivity. These authors believed fission product radiation injury results in a disruption of the calcium absorption mechanism.

Neel, Gillooly, Olafson, Nishita, Steen and Larson (38) grew several crop plants in soils artificially contaminated with various fission products. The found, as did Jacobson and Overstreet, that strontium is absorbed and translocated in much larger amounts than cesium, ruthenium, cerium and yttrium. The observed differences in absorption from the various soils was somewhat correlated with the clay type present. The authors suggest strontium is more easily absorbed because it is less strongly adsorbed on the soil colloids. Of the crop plants studied, bean and radish accumulated the most strontium, barley the least, and lettuce and carrot were intermediate. The highest specific activities were found in leaves. The corresponding roots were somewhat lower in activity and the seeds very much lower.

Rediske and Selders (45) added radiostrontium (Sr^{90}) to the soil solution of young Red Kidney bean plants and grew the plants for extended periods of time. They found there was no significant redistribution of strontium once it was mobilized in a leaf, and the total amount accumulated by a leaf was proportional to its age. Each plant tissue had a maximum total amount that would accumulate for a given nutrient condition. The adsorption of strontium during a four-day treatment period was proportional to its concentration in the nutrient solution up to 100 parts per million when the calcium concentration was constant at 140 parts per million. The strontium content of roots was higher than the tops because of a high proportion of adsorbed strontium. This accumulation of strontium on the roots decreased as the acidity of the nutrient solution increased from pH 7 to pH 4.

Studies Concerned with Foliar Absorption of Nutrients

The literature on foliar absorption and subsequent distribution and utilization of nutrients by plants has been summarized by Wittwer and Tukey (65), Ticknor (59), and Norton (40). In general it has been found that foliar applications of phosphorus, nitrogen and potassium as well as several micronutrients can be beneficial to the plant. All of these elements are apparently easily translocated throughout the plant following absorption by leaves.

Calcium does not appear to be as easily translocated from the site of foliar application as other nutrients. Downes (16) found slight downward (basipetal) translocation from the leaves to the roots of the onion but Norton (40) working with the strawberry found little or no movement of Ca^{45} from treated leaves. Haynes and Robbins (23) and Ririe and Toth (46) demonstrate another pecularity of calcium translocation using the split-root technique with tomato plants. When the root system of a tomato plant was separated into two separate culture media, calcium did not move from one half of the roots into the other half. One part of the root system may die from lack of calcium even when the other side is adequately supplied.

The peanut plant has provided another example of limited calcium movement. Harris (21) and Bledsoe, Comar and Harris (5) demonstrated a calcium supply in the pegging zone is necessary for fruit development and normal yields. Isotope studies with Ca^{45} showed the calcium absorbed by the plant roots is not translocated to the developing fruits once they are established in the ground. The fruits must absorb their own supply of calcium.

The report of Wolf and Cesare (66) mentioned earlier, is the only study located concerning the foliar application of strontium. They reported the correction of a peach leaf chlorosis by strontium sprays. The correction was obtained

only on the branches sprayed indicating there was little or no strontium translocation to branches not sprayed.

The meager evidence available indicates the downward movement of calcium, and possibly strontium, from foliar application is either very limited or does not occur at all.

III. THE PROBLEM FOR INVESTIGATION

It has been demonstrated that plants will absorb strontium from a soil or nutrient solution. In small amounts it does the plant no harm and may even promote growth. In large amounts strontium produces a toxicity which varies in magnitude depending on the plant species and the relative abundance of other available nutrients. Part of this investigation is concerned with the maximum strontium absorption by tomato and beet plants, the effect of plant calcium content upon strontium uptake, and the effect of high plant strontium on the absorption of other plant nutrients.

Trace amounts of radioactive strontium in crop plant tissues represent a health hazard from radiation rather than from the chemical element itself. Therefore the absorption, translocation, and subsequent accumulation of small amounts of radiostrontium in plant tissues will be studied. Equally as important as root absorption is the study of absorption by the above ground plant parts. Recent studies have shown that many micro-nutrient elements and some macro-nutrients can be supplied to plants, including the roots, by applying them to the foliage. This investigation centers on a study of the absorption and translocation of radiostrontium by above ground portions of plants.

IV. MATERIALS AND METHODS

1. General

All experimental work was carried out in the greenhouse during the years 1951, 1952 and 1953. The plants used were tomato, Lycopersicon esculentum, variety Michigan State Forcing; beet, Beta vulgaris, variety Detroit Dark Red; and bean, Phaseolus vulgaris, variety Michelite. Plants were grown in sand or gravel culture using the nutrient solution recommended by Hoagland and Arnon (25) the composition of which is given below. All nutrient carriers used were reagent grade or CP salts.

Hoagland Solution #2

Nutrient	Concentration (ppm)	Nutrient Carrier
Nitrogen	210	$NH_4H_2PO_4$, KNO_3, $Ca(NO_3)_2$
Phosphorus	31	$NH_4H_2PO_4$
Potassium	234	KNO_3
Calcium	160	$Ca(NO_3)_2$
Magnesium	48	$MgSO_4$
Sulfur	64	$MgSO_4$
Iron	0.8	Ferric ammonium citrate
Boron	0.5	H_3BO_3
Manganese	0.5	$MnCl_2 \cdot 4H_2O$
Zinc	0.05	$ZnSO_4 \cdot 7H_2O$
Copper	0.02	$CuSO_4 \cdot 5H_2O$
Molybdenum	0.01	$H_2MoO_4 \cdot H_2O$

This nutrient solution as prepared in 18 liter lots in the greenhouse had a specific conductance of 165 mhos x 10^{-5} and a pH of 7.4. The pH of distilled water provided varied from 6.5 to 7.5. A specific conductance of 165 mhos x 10^{-5} is equivalent to an osmotic pressure of 0.59 atmospheres which is well within the limits recommended by Stout and Overstreet (57) for nutrient solution culture.

Calcium nitrate was withheld from the nutrient solution when a low calcium level was desired. The nitrogen level was maintained by adding an amount of ammonium nitrate equivalent in nitrogen to the nitrogen in calcium nitrate omitted. The plants for whole-plant autoradiograms were grown in regular greenhouse sand. All other plants were grown in either Flint-Shot sand[1] or Wausau Quartz #8[2]. Both were high grade quartz and very low in plant nutrients. Wausau Quartz was used when roots were to be chemically analyzed because the coarse particles could be easily separated from the roots without excessive leaching. Plants were grown in either six-inch clay pots or two gallon glazed crocks, depending on the size desired. The clay pots or glazed crocks were placed in a pan filled with one to two inches of nutrient solution. The solutions were changed regularly and the sand occasionally leached with distilled water to prevent salt accumulation. More specific descriptions of the culture conditions of various experiments

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1. Obtained from Ottawa Silica Sand Co., Ottawa, Illinois.

2. Obtained from American Graded Sand Co., 2940-50 Ashland Ave., Chicago, 13, Illinois.

will be given in the discussion of each. In the one case where field grown plants were used, samples were harvested from several locations at the end of the 1953 growing season and analyzed for strontium and calcium.

2. Chemical Analysis

A Beckman Quartz Spectrophotometer with hydrogen flame attachment was used to determing the strontium, calcium, potassium and sodium content of the plant samples collected. The technique used was based on the method of Hinsvark, Wittwer and Sell (24) but considerable modification was made since a hydrogen instead of acetylene burner was used and the substrate was changed from ten percent to one percent perchloric acid. Their determinations were made on pure salts of calcium, strontium and barium using concentrations much higher than those found in plant tissue unless separation and concentration techniques are used. The high concentrations in their solutions permitted the use of very narrow slit widths and consequently minimized flame background and interference by other ions. The great number of samples and the limited amount of tissue available made separation and concentration techniques impractical in this study. Consequently a method was devised whereby calcium and strontium could be determined in fairly dilute solutions in the presence of the other plant ash constituents, principally potassium, magnesium and sodium.

The plant tissue samples were prepared for analysis using a modification of the A.O.A.C. Methods of Analysis (1) for plant ash constituents. The following procedure was employed:

> Plant tissue samples dried at 70° C were ground in a Wiley mill using a 40 mesh screen. One gram or two gram samples in duplicate were weighed into 40 cc porcelain crucibles and ashed at 550° C for 10-12 hours. When cool the ash was wet with distilled water and then dissolved by adding about two milliliters of (1+3) perchloric acid (Baker's analyzed reagent grade, 70 percent). The ash solution was heated on the steam bath for 30 minutes and filtered while warm through Watman No. 40 filter paper into a 100 ml. volumetric flask. The filter paper was washed several times with warm one percent (by volume) $HClO_4$. When cool the solution was made up to volume with one percent $HClO_4$ and transferred to a four ounce screw cap bottle for storage and subsequent analysis.

The substrate for all samples was one percent (by volume) perchloric acid. The usual dilution factor was one gram of dry plant tissue made up to one hundred milliliters but with tissues low in ash, such as tomato fruits and beet roots, as much as four grams of dry tissue was used. Higher concentrations tended to plug the capillary tube of the hydrogen burner. All plant samples were run in duplicate, the values reported being the average of the two determinations.

Two thousand parts per million stock solutions of the individual metals were obtained by neutralizing reagent grade carbonates with concentrated perchloric acid and making to volume with one percent perchloric acid. Stock solutions were diluted to various concentrations to obtain standard

curves on the flame photometer (Figure 1). Percent transmittance values for the various elements in plant samples as well as in standard solutions were obtained using the conditions shown in Table I. All determinations were made with the spectrophotometer selector switch set at 0.1 and a 10,000 megohn phototube resistor in the circuit. The operating oxygen pressure was held constant at ten pounds per square inch. Standard curves were initially made using a fuel (hydrogen) pressure of 6.5 pounds per square inch but in order to reproduce the standard curve from day to day the fuel pressure had to be varied within the limits shown in Table I. Under these operating conditions there was no flame background in the determinations of strontium, calcium, potassium, and sodium.

The elements causing interference with the flame intensity are also listed in Table I. Brown, Lilleland and Jackson (8, 9) corrected for flame interferences by adding an average amount of the interfering elements to the standard solutions used for making reference curves. This method is apparently satisfactory for field grown plants where the variation in composition is not too great and the interfering elements are always present in the plant tissue. In the present study, strontium, the main element under consideration, varied from 350 to 0.0 parts per million in the solutions analyzed. The mean of two such widely different values, used as the average strontium interference for all samples, would cause considerable error

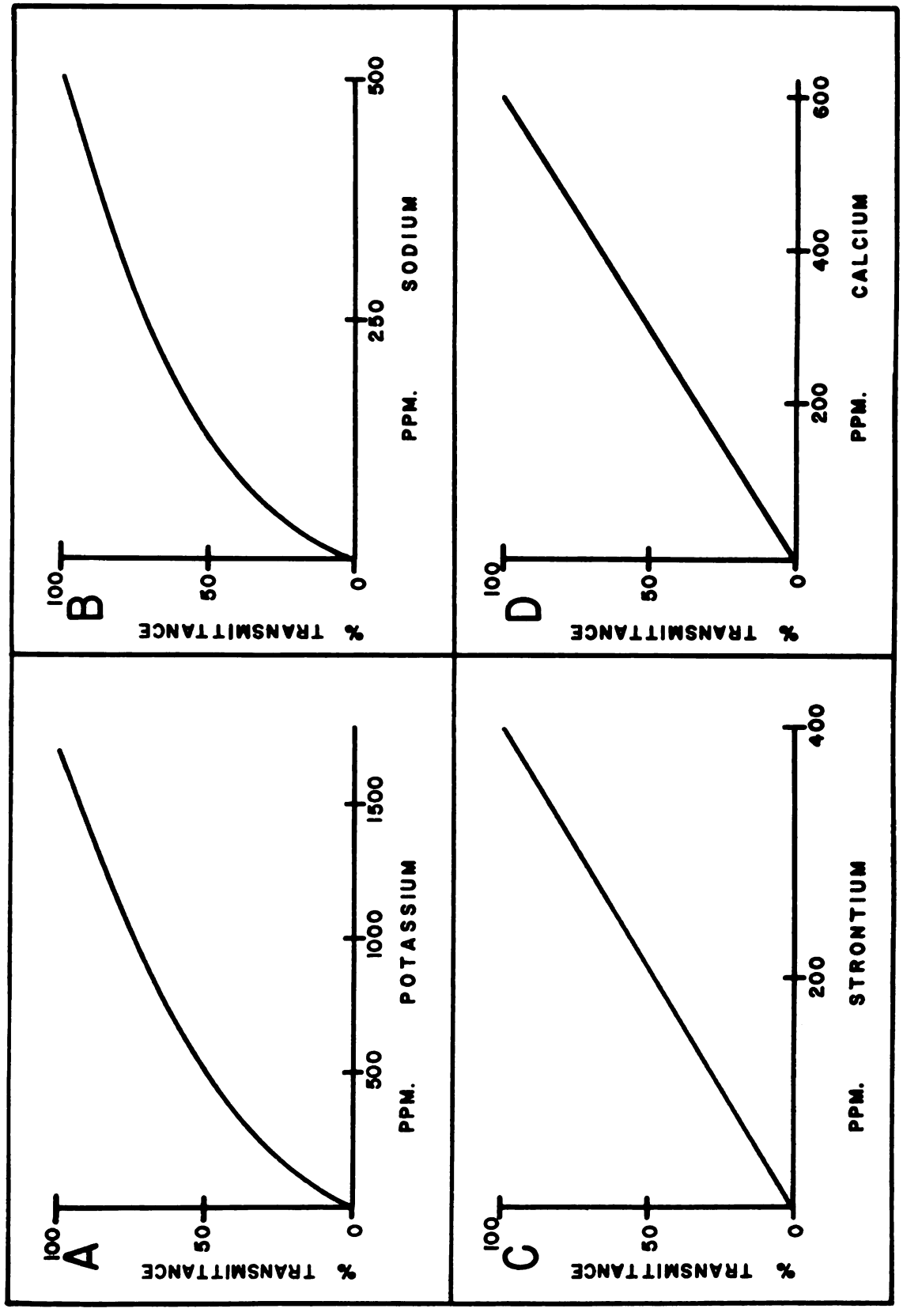

Fig. 1. Standard curves for flame photometry. The relationship between flame intensity and concentration of (A) potassium, (B) sodium, (C) strontium, (D) calcium.

TABLE I

CONDITIONS USED FOR THE FLAME PHOTOMETRIC DETERMINATION OF SEVERAL ELEMENTS PRESENT IN PLANT ASH

Element	Wave Length (millimicrons)	Slit Width (millimeter)	Phototube	Sensitivity Setting	Hydrogen Pressure (pounds per square inch)	Top Standard (parts per million)	Percent Transmittance setting for Top Standard	Elements Causing Flame Interference
Potassium	771.5	0.023	red	midpoint	5.8-7.0	500	50	None
Strontium	681.	0.280	red	midpoint	6.0-7.5	400	100	Potassium Calcium Sodium (above 50 ppm)
Calcium	623.	0.270	red	midpoint	6.0-6.5	600	100	Potassium Strontium
Sodium	589.	0.137	blue	clockwise limit	6.3-6.8	500	100	Not determined

in the calcium determinations. The interference problem was solved by applying individual corrections for the various interfering ions. The corrected percent transmittance could then be converted to parts per million by using the standard curve.

Because of the high flame intensity of potassium as well as its high concentration in the solutions, the slit width was very narrow. Strontium, calcium, magnesium or sodium did not interfere with the observed transmittance of potassium, hence its concentration in an unknown solution could be read directly from the standard curve (Figure 1a) without correction. Potassium however, interfered with both strontium and calcium. Strontium interfered with the flame intensity of calcium, and calcium interfered with strontium. Magnesium at any concentration and sodium below fifty parts per million did not cause any appreciable interference. Above fifty parts per million sodium interfered slightly with strontium flame intensities. All samples from greenhouse grown plants contained less than thirty parts per million of sodium. Only samples from field grown plants required a sodium correction for strontium transmittance. All interferences caused an increase in flame intensity of the element being determined. Thus the corrections were subtracted from the observed percent transmittance to find the transmittance of the element being determined. Where two elements such as calcium and potassium

interfered in the determination of strontium, standard solutions were made up containing both interfering elements and the resulting interference was found to be nearly equal to the sum of their individual interferences. That is, the two interferences were essentially additive (Table II).

To correct for interference, several concentrations of the interfering element were added to each of several concentrations of the element being determined. The deviations of these percent transmittance values from the transmittance of the element alone are shown in Table II, using strontium as an example. Table II shows that calcium interference is essentially independent of strontium concentration but that interference by potassium depends not only upon the concentration of potassium but also on the concentration of strontium. Thus two types of correction curves are necessary as shown in Figure 2. The potassium content of each solution must be determined before a potassium correction can be applied. The potassium correction for calcium transmittance was like Figure 2-A except the corrections were approximately one-third as large. Strontium interference corrections for calcium were similar to but slightly greater than those shown in Figure 2-B.

The concentration of the element in parts per million was obtained from the standard curve (Figure 1) after the corrected percent transmittance was determined. Parts per million in solution was then converted to an expression of plant composition, either percent dry weight or milligrams

TABLE II

INCREASES IN THE PERCENT TRANSMITTANCE OF VARIOUS CONCENTRATIONS OF STRONTIUM CAUSED BY THE FLAME INTERFERENCE BY VARIOUS LEVELS OF POTASSIUM AND CALCIUM

Interfering Element (ppm)	Strontium concentration (ppm) 0	50	100	200	300
	(% Transmittance increases)				
0 K	0.0	0.0	0.0	0.0	0.0
50 K	0.2	0.9	1.2	1.7	2.2
100 K	0.4	1.1	1.8	2.2	3.6
250 K	0.5	1.5	2.4	3.0	4.0
500 K	0.8	1.9	3.0	3.5	5.0
750 K	1.1	2.2	3.4	4.5	5.2
1000 K	1.3	2.5	3.7	5.0	5.9
1500 K	1.6	---	4.0	5.6	6.9
0 Ca	0.0	0.0	0.0	0.0	0.0
50 Ca	0.2	0.0	-0.1	-0.2	0.0
100 Ca	0.4	0.3	0.3	-0.2	0.0
250 Ca	1.0	1.0	1.0	1.0	0.4
500 Ca	1.8	1.9	2.3	1.8	2.1
700 Ca	2.6	---	3.1	2.5	2.8
100 K + 100 Ca			2.3		
250 K + 100 Ca			2.7		
100 K + 250 Ca			2.9		
500 K + 250 Ca			3.9		
1000 K + 500 Ca			5.7		

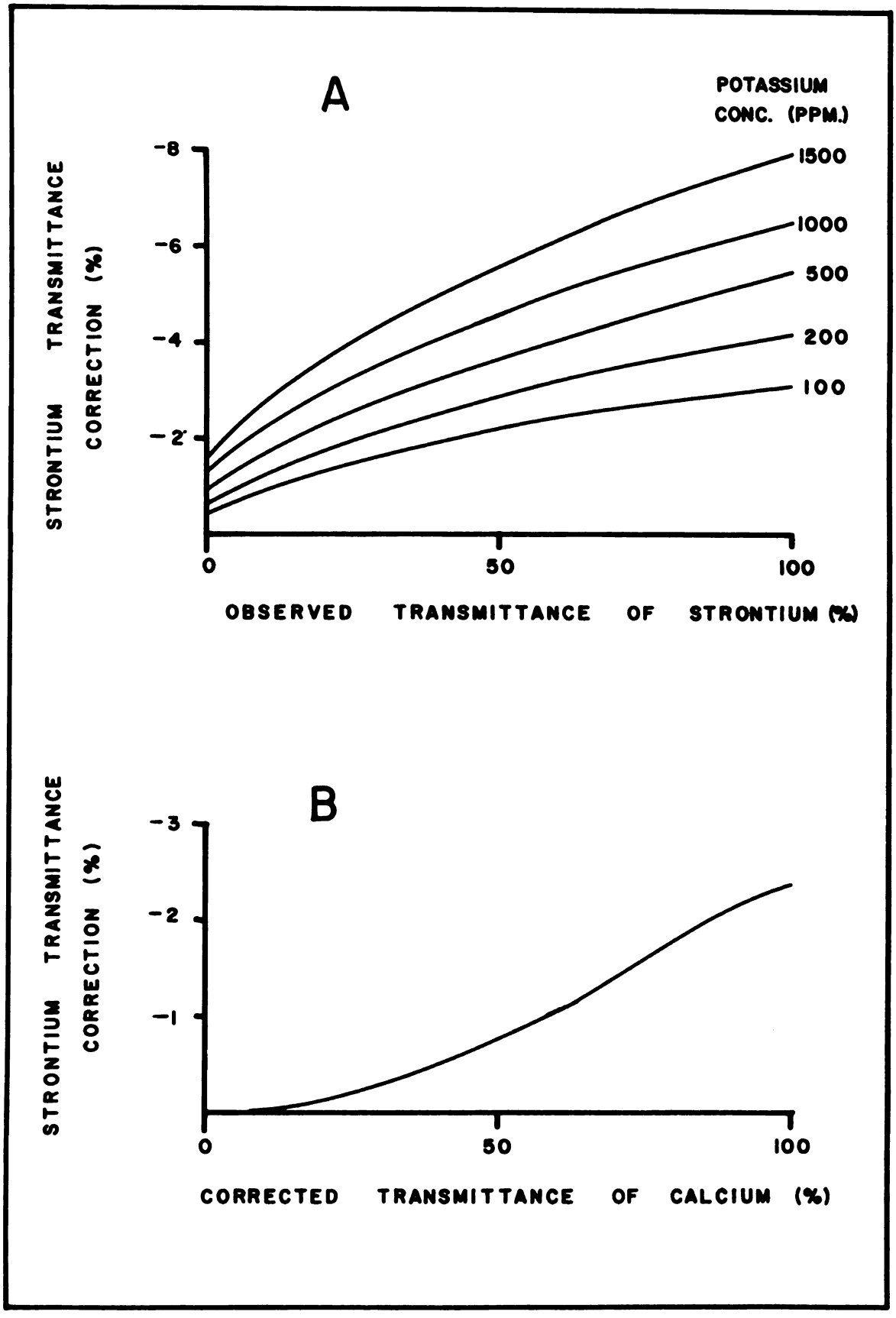

Fig. 2. Corrections applied to the observed strontium transmittance to account for flame interference by (A) potassium and (B) calcium.

of element per gram of dry tissue. All the determinations of strontium, calcium, potassium and sodium for Experiments 1, 2 and 3, as well as the control plants of Experiments 7, 8 and 9, were made by this method.

Spectrographic analyses of Experiment 2 samples for magnesium, phosphorus, iron, manganese, copper and boron were made by the Department of Agricultural Chemistry. The method was an adaptation of the techniques described by Churchill (10), Guettel (19), and Mitchell (37), and is briefly as follows:

> Two grams of oven dried plant tissue were ashed in the muffle overnight at 600° C. The ash was wet with 2 ml. of 5 percent LiCl, which provided the lithium internal standard, and then dissolved by adding 8 ml. of HCl (1 + 1). 0.025 ml. aliquots of the dissolved ash were micropipetted to the polished ends of six carbon electrodes which were then dried rapidly under infra red heat lamps. At the same time electrodes of the referee samples were prepared. Pairs of electrodes were placed in water cooled ignition chamber of a Hilger Large Quartz Spectrograph and subjected to a controlled A. C. spark for sixty seconds. Nine unknown samples (in triplicate) and the four referee samples were run on each spectrograph plate (Kodak spectrum analysis #1) which covered the spectrum range 245.0 to 350.0 millimicrons. After photographic development in D-19 developer, the density of the various lines were read using a Jarrell-Ash Recording Microphotometer. The wave lengths of the spectrum lines used were: boron, 249.7; phosphorus, 253.5; magnesium, 277.8; manganese, 294.9; calcium, 300.6; lithium, 323.2; and copper, 324.7 millimicrons. The intensities observed were then converted to the logarithms of the relative intensity (Log R. I.) based upon the intensity of the internal lithium standard. Standard curves, straight lines on logarithmic paper, were made by plotting the log R. I. for the referee samples against the known concentration of each element in the referee samples.

The referee standards were leaf samples of tree fruits (apple, cherry, peach and citrus) in which the six elements had been previously determined with considerable accuracy. The Log R. I. of the unknown sample was referred to the standard curve to find the percent composition of each element. Each value represents the mean of triplicate determinations on one plant ash solution.

3. Autoradiographic Methods

Autoradiograms of whole plants were used to evaluate the gross intake and distribution of foliar and root applied radioisotopes at various time intervals following treatment. Plants used were tomato, beet and bean, and the radioisotopes studied were Ca^{45}, Sr^{89}, Sr^{90}, and Ba^{140}. Sections of beet roots and tomato fruits one and one-half to two millimeters thick were also used. These were prepared for exposure to the film either by quick freezing or by drying under heat and pressure. The X-Ray film used was 8 x 10 inch Kodak Blue-Brand, or Kodak No-Screen, which was exposed for various time intervals depending upon the radiation intensity. Evans (17) points out that X-ray emulsions are the most sensitive of all emulsions to beta and gamma radiations but the grain is large and irregular. However, for gross studies such as these, their resolving power was adequate. Plants were treated when they were of such a size that the entire plant including roots could be pressed on an area 8 x 10 inches.

Twenty-four autoradiograms could be prepared simultaneously using the method of Wittwer and Lundahl (64). Exposure times varied from a few days to several weeks depending on the level of radioactivity. The exposure for each group of plants was kept constant so that the impression on the film would semi-quantitatively represent the amount of radiation present in the respective tissues from the different treatments. After exposure the films were processed in X-ray developer and fixative.

4. Studies Using Radioactive Isotopes

All radioactive isotopes used in these experiments were obtained from the Atomic Energy Commission at Oak Ridge, Tennessee. Early shipments of radiostrontium were Sr^{89} containing 5 - 10 percent of Sr^{90} and Y^{90}, subsequently referred to as Sr^{89}. Later shipments were received as Sr^{90} with a radiochemical purity of 99 percent. Both isotopes were received as the chlorides in weak HCl. Radiocalcium (Ca^{45}) was received as $Ca^{45}Cl_2$ in weak HCl, and radiobarium (Ba^{140}) was obtained as $Ba^{140}(NO_3)_2$ in weak HNO_3. These isotopes were used to study the absorption and subsequent translocation of these elements following direct leaf or fruit application or addition to the root media. Treating solutions were prepared by adding tracer amounts of the radioactive isotope to solutions of the stable isotope.

The usual concentration of radioactive isotope in foliage treating solutions was one microcurie per milliliter but there were some exceptions. Specific activities, expressed as microcuries of radioisotope per milligram of stable element, will be given with each experiment. For root treatments the foliage treating solution was diluted several-fold with water to assure complete distribution in the sand.

Plants were grown in sand or crushed quartz in the greenhouse as described earlier. When of sufficient size they were randomly selected for treatment. Root treatments were applied by pouring the isotope solution on the sand around the stem. The enamel pans in which the pots or crocks were placed were not emptied between treatment and harvest time. Leaf applications were made by dipping the leaves in a beaker or pan containing the isotope solution. Tomato fruits were treated by painting the isotope solution on the surface or, in one case by injecting it into the fruit with a hypodermic needle. A suitable wetting agent was added to the dipping solutions. The specific conditions of plant growth, nutrient solutions and treatment application will be given with each experiment.

Plant parts were harvested after the specified treatment period, fresh weights determined, dried at 70° C, and then weighed again. Except for Ba^{140} samples, the dry tissue was ground through a 40-mesh screen in a Wiley mill and then

thoroughly mixed. Radiobarium samples were broken up by hand, ashed, and the ash was taken up in dilute HCl. Barium was precipitated as the carbonate, filtered,and the precipitate transferred to round, flat bottom tin boxes.[1] Radiocalcium samples were prepared by weighing 0.2268 gram of tissue, equivalent to twenty milligrams per square centimeter, into a tin box. The tissue was spread uniformly over the bottom of the box and then ashed in the muffle furnace. Radiostrontium samples were prepared for counting merely by uniformly spreading a weighed amount of ground tissue over the bottom of a tin box or Coors capsule.[2] The dry plant tissue was counted without further treatment.

Regardless of the method used to prepare samples for counting, self-absorption curves were made for each isotope in each different geometry using the method of Schweitzer and Stein (50). Sample sizes for counting were chosen so that self-absorption would be negligible. Thus self-absorption was avoided rather than corrected for by calculation. Where corrections for half-life were necessary, the formulas given by Kamen (30) were used. This was ordinarily avoided by counting the treating solution reference samples at the same time as the plant samples and making all counts of comparable

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1. Labelstik tin boxes, gold lacquered, one-half ounce size. Obtained from George D. Ellis and Sons., Inc., Myers Manufacturing Division, Camden, N. J.

2. Coors glazed porcelain ashing capsules, four centimeters in diameter, one centimeter high, with flat bottom and straight sides. Obtained from Central Scientific Company, 1700 Irving Park Road,Chicago, 13, Illinois.

samples within a short time interval. Samples were counted either in a Tracerlab Model SC-1B Autoscaler or a Nuclear Instruments and Chemical Corporation, Model 172 Ultrascaler. Both instruments were equipped with shielded counting chambers.

The final data are expressed in terms of micrograms of the element, per gram of dry tissue, derived from the isotope treatment. Values were calculated as follows. The treating solution was originally prepared to contain a certain molar concentration of the element under study. From this the number of micrograms of the stable element per milliliter of treating solution could be calculated. The weight of the radioisotope was neglected because even Sr^{90} with its long half-life weighs only 6.31×10^{-3} micrograms per microcurie. The counts per minute per milliliter of treating solution were obtained by counting the reference samples. Dividing the counts per minute per milliliter by the micrograms per milliliter gave the number of counts per minute representing one microgram of the element. All plant tissue counts were converted to counts per minute per gram of dry tissue. These values divided by the counts per minute per microgram of the element equal the value for micrograms of the element, derived from the isotope treatment, per gram of dry tissue.

V. RESULTS

The experiments may be separated as follows. Those concerned with the absorption and translocation of strontium, calcium and barium as indicated by, (1) chemical analysis, (2) autoradiography and (3) radiation counting.

A. Absorption and Translocation of Strontium in Tomato and Beet Plants as Determined by Chemical Analysis

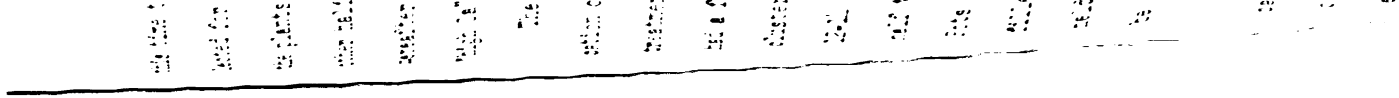
Experiment 1

Objective

To determine the quantity of strontium, calcium and barium absorbed by tomato and beet plants grown at two levels of calcium when the treatment period is short (4 days).

Materials and Methods

Seeds of the two vegetables were planted in Wausau quartz #8 on March 20, 1952. Seedlings were transplanted into six inch clay pots on April tenth. A two-inch square of brass window screen prevented loss of quartz through the drainage hole. Each pot was placed in a two quart enamel pan filled with nutrient solution. All plants were grown in full Hoagland's solution until May 20, a period of forty days. At



this time the 56 most uniform plants of each crop were selected for treatment and divided into two groups. One half of the plants were continued on regular Hoagland's solution; the other half were given a minus calcium nutrient solution. Hereafter the two groups of plants will be referred to as "high Ca" and "low Ca" plants.

These nutrient conditions were continued until application of treatments on May 31 and June 1. At the time of treatment tomato plants were three to four feet tall and had a few small fruits on the second cluster. The first cluster of flowers did not set fruits. Beet plants were 12-14 inches high and had a root diameter of one and one-half to two inches. All plants were normal in appearance. Pots containing plants to be foliage treated were completely filled with sand and then covered with corrugated cardboard, held in place with Scotch tape, so that plant and pot could be inverted without disturbing the roots.

The foliage treating solutions consisted of 0.4 percent calcium chloride (0.0272 M) or chemically equivalent amounts of strontium or barium chlorides. Actual amounts of the three elements in dipping solutions were 1.09 grams Ca per liter, 2.39 grams Sr per liter, and 3.75 grams Ba per liter. Triton B-1956[1] was added as a wetting agent. Tomato plants were marked above the sixth leaf with a ring of absorbent cotton;

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1. Obtained from Rohm and Haas Company, Philadelphia, Pennsylvania.

the stem, leaves and shoots below the mark being designated as "lower foliage", and everything above the mark "upper foliage". The upper foliage of tomato plants and the entire foliage of beet plants were dipped in and thoroughly wet by these solutions. Tomato plants were laid on their side and beet plants were inverted until the dipped portions were thoroughly dry. Each treatment was replicated four times.

Treatments to the root media consisted of adding 160 ppm of calcium or chemically equivalent amounts of strontium (350 ppm) or barium (549 ppm) as the chlorides to the regular "high calcium" and "no calcium" nutrient solutions. The only change made in the basic nutrient solutions was to substitute $MgCl_2$ for the $MgSO_4$ with barium treatments to prevent the precipitation of $BaSO_4$. The six groups of plants and their respective root treating solutions were placed in six large pans 50 by 27 inches and 4 inches deep, each pan holding 36 liters of nutrient solution. No water or additional nutrient solution was added during the four day treating period.

All plants were harvested after 96 hours of treatment. Samples were dried initially at 50-60°C in a large forced air dehydrator and finally in a constant temperature oven at 70°C. Dried samples were weighed and then ground in a Wiley mill using a 40-mesh screen. Two gram samples in duplicate were ashed, taken up in one percent perchloric acid, and analyzed for calcium, strontium and barium on the flame spectrophotometer.

Results

Results of the strontium treatments are shown in Tables III and IV. These data show that there was considerable difference in calcium content of the "high Ca" and "low Ca" plants, with the most marked differences being in beet roots and the upper foliage and roots of tomato. Tomato plants accumulate a higher concentration of strontium in leaves and roots during a four-day period than do beets. The high calcium tomato plants took up more strontium than the low calcium plants while the reverse was indicated for beets. There was little or no downward movement from foliage applications to either tomato or beet.

Calcium analysis of the calcium treated plants showed so much variability than only trends could be noted. High calcium plants appeared to take up as much calcium from root treatments as low calcium plants. There was no evidence of downward movement from foliage applications.

Very high calcium and potassium interference combined with a high flame background prevented a valid determination of barium by the flame photometer method used. There was one interesting observation on the soil treatment of tomato with barium. High calcium plants showed no vixible effect from 549 ppm barium in the nutrient solution but low calcium plants were severely affected. Wilting of foliage began on the third day of treatment and by harvest time all four plants were completely wilted and their roots were dead or dying. Low calcium beet plants were not affected.

TABLE III

THE ABSORPTION AND TRANSLOCATION OF CALCIUM AND STRONTIUM BY THE ROOTS AND LEAVES OF THE TOMATO AND BEET AT HIGH AND LOW LEVELS OF CALCIUM. (Values given are in milligrams per gram of dry tissue - mean of four replications)

Crop	Strontium Treatment	Nutrient Status	Upper Foliage mgm. Ca	Upper Foliage mgm. Sr	Lower Foliage mgm. Ca	Lower Foliage mgm. Sr	Root mgm. Ca	Root mgm. Sr
TOMATO	Applied to roots	High Ca	13.13	1.61	15.92	1.49	16.38	3.84
		Low Ca	4.66	0.91	8.17	1.10	2.15	2.84
	Applied to upper foliage	High Ca	12.89	1.82	15.38	0.00	18.90	0.00
		Low Ca	5.16	1.36	8.00	0.06	2.12	0.00
	Control	High Ca	12.26	0.00	14.89	0.00	18.71	0.00
		Low Ca	4.10	0.04	7.12	0.05	1.74	0.06

Crop	Strontium Treatment	Nutrient Status	Complete Foliage mgm. Ca	Complete Foliage mgm. Sr	Root mgm. Ca	Root mgm. Sr
BEET	Applied to roots	High Ca	14.49	0.61	0.84	0.94
		Low Ca	10.62	0.72	0.36	1.16
	Applied to complete foliage	High Ca	14.88	1.16	0.73	0.01
		Low Ca	10.54	1.21	0.33	0.02
	Control	High Ca	15.08	0.09	1.01	0.04
		Low Ca	10.49	0.10	0.32	0.00

TABLE IV

TOTAL STRONTIUM ACCUMULATED BY THE ROOTS AND LEAVES OF THE TOMATO AND BEET AT HIGH AND LOW LEVELS OF CALCIUM

(Milligrams for total plant organ - mean of four replications)

Crop	Strontium Treatment	Nutrient Status	Upper Foliage mgm Sr	Lower Foliage mgm Sr	Root mgm Sr
TOMATO	Applied to roots	High Ca	65.10	37.88	24.53
		Low Ca	33.79	33.99	18.68
	Applied to upper foliage	High Ca	63.52	0.18	0.00
		Low Ca	47.38	1.94	0.03
	Control	High Ca	0.00	0.00	0.00
		Low Ca	1.34	1.71	0.34

Crop	Strontium Treatment	Nutrient Status	Complete Foliage mgm Sr	Root mgm Sr
BEET	Applied to roots	High Ca	3.66	7.54
		Low Ca	5.08	10.85
	Applied to complete foliage	High Ca	8.15	0.11
		Low Ca	10.72	0.36
	Control	High Ca	0.61	0.38
		Low Ca	0.76	0.00

Experiment 2

Objective

To study the growth and mineral composition of tomato and beet plants when grown for prolonged periods in nutrient solutions containing various amounts of calcium, strontium and combinations of calcium and strontium.

Materials and methods

Plants were grown in twelve different nutrient solutions (Table V). Full Hoagland's solution was used for all treatments except that calcium was reduced, combined with strontium, or substituted by strontium in the various treatments. When the sum of calcium nitrate and strontium nitrate was less than eight milliequivalents per liter, ammonium nitrate was added to make up the lost nitrogen. The treatment designations shown in Table V refer to the equivalent percentage of the element in relation to full Hoagland's solution calcium (160 ppm). These designations will be used in the tables, figures, and discussion which follow.

Tomato seeds were planted in vermiculite on September 23, 1952. Seedlings were transplanted to Wausau Quartz #8 in six-inch clay pots on October 29. Treatments were started two days later. Harvests of five plants each were made after 30 and 46 days of growth in the various nutrient solutions. Beets were seeded in vermiculite on November 23, 1952, and transplanted

TABLE V

[illegible] TO TOMATO AND BEET PLANTS GROWN FOR PROLONGED PERIODS [illegible]

TABLE V

NUTRIENT SOLUTION FORMULATIONS SUPPLIED TO TOMATO AND BEET PLANTS GROWN FOR PROLONGED PERIODS*

Treatment		Parts per million		Milliequivalents per liter		Nitrogen (ppm)		
Number	Designation	Calcium	Strontium	Calcium	Strontium	Ammonium	Nitrate	Total
1	100 Ca	160	0	8	0	14	196	210
2	75 Ca	120	0	6	0	28	182	210
3	50 Ca	80	0	4	0	42	168	210
4	25 Ca	40	0	2	0	56	154	210
5	75 Ca + 25 Sr	120	88	6	2	14	196	210
6	50 Ca + 50 Sr	80	176	4	4	14	196	210
7	25 Ca + 75 Sr	40	264	2	6	14	196	210
8	100 Sr	0	352	0	8	14	196	210
9	75 Sr	0	264	0	6	28	182	210
10	50 Sr	0	176	0	4	42	168	210
11	25 Sr	0	88	0	2	56	154	210
12	0 Ca + 0 Sr	0	0	0	0	70	140	210

* All treatments received equal amounts of potassium, phosphorus, magnesium, sulfur, iron, boron, manganese, zinc, copper and molybdenum.

to new Wausau Quartz #8 on January 4, 1953, at which time treatments were initiated. Five plants were harvested at each of the harvest period, 46, 68, and 90 days after the beginning of treatment. Twelve large pans 50 by 27 inches and four inches deep were used so that the plants for each treatment were continually subjected to the same solution. The nutrient solutions were changed weekly to prevent build-up of salt concentration and algae population.

Yield data collected included height measurements of both tomato and beet, root diameters of beets, fresh weight, and dry weight. The plant tissues were analyzed for potassium, strontium and calcium using the flame spectrophotometer and for the elements magnesium, phosphorus, iron, manganese, copper, and boron using the spectrograph.

The statistical treatment consisted of calculating the standard deviation from the mean of the five values for any particular measurement. In the following discussion any treatment mean which fell outside two standard deviations from the mean of the 100 Ca treatment was considered significantly different from the 100 Ca treatment. Numerical values of the 100 Ca mean plus and minus two standard deviations (s) are given in all tables. In all cases the 100 Ca treatment was used as the basis for comparison. There were some differences between means however, which appear real even though the difference is not as large as two standard deviations. This resulted from high variability in the measurements of

the five 100 Ca samples. The differences among plants treated alike is an indication of natural plant variability and genetic heterogeneity. The analysis of variance was not used because the method of growing plants did not meet the random distribution requirement.

Results

A. Observations. Tomato plants showed no visible effect of the treatments for the first fifteen days. By the twentieth day plants receiving the 100 Sr treatment were showing a lag in growth. At 22 days strontium toxicity symptoms began to appear on the leaves, and by 28 days these symptoms were well developed and began to appear in the 75 Sr and 25 Ca + 75 Sr treatments. However the latter had much less injury than either 75 Sr or 100 Sr. The pattern of leaf necrosis was interesting. The newly formed leaves appeared normal until they became two to three inches long. Of the four or five fully expanded leaves the younger ones showed a marked necrosis of the tips of the leaflets while on older leaves the necrosis appeared at the base of the leaflets with the tip remaining green. At the 30 day harvest, the roots of all plants appeared normal except that roots of plants receiving the 100 Sr treatment were somewhat smaller.

Strontium toxicity continued to increase until the final harvest at 46 days. By this time most leaves of plants

receiving the 100 Sr treatment were completely dead but new leaves continued to form at the apex. A few leaves were also dead on plants grown at 75 Sr. Strontium toxicity was evident on plants in the 50 Sr and 25 Sr treatments but it decreased sharply with the amount of strontium in the nutrient solution. Injury was present on plants in the 25 Ca + 75 Sr treatment but was less severe than with those grown at 75 Sr without calcium. There was no evidence of calcium deficiency or strontium toxicity in other treatments. The plants in the 0 Ca + 0 Sr treatments were as vigorous and healthy as those in treatments receiving calcium. These plants were apparently obtaining sufficient calcium to support growth from impurities in the distilled water or nutrient salts. Tomato roots did not show any of the usual symptoms of calcium deficiency in any treatment. Only the roots of plants in the 100 Sr and 75 Sr treatments were appreciably smaller than those in the 100 Ca treatment. Two of the treatments, 25 Ca and 0 Ca + 0 Sr, appeared to have larger root systems than the 100 Ca treatment. There was one marked difference between high calcium and low or no calcium roots. The fresh tomato roots in the 25 Ca, 50 Ca + 50 Sr, 25 Ca + 75 Sr, 100 Sr, 75 Sr, 50 Sr, 25 Sr, and 0 Ca + 0 Sr treatments were much more brittle than the roots of the other four treatments.

Initial growth of beet plants was very slow through the month of January because of short days and low light

intensity. After thirty days of treatment the plants in the 100 Sr treatment were noticeably smaller than those in all other treatments, and dark red patches began to develop on the leaf blades. This redness of the leaves was also present to a lesser extent on plants in the 75 Sr and 25 Ca + 75 Sr treatments at the time of the first harvest. By the second harvest at 68 days the reddening of younger leaves had become more general on plants in the 100 Sr, 75 Sr and 25 Ca + 75 Sr treatments and was also evident on plants receiving the 50 Sr and 25 Sr treatments. This symptom was much less pronounced on plants in the 25 Ca + 75 Sr treatment than on those in the 75 Sr treatment (see Figure 7). Plants in 100 Sr and 75 Sr treatments were considerably smaller than those in all other treatments. These conditions persisted until the final harvest at 90 days. Shortly after the second harvest the 25 Ca plants nearly stopped growing so at the third harvest these plants were considerably smaller than the 100 Ca plants.

The pictures shown in Figures 3 to 8 were taken two days before the third and final beet harvest. They show the differences between treatments and particularly the poor growth of plants in the 25 Ca, 100 Sr and 75 Sr nutrient solutions. The dark red color produced by leaves of plants in strontium treatments is probably a symptom of strontium toxicity rather than calcium deficiency because

Fig. 3. Beet plants grown for 88 days in nutrient solutions with decreasing calcium content and no strontium.

Fig. 4. Beet plants grown for 88 days in nutrient solutions with decreasing strontium content and no calcium.

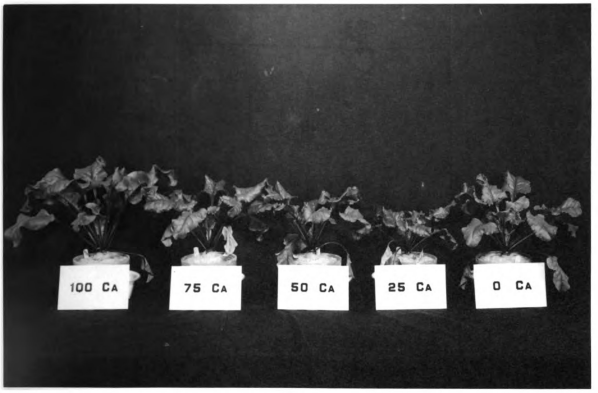

Figure 3

Figure 4

Fig. 5. Beet plants grown for 88 days in nutrient solutions containing the highest levels of calcium (left) and strontium (right) and with various combinations of the two elements (center).

Fig. 6. Beet plants grown for 88 days at the highest levels of calcium (left) and strontium (center) compared with a plant grown in nutrient solution with no calcium or strontium added (right).

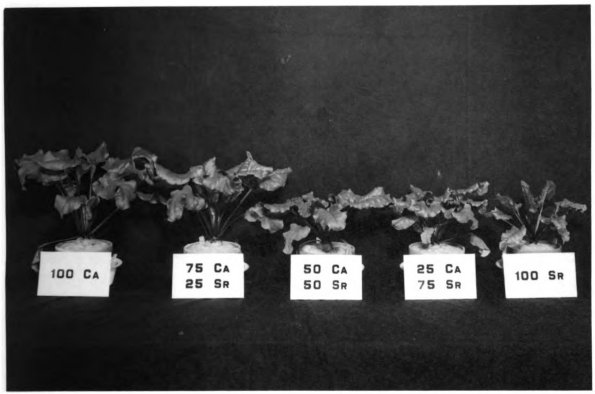

Figure 5

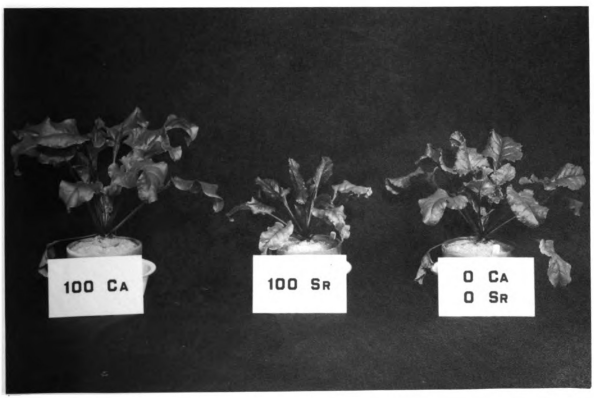

Figure 6

Fig. 7. Beet plants grown for 88 days in the nutrient solutions indicated. Note the greater strontium toxicity when calcium is absent from the nutrient solution.

Fig. 8. Beet plants grown for 88 days in the indicated nutrient solutions showing better growth by a low level of strontium than a low level of calcium.

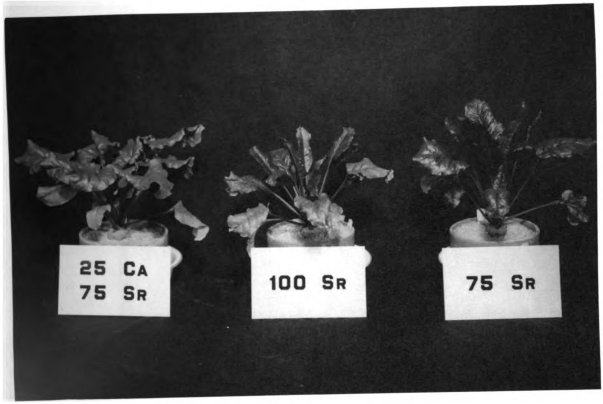

Figure 7

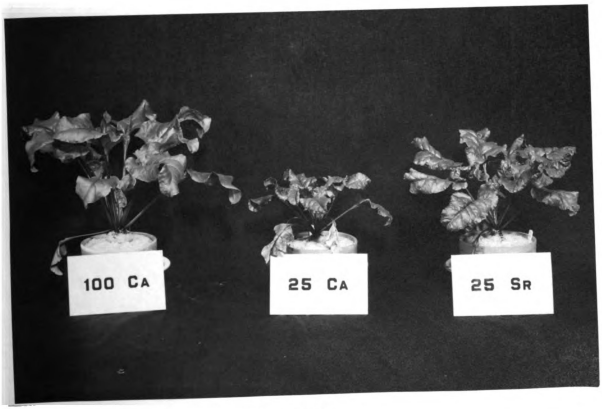

Figure 8

both apical and root growing points were not affected and the 0 Ca + 0 Sr treatment did not have the symptom. Figures 5 and 7 show that the addition of calcium to the nutrient solution suppressed the leaf color change. Many of the red leaves did not develop full size and were more rigid and erect that normal leaves. The beet roots showed no toxicity or deficiency symptoms. The fleshy roots all appeared normal even though there was considerable difference in size. Fibrous roots in the various treatments were all about the same except in the 25 Ca treatment where they were much darker in color.

B. Growth measurements. Several plant measurements were taken at the various harvest times. These are shown in Table VI. Tomato plants were significantly shorter in the high strontium treatments at both harvests. Beet plant heights and root diameters were also less at the high strontium levels but the differences were not as pronounced as with the tomato. The small size of beet plants in the 25 Ca treatment at 90 days is also evident in Table VI. Beets were apparently more tolerant of strontium than tomato plants because there was no necrosis of beet leaves.

The dry weights are shown in Table VII for tomato plants and Table VIII for beet plants. These values are presented graphically in Figures 9 and 10. Total plant dry weights at the final harvests are also shown in Figures 15 and 16.

TABLE VI

THE INFLUENCE OF CALCIUM-STRONTIUM NUTRIENT SOLUTIONS ON HEIGHTS OF TOMATO AND BEET PLANTS AND DIAMETERS OF BEET ROOTS GROWN FOR VARIOUS LENGTHS OF TIME

(Mean of 5 plants)

Solution	Tomato Centimeters in Height		Beet Centimeters in Height		Beet Diameter (Cm.)
	30 days	46 days	68 days	90 days	90 days
100 Ca	40.6	99.8	28.4	32.2	5.4
75 Ca	41.0	96.6	28.6	33.2	5.3
50 Ca	37.2	98.0	27.4	29.2	4.9
25 Ca	34.8	84.6	28.2	25.4	4.0
75 Ca + 25 Sr	34.8	84.4	27.6	35.4	5.6
50 Ca + 50 Sr	32.2	80.6	32.0	32.0	5.6
25 Ca + 75 Sr	31.6	70.2	27.8	26.0	4.8
100 Sr	28.8	47.0	20.2	20.6	4.2
75 Sr	29.6	61.4	21.8	24.2	4.5
50 Sr	34.2	74.4	25.8	27.0	4.5
25 Sr	35.4	79.4	26.2	27.4	5.1
0 Ca + 0 Sr	37.2	82.4	30.0	29.8	5.2
100 Ca Mean +2 s	46.7	109.9	34.2	39.8	7.0
100 Ca Mean -2 s	34.5	89.7	22.6	24.6	3.8

TABLE VII

THE INFLUENCE OF CALCIUM-STRONTIUM NUTRIENT SOLUTIONS ON THE DRY WEIGHT OF TOMATO PLANTS GROWN FOR 30 AND 46 DAYS

(Grams per Plant)

Treatment	30 days			46 days		
	Top	Root	Total Plant	Top	Root	Total Plant
100 Ca	2.49	0.29	2.78	10.20	0.97	11.17
75 Ca	2.40	0.28	2.68	8.84	0.90	9.74
50 Ca	1.91	0.24	2.15	10.39	1.16	11.55
25 Ca	1.89	0.40	2.29	7.78	1.22	9.00
75 Ca + 25 Sr	1.85	0.26	2.11	9.68	1.05	10.73
50 Ca + 50 Sr	1.94	0.28	2.22	9.20	0.87	10.07
25 Ca + 75 Sr	1.65	0.25	1.90	7.90	0.84	8.74
100 Sr	1.28	0.17	1.45	2.51	0.24	2.75
75 Sr	1.27	0.20	1.47	6.05	0.69	6.74
50 Sr	1.97	0.30	2.27	7.90	0.87	8.77
25 Sr	1.76	0.25	2.01	7.02	0.76	7.78
0 Ca + 0 Sr	1.97	0.31	2.28	8.56	1.14	9.70
100 Ca Mean +2 s	3.49	0.43	4.04	14.44	1.35	15.81
100 Ca Mean -2 s	1.49	0.15	1.52	5.96	0.58	6.53

TABLE VIII

THE INFLUENCE OF CALCIUM-STRONTIUM NUTRIENT SOLUTIONS ON THE DRY WEIGHT OF BEET PLANTS GROWN FOR 46, 68, AND 90 DAYS. (Grams per plant)

Treatment	46 days			68 days			90 days		
	Top	Root	Total Plant	Top	Root	Total Plant	Top	Root	Total Plant
100 Ca	1.30	0.40	1.70	4.26	3.20	7.46	9.05	13.12	22.17
75 Ca	1.02	0.31	1.33	4.20	3.03	7.23	9.47	12.03	21.50
50 Ca	0.92	0.23	1.15	4.55	2.88	7.43	7.74	10.93	18.67
25 Ca	1.13	0.31	1.44	4.06	2.78	6.84	5.33	7.39	12.72
75 Ca + 25 Sr	1.22	0.35	1.57	4.48	2.60	7.08	13.35	15.31	28.66
50 Ca + 50 Sr	1.20	0.33	1.53	5.63	2.95	8.48	10.02	13.88	23.90
25 Ca + 75 Sr	1.21	0.37	1.58	4.81	3.01	7.82	7.32	9.33	16.65
100 Sr	0.82	0.22	1.04	2.90	1.88	4.78	4.29	5.89	10.18
75 Sr	1.17	0.32	1.49	3.13	2.41	5.54	5.83	7.22	13.05
50 Sr	1.02	0.30	1.32	3.74	2.86	6.60	7.14	8.90	16.04
25 Sr	1.17	0.34	1.51	4.34	2.84	7.18	7.54	9.83	17.37
0 Ca + 0 Sr	1.12	0.29	1.41	4.84	3.58	8.42	8.26	11.12	19.38
100 Ca Mean +2 s	2.04	0.52	2.52	7.32	6.52	13.82	15.63	21.32	36.74
100 Ca Mean -2 s	0.56	0.28	0.88	1.20	0.00	1.10	2.47	4.92	7.62

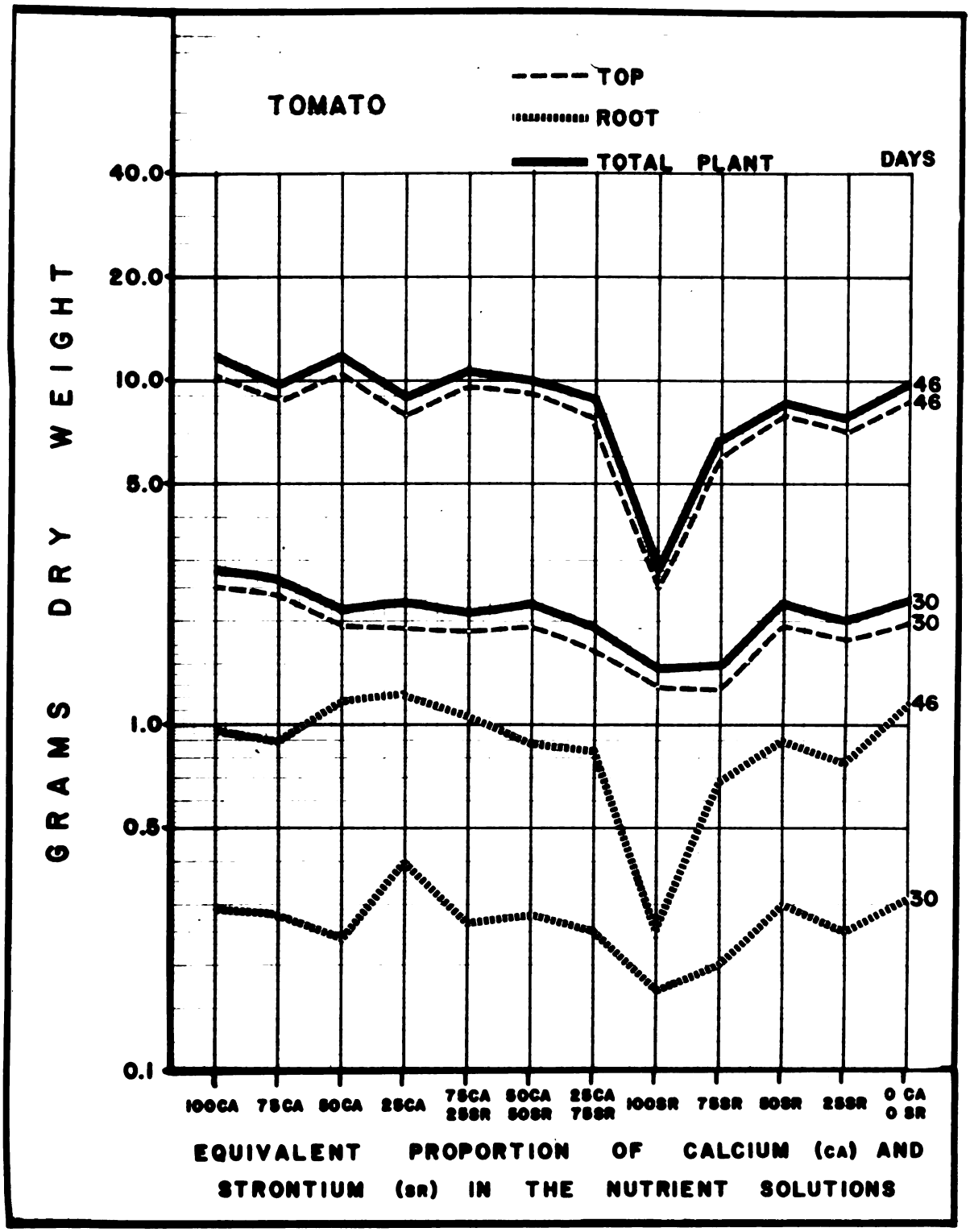

Fig. 9. The influence of calcium-strontium nutrient solutions on the dry weight of tomato plants treated for 30 and 46 days. (Mean of five plants.)

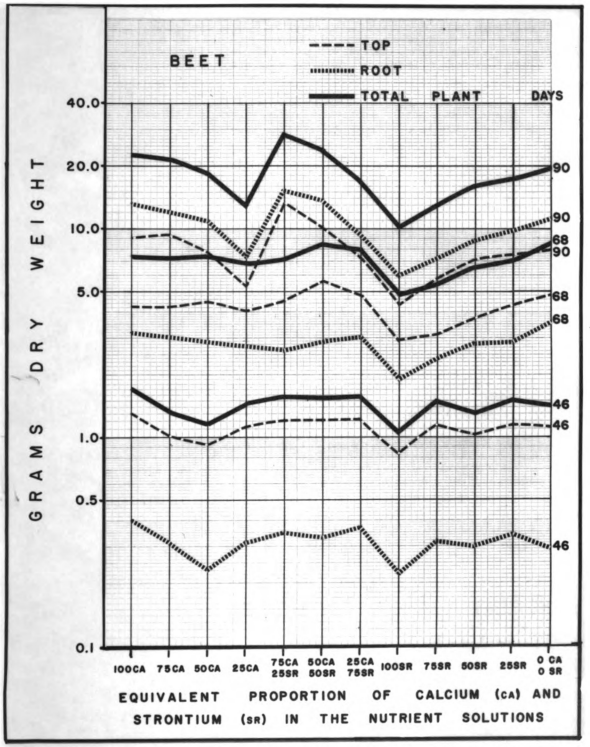

Fig. 10. The influence of calcium-strontium nutrient solutions on the dry weight of beet plants treated for 46, 68 and 90 days. (Mean of five plants.)

Figures 9 and 10 show that top growth and root growth are about equally affected by treatments depressing total growth. Plant growth was least in the 100 Sr treatment by both crops at all harvests. Smaller amounts of strontium in the nutrient solution had much less effect on growth. Where calcium and strontium were present together, growth was better than with the same amount of strontium alone, and for beet plants, it was also better than the same amount of calcium alone. Figure 10 shows that the poor growth of 25 Ca plants did not appear until the 90 day harvest. The normal growth of plants in the 0 Ca + 0 Sr treatment was unexpected but nevertheless apparent at all harvests.

Average Top/Root ratios on a dry weight basis are shown in Table IX. The 25 Ca and 0 Ca + 0 Sr treatments caused a significantly lower tomato plant T/R ratio than any others, due primarily to greater root production. The treatments had no significant effect on the T/R ratio of beets. Treatments also had little or no effect on the percent dry weight of tomato or beet tissues as shown in Table X. The high percent dry weight of tomato tops grown in 25 Ca + 75 Sr, 100 Sr, and 75 Sr treatments was caused by some leaf tissue being dead and dry at the time fresh weights were taken.

C. Chemical Analysis. Spectrographic analysis of the samples harvested from tomato plants grown for 46 days

TABLE IX

DRY WEIGHT TOP/ROOT RATIOS OF TOMATO AND BEET PLANTS GROWN FOR VARIOUS LENGTHS OF TIME IN NUTRIENT SOLUTIONS CONTAINING DIFFERENT AMOUNTS OF CALCIUM AND STRONTIUM.
(Values given are the mean of five plants)

Treatment	Tomato		Beet		
	30 days	46 days	46 days	68 days	90 days
100 Ca	8.71	10.49	3.27	1.43	.686
75 Ca	8.73	9.85	3.37	1.45	.804
50 Ca	8.11	9.10	3.90	1.58	.721
25 Ca	4.73	6.35	3.64	1.49	.733
75 Ca + 25 Sr	7.11	9.25	3.54	1.72	.870
50 Ca + 50 Sr	6.83	10.56	3.72	1.97	.720
25 Ca + 75 Sr	6.65	9.47	3.40	1.64	.808
100 Sr	7.59	10.71	3.73	1.65	.745
75 Sr	6.57	9.60	3.80	1.36	.813
50 Sr	6.71	9.10	3.46	1.40	.804
25 Sr	7.08	9.49	3.48	1.54	.780
0 Ca + 0 Sr	6.43	7.43	3.91	1.43	.743
100 Ca Mean +2 s	9.83	11.71	4.53	1.99	.880
100 Ca Mean -2 s	7.59	9.27	2.01	0.87	.492

TABLE X

PERCENT DRY WEIGHT OF TOMATO AND BEET PLANTS GROWN IN VARIOUS CALCIUM-STRONTIUM NUTRIENT SOLUTIONS AND HARVESTED AT DIFFERENT TIME INTERVALS

(Values given are the mean of five plants.)

Treatment	Tomato		Beet					
	30 days	46 days	46 days		68 days		90 days	
	Top	Top	Top	Root	Top	Root	Top	Root
100 Ca	6.18	7.45	9.83	11.23	9.90	10.86	11.05	13.39
75 Ca	6.02	7.13	10.57	11.83	10.49	11.20	10.76	12.73
50 Ca	6.16	7.13	9.20	8.98	10.22	10.17	10.99	11.98
25 Ca	6.92	7.59	9.64	8.39	10.75	10.84	11.90	12.39
75 Ca + 25 Sr	6.20	7.59	9.37	9.86	9.80	10.73	10.25	12.91
50 Ca + 50 Sr	6.48	7.47	9.03	9.86	9.86	11.26	10.04	13.35
25 Ca + 75 Sr	6.60	8.49	9.33	10.02	9.42	10.84	10.19	13.71
100 Sr	8.16	10.39	9.57	10.31	9.48	11.53	10.04	12.61
75 Sr	7.13	8.60	9.21	9.41	9.91	12.33	10.32	12.63
50 Sr	6.59	7.66	9.45	9.55	10.21	11.94	10.60	12.59
25 Sr	6.47	7.39	9.57	8.78	9.25	10.13	10.22	11.61
0 Ca + 0 Sr	6.68	7.91	9.23	10.24	9.94	11.13	10.39	11.55
100 Ca Mean +2 s	6.56	8.37	10.67	13.93	11.86	11.70	12.71	16.63
100 Ca Mean -2 s	5.80	6.53	8.99	8.53	7.94	10.02	9.39	10.15

in the various culture solutions are shown in Table XI. Table XII contains the same data for the 90 day beet plant samples. Tops and roots were analyzed for the elements magnesium, boron, phosphorus, iron, manganese and copper. Tables XIII and XIV show the top and root content of potassium, calcium and strontium in tomatoes and beets at all harvests. These values were determined by use of the flame spectrophotometer. The plant composition of all nine elements at the time of final harvest are shown in Figures 11, 12, 13, and 14 for tomato tops, tomato roots, beet tops and beet roots respectively.

These tables and figures show that the nutrient solution variables, calcium and strontium, vary in the plant tissue in proportion to the amount in the nutrient solution. The only exception was the strontium content of beet roots where both 50 Sr and 75 Sr treated roots contained more strontium than those in the 100 Sr treatment. All plants contained some calcium even where none was added to the nutrient solution. The different nutrient treatments had little effect on the content of potassium and copper in any of the four plant tissues.

The effect of treatment on plant tissue content of the other five elements can be summarized as follows. The mineral concentration in tissues from plants grown in the 100 Ca nutrient solution was used as the standard for comparison.

TABLE XI

THE INFLUENCE OF VARIOUS CALCIUM-STRONTIUM NUTRIENT SOLUTIONS ON THE MINERAL CONTENT OF TOMATO PLANTS TREATED FOR 46 DAYS

(Spectrographic analysis. Concentration expressed as percent of the dry weight.)

Treatment	Magnesium		Boron		Phosphorus		Iron		Manganese		Copper	
	Top	Root	Top	Root	Top	Root	Top	Root	Top	Root	Top	Root
100 Ca	.473	.575	.0040	.0028	.537	.892	.0151	.0350	.0063	.0423	.0021	.0290
75 Ca	.534	.482	.0043	.0029	.555	1.183	.0106	.0423	.0061	.0553	.0025	.0337
50 Ca	.489	.362	.0033	.0030	.551	1.167	.0068	.0450	.0062	.0447	.0025	.0367
25 Ca	.514	.453	.0045	.0022	.453	.833	.0101	.0318	.0064	.0215	.0023	.0270
75 Ca + 25 Sr	.509	.483	.0043	.0024	.510	.845	.0167	.0302	.0071	.0380	.0029	.0383
50 Ca + 50 Sr	.587	.585	.0032	.0030	.442	1.025	.0085	.0345	.0067	.0495	.0026	.0365
25 Ca + 75 Sr	.510	.620	.0025	.0031	.356	1.150	.0085	.0330	.0073	.0520	.0026	.0377
100 Sr	.474	--	.0037	--	.520	--	.0095	--	.0083	--	.0022	--
75 Sr	.721	--	.0040	--	.664	--	.0116	--	.0105	--	.0026	--
50 Sr	.744	.415	.0048	.0036	.830	1.022	.0133	.1125	.0101	.0477	.0028	.0300
25 Sr	.819	.287	.0065	.0033	1.045	.960	.0205	.0570	.0111	.0453	.0028	.0280
0 Ca + 0 Sr	.784	.507	.0063	.0030	1.290	1.450	.0162	.0670	.0095	.0413	.0024	.0237
100 Ca Mean +2 s	.724	--	.0056	--	.769	--	.0245	--	.0089	--	.0028	--
100 Ca Mean -2 s	.222	--	.0024	--	.305	--	.0057	--	.0037	--	.0014	--

TABLE XII

THE INFLUENCE OF VARIOUS CALCIUM-STRONTIUM NUTRIENT SOLUTIONS ON THE MINERAL CONTENT OF BEET PLANTS TREATED FOR 90 DAYS

(Spectrographic analysis. Concentration expressed as percent of the dry weight.)

Treatment	Magnesium		Boron		Phosphorus		Iron		Manganese		Copper	
	Top	Root	Top	Root	Top	Root	Top	Root	Top	Root	Top	Root
100 Ca	.656	.281	.0056	.0021	.260	.325	.0091	.0185	.0113	.0040	.0023	.0047
75 Ca	.712	.390	.0049	.0019	.309	.449	.0050	.0210	.0125	.0059	.0034	.0067
50 Ca	.790	.349	.0070	.0018	.401	.321	.0090	.0324	.0160	.0071	.0039	.0091
25 Ca	.661	.309	.0083	.0022	.272	.331	.0108	.0353	.0119	.0061	.0020	.0063
75 Ca + 25 Sr	.971	.407	.0070	.0019	.258	.302	.0112	.0308	.0121	.0055	.0033	.0062
50 Ca + 50 Sr	.943	.342	.0070	.0021	.235	.318	.0107	.0283	.0117	.0052	.0036	.0058
25 Ca + 75 Sr	.872	.462	.0054	.0022	.365	.569	.0079	.0250	.0109	.0063	.0022	.0051
100 Sr	.932	.496	.0084	.0021	.473	.618	.0067	.0150	.0164	.0092	.0026	.0069
75 Sr	.849	.432	.0091	.0022	.639	.521	.0086	.0223	.0193	.0101	.0028	.0066
50 Sr	.883	.333	.0088	.0020	.650	.481	.0134	.0181	.0206	.0083	.0039	.0086
25 Sr	.902	.311	.0096	.0021	.694	.462	.0136	.0152	.0211	.0085	.0031	.0061
0 Ca + 0 Sr	.900	.331	.0122	.0023	1.149	.682	.0177	.0271	.0186	.0080	.0038	.0061
100 Ca Mean +2 s	.811	.347	.0108	.0045	.317	.447	.0162	.0407	.0147	.0052	.0031	.0083
100 Ca Mean -2 s	.501	.215	.0004	.0000	.203	.203	.0020	.0000	.0079	.0028	.0015	.0011

TABLE XIII

THE INFLUENCE OF VARIOUS CALCIUM-STRONTIUM NUTRIENT SOLUTIONS ON THE POTASSIUM, CALCIUM AND STRONTIUM CONTENT OF TOMATO PLANTS TREATED FOR 30 AND 46 DAYS

(Flame photometric analysis. Concentration expressed as percent of the dry weight.)

Treatment	Growth Period	Potassium		Calcium		Strontium	
		Top	Root	Top	Root	Top	Root
100 Ca	30 days	8.48	7.07	1.34	0.37	0.02	0.01
	46 days	7.19	6.16	1.43	0.49	0.01	0.02
75 Ca	30 days	8.69	6.95	1.07	0.26	0.01	0.01
	46 days	7.50	6.51	1.01	0.16	0.02	0.01
50 Ca	30 days	8.65	6.91	0.71	0.14	0.02	0.01
	46 days	7.68	6.28	0.65	0.13	0.01	0.02
25 Ca	30 days	7.01	5.86	0.74	0.12	0.02	0.02
	46 days	6.93	5.66	0.51	0.08	0.02	0.02
75 Ca + 25 Sr	30 days	8.09	6.69	1.27	0.43	0.58	0.24
	46 days	7.14	5.85	1.28	0.40	0.63	0.42
50 Ca + 50 Sr	30 days	7.69	6.58	1.07	0.33	1.00	0.58
	46 days	7.38	5.87	0.94	0.29	1.14	0.72
25 Ca + 75 Sr	30 days	8.01	6.30	0.79	0.22	1.48	0.76
	46 days	6.78	5.50	0.66	0.16	1.65	0.78
100 Sr	30 days	7.15	6.83	0.61	0.15	2.36	1.07
	46 days	7.01	6.36	0.41	0.10	2.34	1.02
75 Sr	30 days	7.78	6.56	0.44	0.07	1.32	0.94
	46 days	7.21	5.23	0.27	0.04	1.51	0.70
50 Sr	30 days	8.02	6.32	0.34	0.05	0.88	0.46
	46 days	7.65	5.45	0.24	0.04	0.91	0.64
25 Sr	30 days	7.79	6.15	0.24	0.05	0.48	0.25
	46 days	7.34	5.74	0.18	0.04	0.47	0.46
0 Ca + 0 Sr	30 days	7.84	6.14	0.14	0.04	0.01	0.02
	46 days	7.05	6.14	0.11	0.03	0.00	0.01
100 Ca Mean +2 s	46 days	8.07	--	1.49	--	0.02	--
100 Ca Mean -2 s	46 days	6.31	--	1.37	--	0.00	--

TABLE XIV

THE INFLUENCE OF VARIOUS CALCIUM-STRONTIUM NUTRIENT SOLUTIONS ON THE POTASSIUM CALCIUM AND STRONTIUM CONTENT OF BEET PLANTS TREATED FOR 46, 68 AND 90 DAYS

(Flame Photometric analysis. Concentration expressed as percent of the dry weight)

Treatment	Growth Period	Potassium		Calcium		Strontium	
		Top	Root	Top	Root	Top	Root
100 Ca	46 days	8.59	4.90	1.51	0.25	0.03	0.02
	68 days	8.26	3.94	1.98	0.20	0.06	0.01
	90 days	9.07	3.99	1.85	0.19	0.02	0.02
75 Ca	46 days	7.22	4.08	1.53	0.24	0.10	0.03
	68 days	7.71	3.92	1.52	0.14	0.07	0.01
	90 days	8.35	3.94	1.64	0.14	0.02	0.01
50 Ca	46 days	7.60	5.12	1.08	0.20	0.16	0.08
	68 days	7.39	3.90	1.14	0.10	0.10	0.02
	90 days	8.02	4.03	1.22	0.09	0.03	0.01
25 Ca	46 days	7.34	4.52	0.60	0.06	0.08	0.02
	68 days	6.92	4.02	0.76	0.04	0.07	0.01
	90 days	6.93	3.37	0.80	0.05	0.07	0.02
75 Ca + 25 Sr	46 days	8.16	5.09	1.40	0.23	0.60	0.15
	68 days	7.89	4.04	1.70	0.18	0.78	0.14
	90 days	8.10	3.58	1.70	0.13	0.75	0.23
50 Ca + 50 Sr	46 days	8.47	5.42	1.10	0.21	1.24	0.41
	68 days	7.74	3.71	1.18	0.14	1.52	0.30
	90 days	8.48	3.37	1.40	0.07	1.68	0.40
25 Ca + 75 Sr	46 days	8.44	4.84	0.72	0.12	1.84	0.50
	68 days	7.78	4.18	0.96	0.10	2.59	0.49
	90 days	8.78	3.87	0.91	0.07	2.37	0.44
100 Sr	46 days	7.99	5.01	0.49	0.08	2.14	0.69
	68 days	8.42	3.88	0.48	0.05	2.94	0.59
	90 days	9.15	4.05	0.48	0.04	2.99	0.38
75 Sr	46 days	7.82	4.88	0.58	0.09	1.69	0.66
	68 days	8.01	3.54	0.48	0.06	1.83	0.53
	90 days	8.78	3.74	0.39	0.04	2.04	0.58
50 Sr	46 days	7.38	4.62	0.50	0.08	0.92	0.68
	68 days	7.76	3.72	0.52	0.04	1.18	0.63
	90 days	8.14	3.65	0.44	0.04	1.18	0.76
25 Sr	46 days	7.40	4.50	0.44	0.07	0.51	0.32
	68 days	8.26	4.22	0.38	0.04	0.48	0.38
	90 days	8.34	4.05	0.36	0.02	0.53	0.33
0 Ca + 0 Sr	46 days	8.11	4.85	0.25	0.04	0.06	0.04
	68 days	8.11	3.66	0.26	0.02	0.01	0.01
	90 days	7.90	3.37	0.27	0.02	0.03	0.00
100 Ca Mean + 2 s	90 days	10.81	5.99	2.29	0.28	0.05	0.03
100 Ca Mean −2 s	90 days	7.33	1.99	1.37	0.10	0.00	0.00

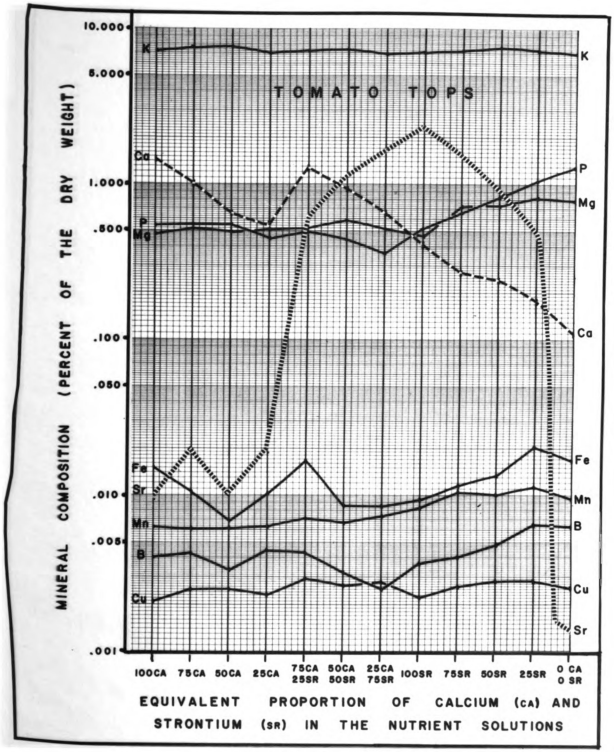

Fig. 11. The influence of various calcium-strontium nutrient solutions on the mineral content of tomato tops treated for 46 days.

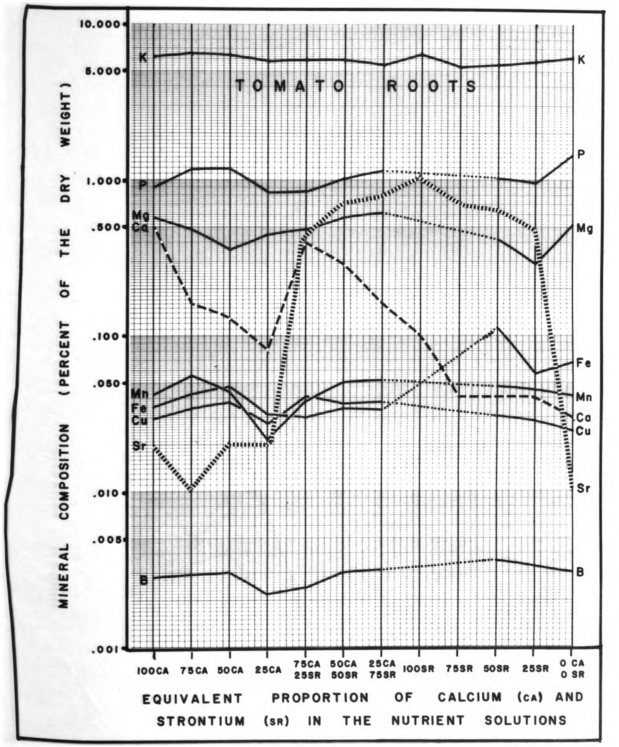

Fig. 12. The influence of various calcium-strontium nutrient solutions on the mineral content of tomato roots treated for 46 days.

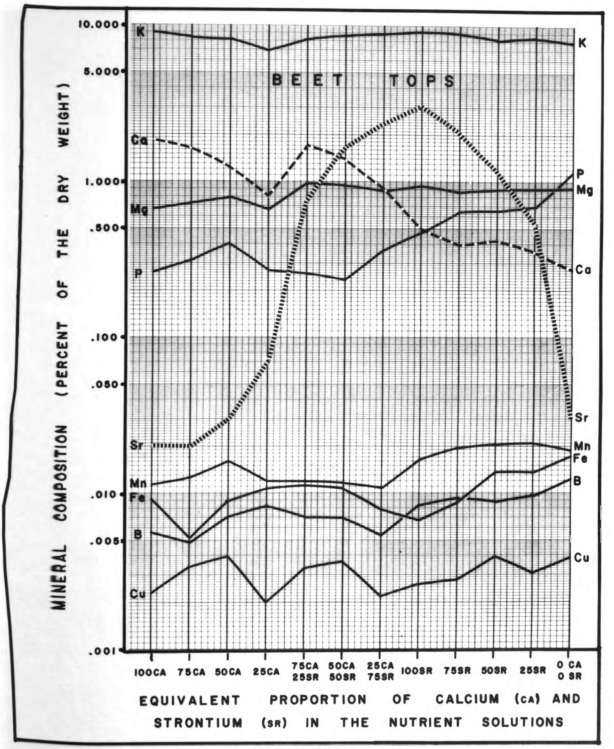

Fig. 13. The influence of various calcium-strontium nutrient solutions on the mineral content of beet tops treated for 90 days.

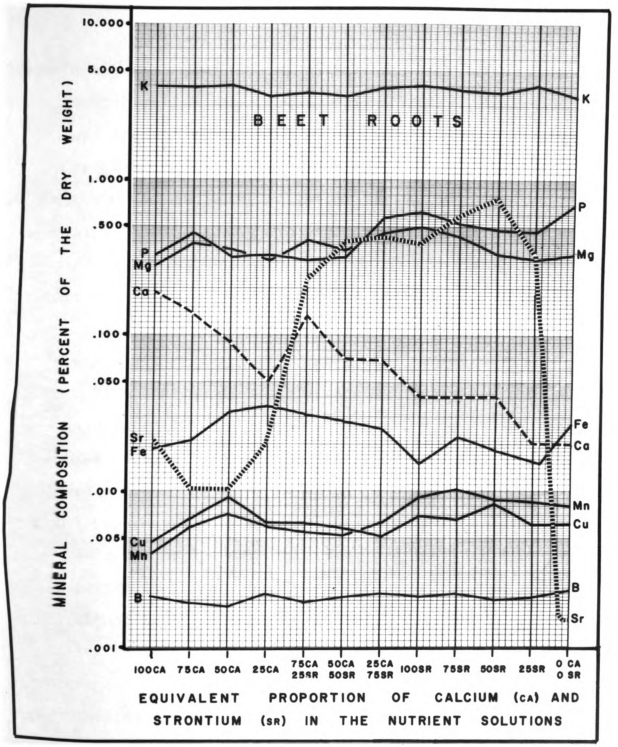

Fig. 14. The influence of various calcium-strontium nutrient solutions on the mineral content of beet roots treated for 90 days.

Tomato tops: The iron concentration varied somewhat but variation was not correlated with treatment. Boron was significantly higher in the 25 Sr and 0 Ca + 0 Sr treatments but was otherwise relatively constant. All the 0 Ca treatments except 100 Sr and 75 Sr showed a significant increase in phosphorus, magnesium and manganese concentration.

Tomato roots: Variation in nutrient solutions had little effect on magnesium and boron concentration. Phosphorus and manganese were also fairly constant except that 0 Ca + 0 Sr showed a considerably higher phosphorus concentration and 25 Ca roots had low manganese. Iron was much higher when calcium was absent from the nutrient solution.

Beet tops: A lack of calcium in the nutrient solution caused some increase in boron, and a significant increase in phosphorus and manganese. Iron was appreciably higher in the 50 Sr, 25 Sr, and 0 Ca + 0 Sr treatments. The addition of strontium to the nutrient solution, regardless of calcium content, caused a significant increase in magnesium content.

Beet roots: The treatments had no significant effect on boron and iron content. Lack of calcium in the nutrient solution caused an increase in manganese content; high

strontium caused an increase in magnesium; while either a lack of calcium or high strontium caused an increase in phosphorus content.

These results show that in many cases strontium can be added or substituted for the nutrient solution calcium and not cause any pronounced effect upon the absorption and accumulation of other plant nutrients. On the other hand the tissue accumulation of some elements is considerably affected by the addition of strontium or the withholding of calcium.

The plants in this experiment were found to contain generally higher concentrations of several elements than those given by Beeson (2) and Goodall and Gregory (18) for tomatoes and beets. However, the analyses for calcium, potassium, magnesium and phosphorus agree well with those of Newton (39) who grew plants in nutrient solutions very similar to the 100 Ca treatment here. He noted that plants grown in sand or solution culture are often higher in mineral constituents, probably because nutrient solutions are more concentrated than normal soil solutions.

It is interesting to compare the mineral content of plant tops with that of the roots. Tomato tops contain more potassium, calcium, magnesium and boron, while the roots are higher in phosphorus, iron, manganese and copper. Beet tops contain more potassium, calcium, magnesium, boron and manganese, while the roots are higher in iron and copper. It should

be recognized that some and perhaps much of the mineral concentration recorded for roots represents adsorbed rather than absorbed nutrients. Phosphorus is about the same in beet tops and roots. Both tomato and beet plants accumulate a higher concentration of strontium in the tops than in the roots when grown for prolonged periods in strontium solutions. Where analyses were made at all times of harvest (Tables XIII and XIV) it was found that the potassium content of beet tops tends to increase with age while in beet roots, tomato tops and tomato roots the tendency is for a decrease.

A comparison of calcium and strontium absorption on a percent dry weight basis is not strictly valid because of the higher atomic weight of strontium. Therefore the plant content of these two elements was converted to milliequivalents per gram of dry tissue. These values are shown in Table XV for tomato and Table XVI for beet. They are also shown in Figures 15 and 16 where a comparison is made with the total plant dry weight at the last harvest. On a milliequivalents basis tomato tops and beet tops can accumulate nearly as much strontium as calcium. Tomato and beet roots appear to take up as much or more strontium than calcium but part of the strontium determined in root samples may be adsorbed on the roots rather than absorbed into them. It should also be noted that the addition of strontium to the 75, 50 and 25 calcium levels generally caused an increased accumulation of calcium in all four tissues, although the increase

TABLE XV

CALCIUM AND STRONTIUM CONTENT OF TOMATO PLANTS EXPRESSED AS MILLIEQUIVALENTS PER GRAM OF DRY TISSUE AFTER 30 AND 46 DAYS OF GROWTH IN VARIOUS CALCIUM - STRONTIUM NUTRIENT SOLUTIONS. (Values given are the average of five plants.)

Treatment	30 days				46 days			
	Calcium		Strontium		Calcium		Strontium	
	Top	Root	Top	Root	Top	Root	Top	Root
100 Ca	.695	.185	.004	.002	.715	.245	.002	.004
75 Ca	.535	.130	.002	.002	.505	.080	.004	.002
50 Ca	.355	.070	.004	.002	.325	.065	.002	.004
25 Ca	.370	.060	.004	.004	.255	.040	.004	.004
75 Ca + 25 Sr	.635	.215	.132	.054	.640	.200	.143	.095
50 Ca + 50 Sr	.535	.165	.227	.134	.470	.145	.259	.163
25 Ca + 75 Sr	.395	.110	.336	.172	.330	.080	.374	.177
100 Sr	.305	.075	.536	.243	.205	.050	.531	.232
75 Sr	.220	.035	.300	.213	.135	.020	.343	.159
50 Sr	.170	.025	.200	.104	.120	.020	.206	.145
25 Sr	.120	.025	.109	.057	.090	.020	.107	.104
0 Ca + 0 Sr	.070	.020	.002	.004	.055	.015	.000	.004

TABLE XVI

CALCIUM AND STRONTIUM CONTENT OF BEET PLANTS EXPRESSED AS MILLIEQUIVALENTS PER GRAM OF DRY TISSUE AFTER 46, 68 AND 90 DAYS OF GROWTH IN VARIOUS CALCIUM-STRONTIUM NUTRIENT SOLUTIONS

(Values given are the average of five plants)

Treatment	46 days				68 days				90 days			
	Calcium		Strontium		Calcium		Strontium		Calcium		Strontium	
	Top	Root	Top	Root	Top	Root	Top	Root	Top	Root	Top	Root
100 Ca	.755	.125	.007	.004	.990	.100	.014	.002	.915	.095	.004	.004
75 Ca	.765	.120	.023	.007	.760	.070	.016	.002	.820	.070	.004	.002
50 Ca	.540	.100	.036	.018	.570	.050	.023	.004	.610	.045	.007	.002
25 Ca	.300	.030	.018	.004	.380	.020	.016	.002	.400	.025	.016	.004
75 Ca + 25 Sr	.700	.115	.136	.034	.850	.090	.177	.032	.850	.065	.170	.052
50 Ca + 50 Sr	.550	.105	.281	.093	.590	.070	.345	.068	.700	.035	.381	.091
25 Ca + 75 Sr	.360	.060	.418	.114	.480	.050	.588	.111	.455	.035	.538	.100
100 Sr	.245	.040	.486	.157	.240	.025	.667	.134	.245	.020	.679	.086
75 Sr	.290	.045	.384	.150	.240	.030	.415	.120	.195	.020	.463	.132
50 Sr	.250	.040	.209	.154	.260	.020	.268	.143	.220	.020	.268	.172
25 Sr	.220	.035	.116	.073	.190	.020	.109	.086	.180	.010	.120	.075
0 Ca + 0 Sr	.125	.020	.014	.009	.130	.010	.002	.002	.135	.010	.007	.000

Fig. 15. Tomato plant calcium and strontium content in relation to total dry weight after 46 days of treatment with various calcium-strontium nutrient solutions. (Mean of five plants.)

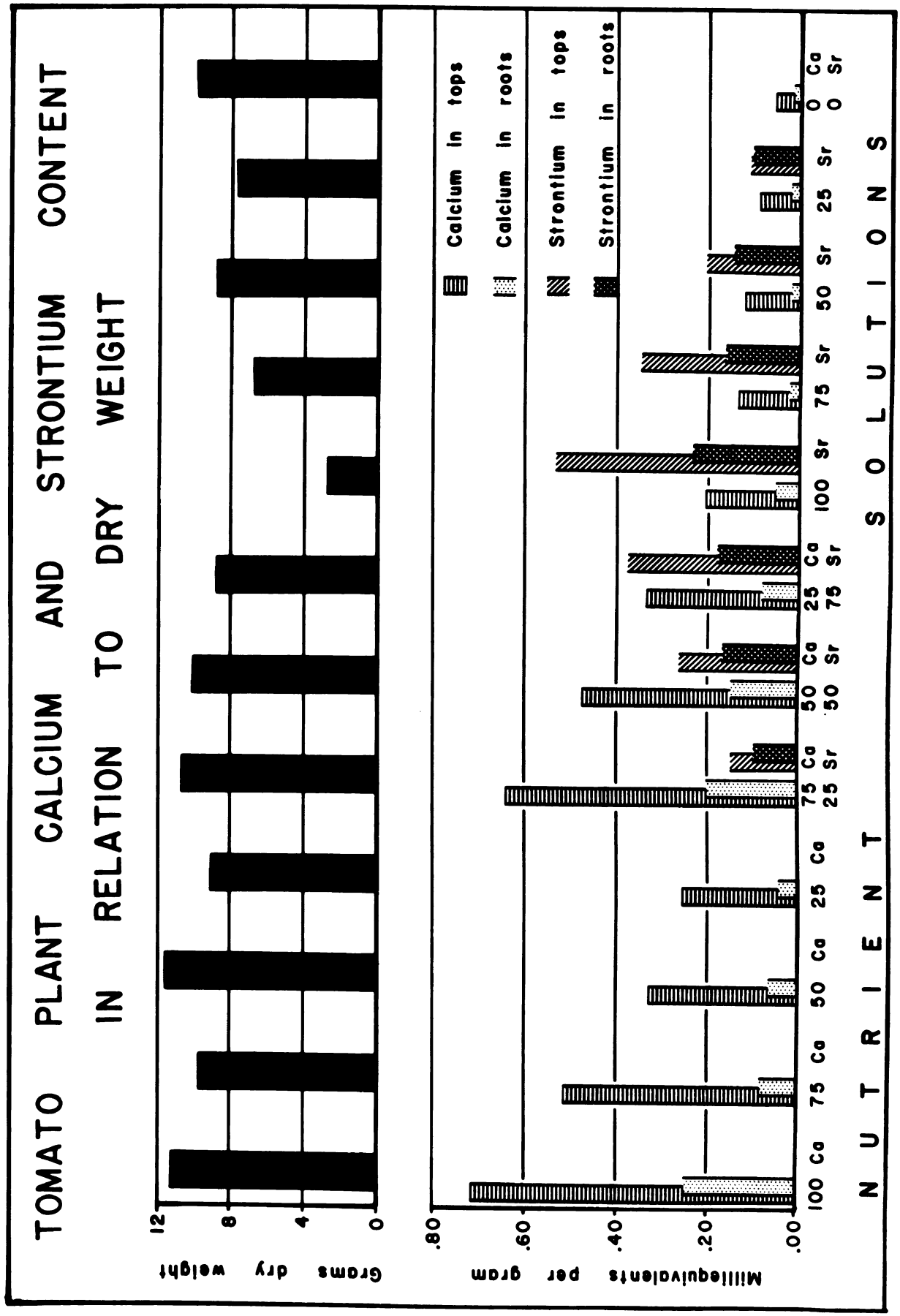
TOMATO PLANT CALCIUM AND STRONTIUM CONTENT
IN RELATION TO DRY WEIGHT
Grams dry weight
12
8
4
0
Milliequivalents per gram
.80
.60
.40
.20
.00
Calcium in tops
Calcium in roots
Strontium in tops
Strontium in roots
100 Ca
75 Ca 25 Sr
50 Ca 50 Sr
25 Ca 75 Sr
100 Sr
75 Ca 25 Sr
50 Ca 50 Sr
25 Ca 75 Sr
0 Ca 0 Sr
NUTRIENT SOLUTIONS

Figure 15

Fig. 16. Beet plant calcium and strontium content in relation to total dry weight after 90 days of treatment with various calcium-strontium nutrient solutions. (Mean of five plants.)

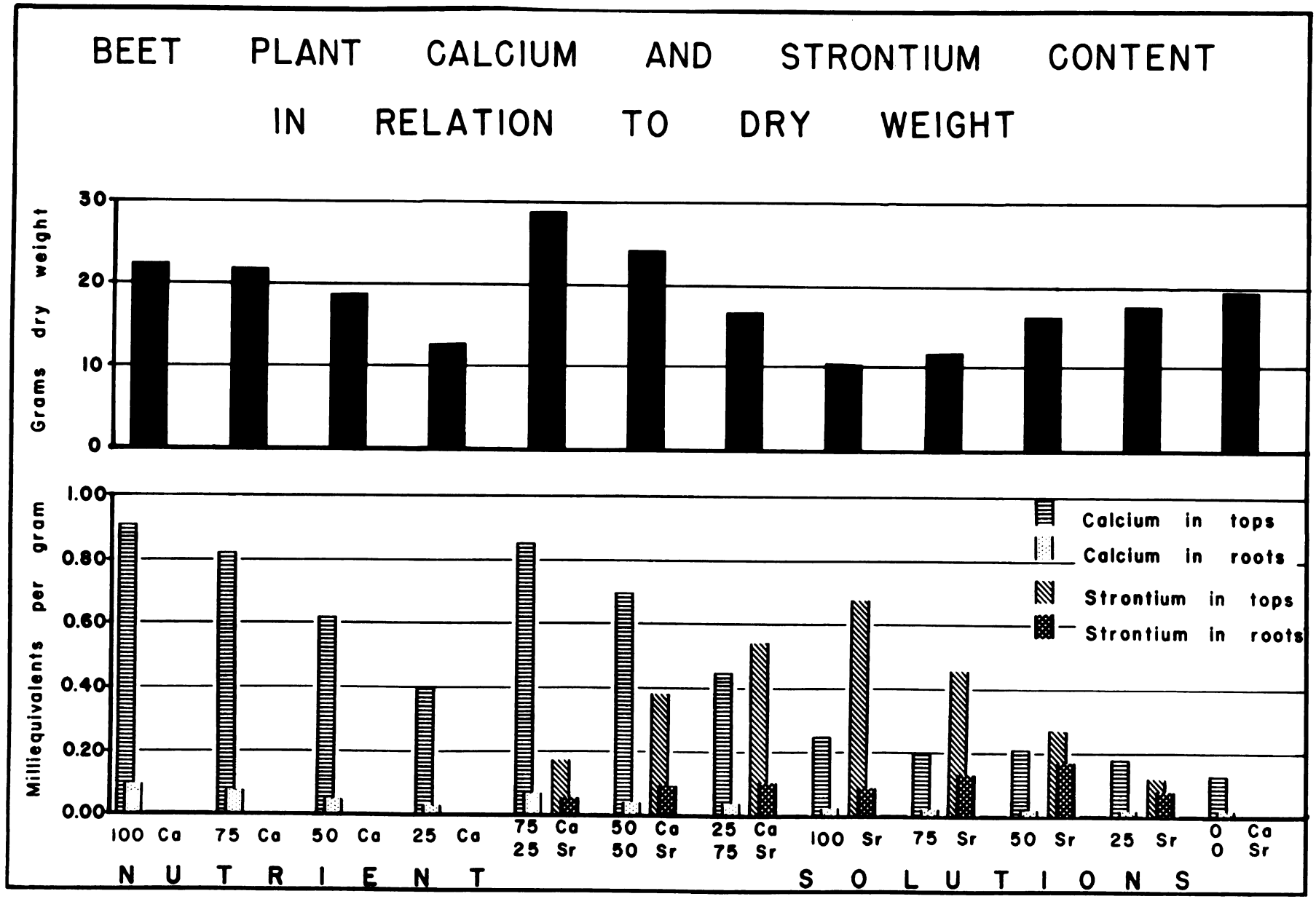
BEET PLANT CALCIUM AND STRONTIUM CONTENT
IN RELATION TO DRY WEIGHT
Grams dry weight
30
20
10
0
Milliequivalents per gram
1.00
0.80
0.60
0.40
0.20
0.00
Calcium in tops
Calcium in roots
Strontium in tops
Strontium in roots
100 Ca
75 Ca
50 Ca
25 Ca
75 Ca 25 Sr
50 Ca 50 Sr
25 Ca 75 Sr
100 Sr
75 Sr
50 Sr
25 Sr
0 Ca 0 Sr
NUTRIENT SOLUTIONS

Figure 16

was less pronounced in beet roots than the other tissues. Conversely, the addition of calcium to the 75, 50, and 25 strontium levels resulted in increased strontium accumulation in tomato tops and beet tops, had little effect on the strontium content of tomato roots, and depressed the strontium content of beet roots. Thus it would appear that calcium and strontium, when present together in a nutrient solution, generally aid the accumulation of each other in beet tops and tomato tops.

Experiment 3

Objective

To analyze field grown plants for strontium and calcium. The determination of strontium should show whether the soils in the vicinity of East Lansing, Michigan, contain any appreciable available strontium. Calcium analysis will allow comparison between field grown plants and those grown in sand culture greenhouse experiments.

Materials and Methods

Tomato, beet, pepper and eggplant samples were collected from three locations on September 23, 1953. Samples one through six came from several locations at the Horticulture Farm. Samples seven through ten were taken from the author's home garden, and samples eleven and twelve came from a garden

north of East Lansing. Duplicate four gram samples of oven dried tissue were ashed in the muffle at 600° C for twenty hours and taken up in one percent perchloric acid in the usual manner. Potassium, sodium, calcium and strontium in these solutions were determined on the flame spectrophotometer by the method described earlier. The potassium and sodium determinations were used only to correct for flame interference with calcium and strontium.

Results

The plant tissue concentration of calcium and strontium expressed as percent of the oven dry weight are shown in Table XVII. A few samples contained trace amounts of strontium but in most samples none could be detected by the flame spectrophotometer method. These data indicate there is very little available strontium in the soils of this area. The analyses show that the test plant leaves contain considerable calcium while tomato fruits, pepper fruits, and beet roots are normally low in this element. Samples two and four, where beet leaf blades and petioles were analyzed separately, show that most of the beet leaf calcium is contained in the blade.

TABLE XVII

CALCIUM AND STRONTIUM CONTENT OF TOMATO, BEET, EGGPLANT AND PEPPER PLANTS GROWN UNDER FIELD CONDITIONS

Sample	Plant Tissue	Percent of the Dry Weight	
		Calcium	Strontium
1a	Beet roots	0.06	.004
b	Beet tops	1.54	.000
2a	Beet leaf blades	1.67	.000
b	Beet leaf petioles	0.28	.002
3a	Beet roots	0.06	.002
b	Beet tops	1.41	.000
4a	Beet leaf blades	1.42	.000
b	Beet leaf petioles	0.24	.000
5a	Pepper fruits	0.02	.005
b	Pepper leaves	2.35	.004
6a	Tomato fruits	0.02	.004
b	Tomato leaves	4.06	.000
7a	Beet tops	2.05	.000
b	Beet roots	0.18	.000
8a	Tomato fruits	0.03	.000
b	Tomato leaves	4.78	.000
9a	Pepper fruits	0.04	.000
b	Pepper leaves	4.67	.000
10a	Eggplant leaves	3.88	.000
11a	Beet tops	1.94	.000
b	Beet roots	0.09	.000
12a	Tomato leaves	4.42	.000
b	Tomato fruits	0.03	.002

B. Comparative Absorption and Translocation of Radiostrontium, Radiocalcium and Radiobarium in Tomato, Beet and Bean Plants as Determined by Autoradiography

Experiment 4

Objective

The semi-quantitative determination of calcium, strontium and barium absorbed and translocated by bean, tomato and beet plants following application to the roots or leaves.

Materials and Methods

Plants were grown in the greenhouse during the fall and winter of 1951-1952, and treated when of sufficient size to be pressed flat on an eight by ten inch area. Bean, tomato and beet plants were treated with Ca^{45} and Sr^{89} while only tomato and beet received Ba^{140}. The plants were harvested, dried and prepared for exposure to X-ray film as described earlier. Details of the treating solutions and times of exposure to X-ray film are given in Table XVIII. A low calcium nutrient solution was used for growing all bean plants while tomatoes and beets were grown at two levels of calcium. Bean plants were treated in three ways by (a) dipping the first trifoliate leaf in the isotope solution, (b) dipping the first pair of leaves, or (c) adding the isotope to the root medium. Tomatoes and beets were treated by either dipping the entire foliage or adding the isotope to the root medium. Bean

TABLE XVIII

CHARACTERISTICS OF RADIOISOTOPE SOLUTIONS UTILIZED FOR TREATING PLANTS FOR AUTORADIOGRAPHY, AND EXPOSURE TIMES FOR THE AUTORADIOGRAMS

Plant	Date of Treatment	Radio-isotope	Radioisotope Concentration (microcuries per ml.)	(microcuries per mg. of stable element)	Concentration of Stable Element (milliequivalents per ml.)	X-ray Film Exposure Time (days)
Bean	10-15-51	Ca^{45}	1.0	0.93	.054	7
		Sr^{89}	1.0	0.60	.038	7
Tomato	2-23-52	Ca^{45}	1.0	1.67	.030	4
and		Sr^{89}	0.5	0.38	.030	5
Beet		Ba^{140}	0.05	0.024	.030	15

plants were harvested at 8, 24, 60 and 120 hours after treatment while beet and tomato plants were harvested at 8, 24, and 96 hours. Root applications consisted of five milliliters of the treating solutions for beans and ten milliliters of each treating solution for tomatoes and beets. All X-ray films were developed for six minutes in Kodak X-ray Developer following exposure to the radioactive plants.

Results

Autoradiograms of radiocalcium and radiostrontium applied to bean plants are shown in Figures 17 and 18. These show the distribution of the two elements is very much alike, and neither one exhibits much translocation from the site of a leaf application. The X-ray negatives of some foliar treated plants showed slight traces of radioactivity in the stem and other plant parts but the impression on the film was usually too faint to be reproduced photographically. This movement of trace amounts was independent of time, often being higher at 8 and 24 hours after treatment than at 120 hours.

Root applications, on the other hand, showed absorption and translocation of the radioisotope to be directly proportional to treatment period. The distribution of radiocalcium following root absorption was very uniform throughout the bean plant; old leaves accumulating as much as young leaves.

Fig. 17. Autoradiograms of radiocalcium (Ca^{45}) in bean plants.

Top: First trifoliate leaf dipped in isotope solution.
Center: First pair of leaves dipped in isotope solution.
Bottom: Isotope added to root medium.

Left: 24 hours after treatment
Right: 60 hours after treatment

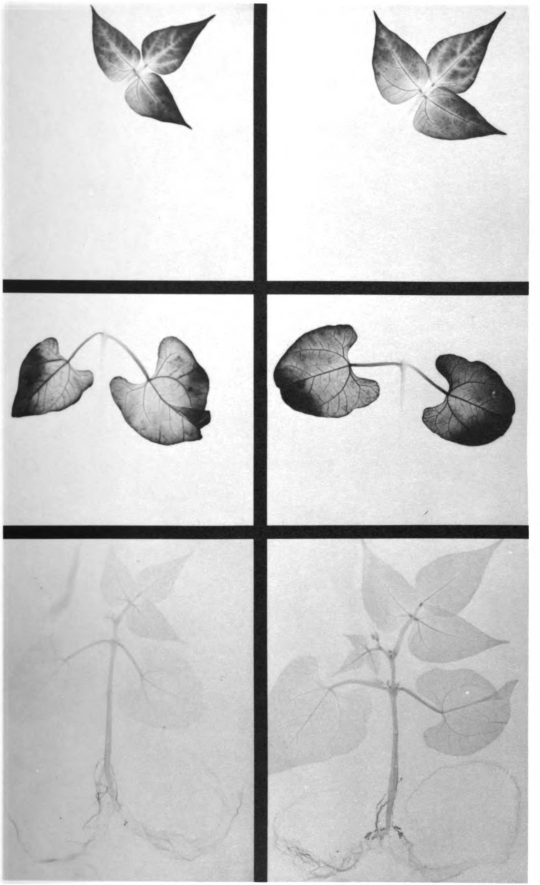

Figure 17

Fig. 18. Autoradiograms of radiostrontium (Sr^{89}) in bean plants.

Top: First trifoliate leaf dipped in isotope solution
Center: First pair of leaves dipped in isotope solution
Bottom: Isotope added to root medium

Left: 24 hours after treatment
Right: 60 hours after treatment

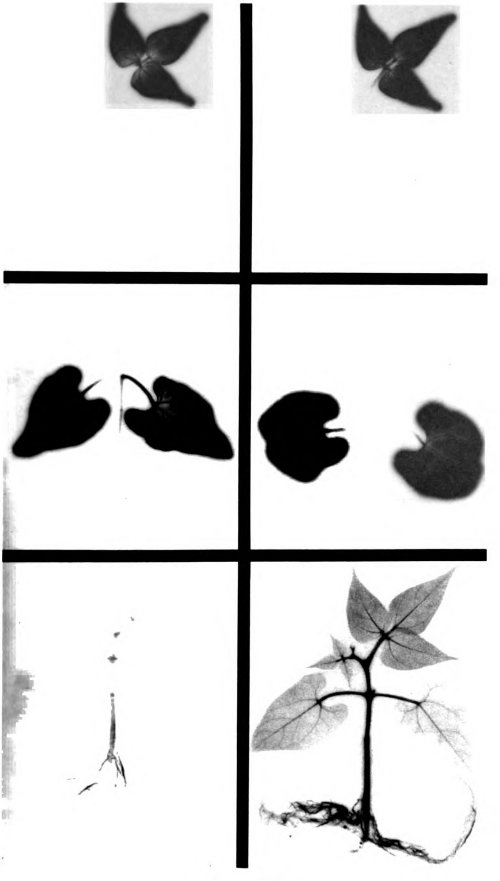

Figure 18

Radiostrontium showed a slight tendency to accumulate in the vascular tissue but was otherwise uniformly distributed throughout the plant. Both calcium and strontium accumulated in the nodules on the bean roots.

Tomato plants harvested 96 hours after treatment with radiocalcium (Ca^{45}), radiostrontium (Sr^{89}) and radiobarium (Ba^{140}) are shown in Figures 19, 20 and 21 respectively. There was no detectable downward movement of these elements from a leaf application to tomato plants. The initial calcium content of the plants had considerable effect on the uptake of the radioisotopes from the root medium. Plants low in calcium took up more Ca^{45}, the same amount of Sr^{89}, and less Ba^{140} than plants higher in calcium. Radiocalcium and radiostrontium in the plants increased with the treatment period. Radiobarium content, on the other hand, was the same at 8, 24, and 96 hours. Similar to beans, translocation from the roots to all tomato plant parts was general for all three isotopes, but distribution within plant parts varied. Calcium was distributed uniformly throughout the plant while strontium and barium accumulated in the vascular tissue.

Beet plants treated with the three radioisotopes and harvested 96 hours later are also shown in Figures 19, 20 and 21. Downward movement from treated leaves into the small fleshy root occurred with all three isotopes although the darkening of the X-ray emulsion by Ca^{45} was so slight that it

Fig. 19. Autoradiograms of tomato and beet plants harvested 96 hours subsequent to treatment with radiocalcium (Ca^{45}).

Left: Root application
Right: Foliage application

Figure 19

Fig. 20. Autoradiograms of tomato and beet plants harvested 96 hours subsequent to treatment with radiostrontium (Sr^{89}).

Left: Root application
Right: Foliage application

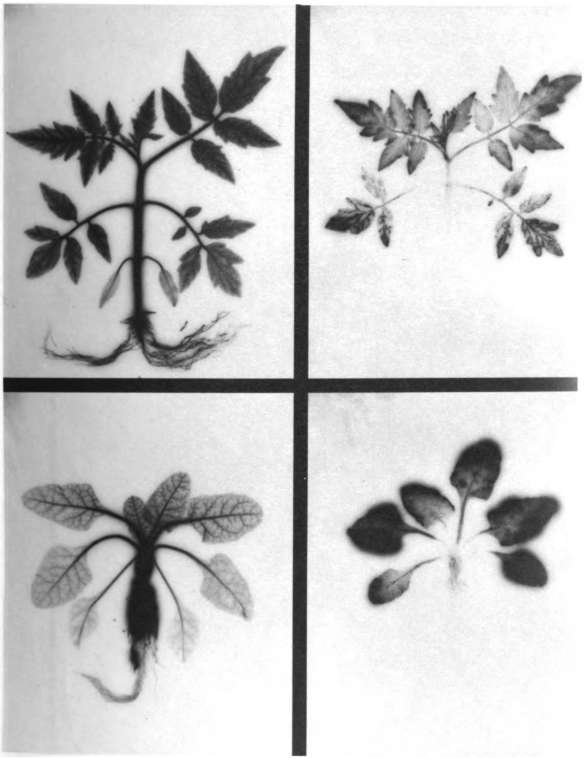

Figure 20

Fig. 21. Autoradiograms of tomato and beet plants harvested 96 hours subsequent to treatment with radiobarium (Ba^{140}).

Left: Root application
Right: Foliage application

Figure 21

could not be reproduced (Figure 19). The amount of downward movement by all three isotopes was apparently the same at 8, 24 and 96 hours. The quantity of radiostrontium and radiobarium taken up by beets from a root application appeared also to be the same at all three harvest periods while radiocalcium progressively accumulated at each succeeding harvest. Only radiocalcium absorption was affected by the initial calcium content of the beet plants. At eight hours the low calcium plants had accumulated considerably more Ca^{45} than high calcium plants but by 24 hours this difference had disappeared. When absorbed by beet roots, calcium and barium spread uniformly throughout the leaves while strontium accumulated in the leaf veins and appeared to be more concentrated in the younger leaves. Barium is accumulated in large amounts in the stem and transition zone between the root and the stem of the beet plant.

Experiment 5

Objective

Determine the distribution of radiostrontium and radiocalcium in beet roots after addition of radioisotopes to the nutrient solutions in which the roots were growing.

Materials and Methods

Beets were grown in the greenhouse in six inch pots filled with sand. Each clay pot was set in a two quart enamel

pan partly filled with Hoagland's nutrient solution. Ten microcuries of radiostrontium (Sr^{90}) were added to each of the nutrient solutions August 2, 1952, when the beet roots reached a diameter of five to six centimeters. Beet roots were harvested 36 hours later. Another set of plants were grown the following year and these were each treated with 50 microcuries of Ca^{45} on August 4, 1953, and harvested after 80 hours. Transverse and longitudinal sections approximately 1 1/2 millimeters thick were cut with a home-made vegetable slicer. Radiostrontium treated sections were dried under pressure with heat lamps while the radio-calcium sections were dried under pressure in a circulating 70°C oven. The latter method was found the more satisfactory. Shrinkage amounted to about ten percent of the diameter. Radiostrontium treated sections were exposed to X-ray film for 19 days and radiocalcium sections for 33 days.

Results

Distribution of radiostrontium and radiocalcium in the fleshy roots of beets is shown in Figure 22. A quantitative estimation of the radiostrontium or calcium in these sections is not possible because of differences in beta particle energy and conditions of treatment and exposure. The pattern of distribution, however, is very similar for the two elements. The greatest accumulation is in the basal parts of the root and in the stem portions with most of the upward movement

Fig. 22. Autoradiograms of transverse and longitudinal sections of beet roots showing the distribution of radiostrontium (above) and radiocalcium (below) following isotope additions to the root medium. (Actual diameter of roots 5-6 centimeters).

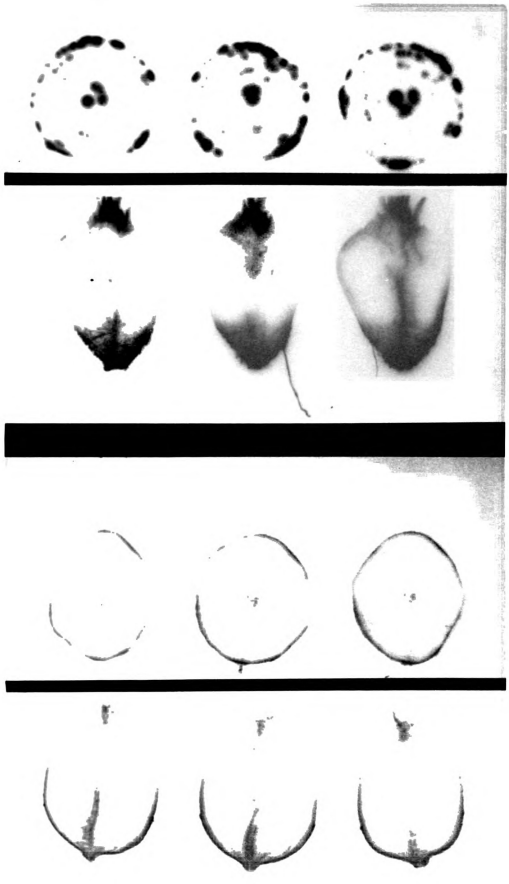

Figure 22

taking place in the central zone of primary and secondary vascular tissues or in the tertiary tissues at the periphery of the root.

Experiment 6

Objective

Determine the pattern of strontium absorption by tomato fruits following root application and direct treatment of the intact skin.

Materials and Methods

Two tomato plants from the high calcium series of subsequently described Experiment 9 (page 99) were used. The plants were grown in Hoagland's nutrient solution until the first cluster fruits were six to seven centimeters in diameter. Fruits were set with a 30 parts per million solution of p-chlorophenoxyacetic acid and consequently were mostly seedless. However, one fruit of the soil treated plant contained seeds. (See bottom two sections, Figure 24) The fruits of one plant were painted twice on August 4, 1953, with the radioactive strontium chloride dipping solution used in Experiment 9 (see page 100). According to the counting data the application was approximately 0.25 microcuries of Sr^{90} per fruit. Treatment of the other plant consisted of adding 30 microcuries of Sr^{90} to the nutrient solution. Painted

fruits were harvested at 36 hours and fruits from the root treated plant were collected after 80 hours. Approximately 1 1/2 millimeter median transverse sections were cut from the fruits and dried in a 70°C forced air oven. The Sr^{90} painted fruits were exposed to X-ray film for seven days while fruit sections from the root treated plant required an eighteen day exposure.

Results

The absorption of radiostrontium through the skin of tomato fruits is demonstrated by Figure 23. A considerable amount of Sr^{90} moved into the interior of the fruit without accumulation in any particular tissue. Figure 24 shows the distribution of radiostrontium in tomato fruits following absorption by the roots. The greatest concentration was in or near the vascular strands. There was no movement into the seeds.

Fig. 23. Distribution of radiostrontium (Sr^{90}) in tomato fruit 36 hours after painting radiostrontium on the surface. (Actual diameter of fruit 6 centimeters.)

Top: Autoradiograms
Bottom: Photographs of the fruit sections

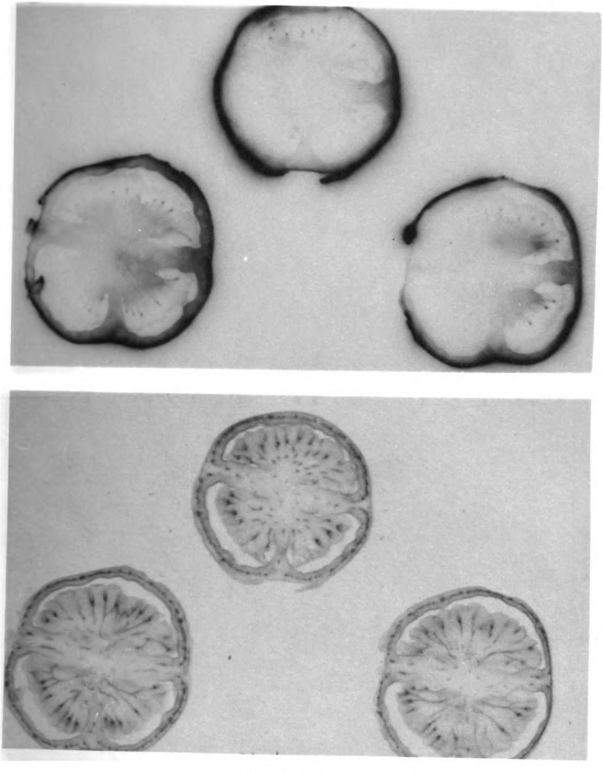

Figure 23

Fig. 24. Distribution of radiostrontium (Sr^{90}) in tomato fruits 80 hours after radiostrontium application to the plant roots. (Actual diameter of fruits 6-7 centimeters).

Left: Autoradiograms
Right: Photographs of the fruit sections

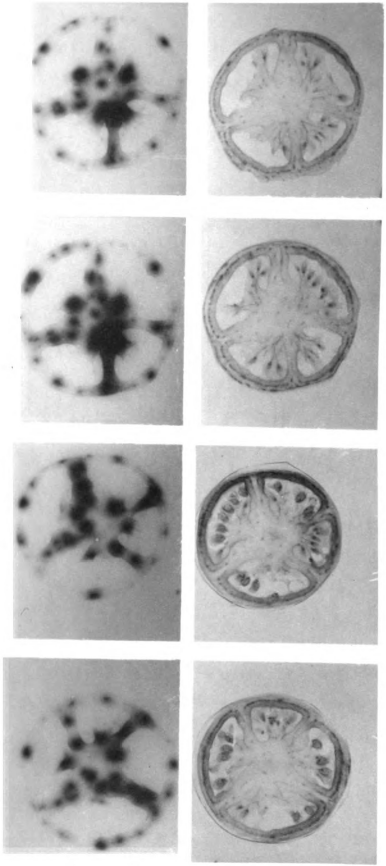

Figure 24

C. Comparative Absorption and Translocation of Strontium, Calcium and Barium in Tomato and Beet Plants as Indicated by Radioactive Isotopes

Experiment 7

Objective

Determine the relative uptake of radiocalcium, radiostrontium and radiobarium by the leaves and roots of beet plants during a four day treatment period.

Materials and Methods

Beets were seeded in a flat of sand on June 19, 1952, and pricked off on July 14, into six inch clay pots filled with Wausau Quartz #8. The pots were placed in large painted metal pans containing one to two inches of Hoagland's nutrient solution. On August third, one-half of the plants were changed to a nutrient solution without calcium. These two groups of plants will be referred to hereafter as "high calcium" and "low calcium" plants. All plants were treated on August 16, 1952, and harvested four days later.

Treating solutions were made by adding one microcurie per millilieter of Ca^{45}, or Sr^{90} and 0.16 microcurie per milliliter of Ba^{140} respectively to 0.0272 molar solutions of $CaCl_2$, $SrCl_2$ and $BaCl_2$. Thus the treating solutions had the same concentrations on the basis of chemical equivalents. Specific activities of these solutions were 0.93 microcuries

of Ca^{45} per milligram of calcium, 0.42 microcuries of Sr^{90} per milligram of strontium, and 0.043 microcuries of Ba^{140} per milligram of barium. Plants were selected at random and all treatments were replicated four times. Roots were treated by adding ten milliliters of the treating solution to the plant's nutrient solution held in a two quart pan. Foliage treatment consisted of inverting the plant and dipping all leaves in the treating solution. Inverted plants were supported in this position until the leaves were dry. It was calculated that approximately two milliliters of solution remained on the leaves.

All plants were harvested after 96 hours of treatment. Foliage dipped plants were divided into two samples, leaves and root; while root treated plants were divided into three samples, the three or four youngest leaves, the remaining leaves, and the root. Samples were dried at 70°C, weighed and prepared for counting. Ba^{140} was counted as the dried barium carbonate precipitated from a solution of the plant ash; Ca^{45} was counted as the ash of ground tissue; and Sr^{90} was counted simply as dry ground tissue. Grinding was done in a Wiley mill using a 40-mesh screen. Self-absorption curves were plotted for all three materials, and then samples small enough to have little or no self-absorption were used. Radiobarium and radiocalcium were counted in a Tracerlab, Model SC-1B, autoscaler and radiostrontium was counted

in a Nuclear Instruments and Chemical Corporation Ultrascaler, Model 172. In all cases aliquots of the treating solution as reference standards were counted along with the plant tissue samples. Weight in micrograms of the element in the plant tissue sample derived from the treatment was calculated from the known concentration of the treating solution and the measured radiation from the plant tissue and the treating solution. To more accurately evaluate the ionic absorption, micrograms were converted to microequivalents by dividing by the equivalent weight of the element.

Results

Calcium, strontium and barium absorption by beet leaves and roots is shown in Table XIX. Flame spectrophotometer analysis showed that "high calcium" plants contained 0.86, 1.59 and 0.11 percent calcium in the dry tissue of young leaves, old leaves and roots respectively. Comparable "low calcium" plants contained 0.19, 0.94 and 0.04 percent calcium in these same tissues. In spite of this wide difference in plant calcium content there was very little difference in radiocalcium, radiostrontium or radiobarium absorption between "high calcium" and "low calcium" plants. The 160 parts per million of calcium in the "high calcium" nutrient solutions also had no effect on root absorption of the isotope treatment material. The equivalent amounts of the three elements translocated to the leaves from a root application have

TABLE XIX

ABSORPTION AND REDISTRIBUTION OF CALCIUM, STRONTIUM AND BARIUM BY LEAVES AND ROOTS OF BEET PLANTS AS INDICATED BY RADIOACTIVE ISOTOPES

(Average of four replications)

Nutritional status of plants	Isotope applied to	Plant part	Plant part dry weight (grams)			Calcium, strontium and barium derived from the respective isotope treatment: Micrograms per gram of dry tissue			Calcium, strontium and barium derived from the respective isotope treatment: Microequivalents per gram of dry tissue		
			Ca	Sr	Ba	Ca	Sr	Ba	Ca	Sr	Ba
HIGH CALCIUM	Foliage	All leaves	2.84	3.22	3.58	553.	1760.	1886.	27.66	40.00	27.33
		Root	3.33	3.85	3.96	2.8	0.5	1.1	0.14	0.01	0.02
	Roots	Young leaves	0.94	0.83	1.18	16.9	350.	289.	0.84	7.95	4.32
		Old leaves	3.54	2.59	3.21	8.8	192.	140.	0.44	4.36	2.03
		Root	4.27	3.94	4.31	5.5	117.	377.	0.28	2.66	5.46
LOW CALCIUM	Foliage	All leaves	3.47	3.15	4.06	600.	2242.	2136.	30.01	50.95	30.96
		Root	3.93	2.95	4.07	0.8	0.3	3.8	0.04	0.01	0.06
	Roots	Young leaves	1.02	1.08	0.96	14.8	351.	324.	0.74	7.98	4.70
		Old leaves	2.70	2.65	2.61	7.6	191.	160.	0.38	4.34	2.32
		Root	3.93	4.77	3.71	6.0	125.	406.	0.30	2.84	5.88

a Ca:Sr:Ba ratio of about 1:10:5 while the roots contain the ratio 1:10:20. The high value for barium content of roots suggests that part of it may be adsorbed on the surface rather than absorbed into the roots. The autoradiogram in Figure 21 (lower left) also shows that barium accumulates in the roots. All three elements were approximately twice as high in the young leaves as the older leaves. There is an indication of downward translocation of all three elements from a foliar application but quantitatively it amounts to no more than a trace of that applied.

Experiment 8

Objective

To study the absorption and translocation of strontium by the fruits, leaves and roots of the tomato.

Materials and Methods

Tomato seeds were started in sand June 19, 1952. Seedlings were pricked off into six-inch pots containing Wausau Quartz #8 on July fourth and transplanted to two-gallon crocks of Flint-Shot sand on August fourth. A four-quart, enamel pan was placed under each crock and contained a reservoir of Hoagland's nutrient solution. On August tenth, one-half of the plants were started on a nutrient solution containing no calcium so there would be a "high calcium" and a "low calcium" series of plants. During the period of August 6 - 12, fruit

were set on the first cluster by dipping the open flowers into a 30 ppm solution of p-chlorophenoxyacetic acid. As soon as fruit set was assured all 48 plants were topped, leaving two leaves above the fruit cluster and all auxiliary shoots were removed. During late August the "low calcium" plants were supplied calcium occasionally to arrest the blossom-end rot of the fruit that developed in the "low calcium" series. When the clusters were pruned to two fruits prior to treatment, all abnormal specimens were removed. The fruits on all plants were nearly fully developed when treated. Plants were similar to the one shown in Figure 25 (page 103) except that there were only two fruits per cluster.

The radiostrontium treating solution consisted of 0.0272 M $SrCl_2$ containing one microcurie of Sr^{90} per milliliter. This solution contained 2,383 micrograms of strontium per milliliter and had a specific activity of 0.42 microcuries of Sr^{90} per milligram of strontium. There were three replications of eight treatments at each calcium level. The treatments follow:

1. Both fruits dipped in Sr^{90} solution three times.
2. Both fruits dipped in Sr^{90} solution once.
3. The two leaves above fruit cluster dipped three times.
4. The two leaves above fruit cluster dipped once.
5. The two leaves below fruit cluster dipped three times.
6. The two leaves below fruit cluster dipped once.

7. Twenty milliliters of treating solution added to the root medium.
8. Control. No Sr^{90} added. Samples to be analyzed for total calcium.

The three applications in treatments 1, 3, and 5, were made on successive days. Contamination of untreated plant parts was prevented by covering them with pliofilm while the leaves or fruits were being dipped and dried.

All plants were first treated on August 31, 1952, and harvested on September 13. Originally it was intended to continue treatments until fruits ripened but due to an unfortunate accident, nearly all the "high calcium" plants died from lack of water on or about September eighth. Therefore, the treatment period for "high calcium" plants was about 8 days and for "low calcium" plants 13 days.

Samples collected were the fruits, the two leaves above the fruit cluster, and the two leaves below the cluster. Peduncles were collected as a separate sample in the soil and control treatments. The dipped fruits from treatment 2 were skinned by dipping them in hot ten percent potassium hydroxide. Treatment 1 fruits were washed thoroughly with soap and water to remove excess treating solution. Dipped leaves were not counted. All other samples were dried, ground in a Wiley mill, and counted as dry plant tissue with the Tracerlab autoscaler. Tissues from control plants were analyzed for calcium in the usual manner using the flame spectrophotometer.

Results

Flame photometer analysis of check plants showed the following calcium content on a percent dry weight basis.

	Fruit	2 leaves above	2 leaves below	Peduncle and calyx
High calcium plants	0.05	3.05	3.29	0.86
Low calcium plants	0.04	1.59	1.71	0.46

These data show there was a considerable difference in the calcium content of the two groups of plants. The micrograms of strontium in various plant parts are shown in Table XX. Dipped leaves were not counted but an estimation of the amount of strontium applied can be obtained from Experiment 9 (page 109). There it was found that two leaves, similar in size to the ones here, would retain about seven milliliters of solution from a single dip. Therefore the single dip leaf treatments would be approximately 16,000 micrograms of strontium and the triple dip three times as much.

The data in Table XX show that strontium is absorbed through the skin into the fruit tissues but does not move into the leaves above or below the fruit cluster. Strontium applied to the leaves of plants low in calcium does not move out of the treated area into other leaves or into the fruits. Plants high in calcium show translocation of very small amounts of

TABLE XX

THE ABSORPTION AND TRANSLOCATION OF STRONTIUM BY THE FRUIT, LEAVES AND ROOTS OF TOMATO AS INDICATED BY Sr^{90}

(Average of three replications)

Strontium Treatment	Plant Part	Micrograms of strontium per gram of dry tissue	
		High calcium plants	Low calcium plants
Fruit dipped 3 times	Fruit	85	95
	2 leaves above	0	0
	2 leaves below	0	0
Fruit dipped once	Fruit interior	30	23
	2 leaves above	0	0
	2 leaves below	0	0
2 leaves above fruit	Fruit	0	0
Cluster dipped 3 times	2 leaves below	1	0
2 leaves above fruit	Fruit	0	0
Cluster dipped once	2 leaves below	5	0
2 leaves below fruit	Fruit	1	0
Cluster dipped 3 times	2 leaves above	2	0
2 leaves below fruit	Fruit	0	0
Cluster dipped once	2 leaves above	0	0
One root medium	Fruit	14	4
addition of 20	2 leaves above	327	207
microcuries and	2 leaves below	360	195
48,000 micrograms	Peduncle and calyx	333	75

strontium into other tissues. Selected tissues of plants high in calcium absorbed nearly twice as much strontium from a root application as plants low in calcium despite the five day difference in treatment period. Fruits are not able to accumulate nearly as much strontium from a soil application as other plant organs. Even the peduncle and calyx contained twenty times as much strontium as the fruit. It may be recalled in this connection that here again strontium is similar to calcium in that fruits also absorb very little calcium.

Experiment 9

Objective

To investigate further the absorption and translocation of strontium by the fruit, leaves and roots of the tomato.

Materials and Methods

Tomatoes were started from seed on March 28, 1953. Seedlings were transplanted to sand in four-inch clay pots on May fifth. They were fed weekly with an all-soluble high analysis fertilizer (10-52-17) until June first when they were transplanted to two-gallon crocks of Flint-Shot sand. Subsequently they were fed Hoagland's nutrient solution in the usual manner. Fruits were set by dipping flowers in a 30 ppm solution of p-chlorophenoxyacetic acid. First cluster flowers were all set during the period of June 23-29, and second cluster flowers for treatment #1 were set July 3-7. Minus calcium or low

calcium nutrient solutions were alternately supplied to half of the plants after July first. On July 17 all plants except those for treatment #1 were topped, leaving three leaves above the first fruit cluster. Axillary shoots were removed as they appeared. High and low calcium nutrient solutions were continued until fruits of the first cluster were nearly full size. In final preparation for treatment the leaves below the first cluster were reduced to six, all remaining axillary ahoots were removed, distilled water was substituted for the nutrient solutions, and fruit clusters were reduced to five fruits for treatment 1, four fruits for treatments 2-7, and three fruits for treatments 8-12. To facilitate harvesting the leaves were numbered consecutively up the stem and fruits were numbered from the stem outward. The first cluster was always between leaves six and seven and the second cluster (treatment 1) between leaves nine and ten. Stem sections were (1) soil surface to the internode between leaves three and four, (2) from this internode to the first cluster, (3) all stem above the fruit cluster (treatments 2-11) or from the first cluster to the second cluster (treatment 1), and (4) from the second cluster to just above the sixteenth leaf in treatment 1.

Treating solutions were 0.00375 Molar, containing 329 micrograms of strontium and one microcurie of Sr^{90} per milliliter. Their specific activity was 3.04 microcuries of Sr^{90}

per milligram of strontium. In one treating solution the strontium was in ionic form as the chloride; in the other it was chelated by adding a slight excess of Sequestrene Na_4.[1] All treating solutions were adjusted to pH 9-10, the range at which chelated alkali metals are most stable. It was thought that chelation might facilitate strontium translocation from the site of foliar applications. Addition of oxalate to samples of the two treating solutions showed them to be different in that strontium oxalate precipitated from the chloride solution but not from the chelated solution.

The treatments were as follows:

1. Thirty ml of $Sr^{90}Cl_2$ treating solution added to the root medium. These were the only plants not topped. They had 20-25 leaves, two clusters of five fruit each, and were about five feet in height.
2. Fifteen ml. of $Sr^{90}Cl_2$ added to the root medium.
3. Fifteen ml. of chelated Sr^{90} added to the root medium.
4. One ml of $Sr^{90}Cl_2$ injected into fruit #1.
5. One ml. of chelated Sr^{90} injected into fruit #1.
6. Fruits 2, 3, and 4 painted with $Sr^{90}Cl_2$.
7. Fruits 2, 3 and 4 painted with chelated Sr^{90}.
8. Leaves 7 and 8 dipped in $Sr^{90}Cl_2$.
9. Leaves 7 and 8 dipped in chelated Sr^{90}.
10. Leaves 5 and 6 dipped in $Sr^{90}Cl_2$.

---

1. Tetrasodium ethylenediamine tetraacetate obtained from Geigy Company, Inc., 89 Barclay Street, New York 8, New York.

11. Leaves 5 and 6 dipped in chelated Sr^{90}.

12. Control, no strontium applied. Plant samples to be analyzed for total calcium.

Eight plants comprised each treatment, including four "high calcium" and four "low calcium" plants. A typical plant is shown in Figure 25. The fruit injections were made with a one-inch 23-gauge hypodermic needle attached to a one cubic centimeter syringe. In treatments 6 and 7, fruits 2, 3 and 4 were painted a second time shortly after the first application was dry. Non-treated portions of the foliage of treated plants were protected from accidental contamination by covering with sheets of pliofilm.

Treatments were applied July 24 and 25, 1953. All above ground vegetative portions were harvested 192 hours later. The five fruits on both clusters of treatment 1 plants were harvested from the stem outward at 12, 24, 48, 96, and 192 hours. Fruits of treatments 2 and 3 were collected at 24, 48, 96, and 192 hours and those of treatments 8, 9, 10 and 11 were harvested at 24, 72 and 192 hours. The non-treated fruits of treatments 4 and 5 were removed at 24, 72 and 192 hours while all fruits on treatments 6 and 7 were harvested at 192 hours. All leaves, stem sections and peduncles of root treated plants were harvested as individual samples. In the foliage and fruit treatments, leaves near the treated area were harvested individually while those farther away were collected in groups of two or three. The

Fig. 25. Tomato plant typical of those used in Experiment 9.

Enamel pan contains nutrient solution.

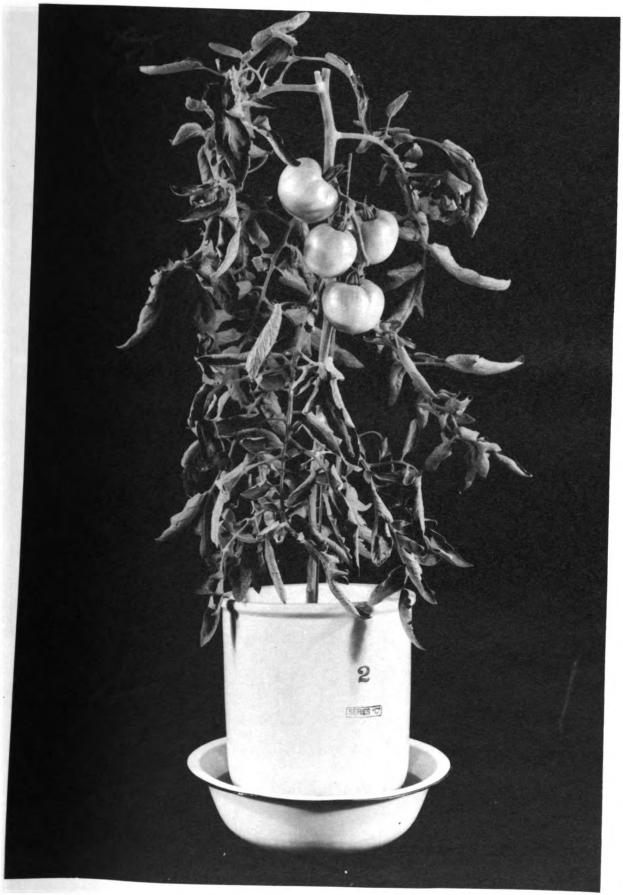

Figure 25

two treated leaves for each plant in treatments 8 to 11 were harvested together, dried, weighed and then combined as two large samples (ionic Sr^{90} dipped and chelated Sr^{90} dipped) for radioactive counting. Painted or injected fruits were counted as individual samples for each plant. Radioactive assay of these samples was necessary for calculating the amount of strontium actually applied. Control plants were harvested on July 27 and divided into six samples for calcium analysis by the flame spectrophotometer. There was a total of 1,312 tissue samples for radioactive counting and 48 samples for calcium analysis. The radioactive samples were dried, weighed, ground in a Wiley mill and counted as dry tissue in four centimeter Coors capsules. Counting time was ten minutes for samples showing little or no activity and less than ten minutes for those with appreciable radioactivity. Samples of all treating solutions were counted at the same time. These counts and the known concentration of strontium in the treating solutions enabled the counts per minute per gram of dry tissue to be converted to micrograms of strontium per gram of dry tissue.

Results

Flame photometer analysis of control plants showed a real difference in calcium content between "high calcium" and "low calcium" plants. The following amounts of calcium (percent dry weight) were found:

	Leaves 1-3	Leaves 4-6	Leaves 7-9	Stem	Peduncle	Fruit
High Ca plants	4.45	3.50	2.98	1.14	0.61	0.05
Low Ca plants	3.24	2.14	1.54	0.62	0.27	0.03

Another indication of a difference between these two groups of plants was the prevalence of blossom-end rot. Thirty of the fifty plants grown in the "low calcium" series developed blossom-end rot on one or more fruits while only three of the "high calcium" plants showed symptoms. All affected fruits were removed when the plants were prepared for treatment.

The only appreciable absorption and translocation of strontium was by the roots. Amounts of strontium found in the above ground portions of root treated plants are shown in Tables XXI and XXII. These show that the "high calcium" plants absorb more strontium than "low calcium" plants when the treating solution is strontium chloride. On the other hand, when chelated strontium is used, vegetative parts of "low calcium" plants take up more strontium than "high calcium" plants. These differences are shown in Figures 26 and 27, which also show the great variability in uptake by the various leaves of the plant. Figures 26 and 27 also show that fruits accumulate much less strontium than vegetative plant parts. It should be noted in the treatment 1 data (Table XXI) that the oldest and youngest leaves are lower in strontium content than intermediate leaves.

TABLE XXI

MICROGRAMS OF STRONTIUM ABSORBED BY THE ROOTS AND TRANSLOCATED TO THE TOPS OF TREATMENT #1 TOMATO PLANTS DURING EIGHT DAYS OF TREATMENT WITH STRONTIUM CHLORIDE

(Average of four replications.)

Plant Part	Micrograms of strontium per gram of dry tissue		Plant part	Micrograms of strongium per gram of dry tissue	
	High calcium plants	Low calcium plants		High calcium plants	Low calcium plants
Leaf 1	15.6	13.9	Stem sections 1, 2	20.5	27.2
Leaf 2	18.6	15.9	Stem section 3	20.4	28.2
Leaf 3	21.8	12.5	Stem section 4	29.4	31.7
Leaf 4	14.5	11.7			
Leaf 5	25.4	17.1	Peduncle 1	22.8	21.4
Leaf 6	24.6	17.1			
Leaf 7	21.8	17.5	Fruit 1 (12 hrs.)	0.35	0.16
Leaf 8	31.3	18.8	Fruit 2 (24 hrs.)	0.60	0.21
Leaf 9	40.7	33.0	Fruit 3 (48 hrs.)	0.68	0.26
Leaf 10	35.3	25.9	Fruit 4 (96 hrs.)	0.84	0.34
Leaf 11	51.9	32.9	Fruit 5 (192 hrs.)	0.99	0.34
Leaf 12	43.1	27.3			
Leaf 13	49.7	24.9	Peduncle 2	20.8	19.5
Leaf 14	42.2	23.2			
Leaf 15	64.3	31.0	Fruit 1a (12 hrs.)	0.49	0.30
Leaf 16	36.2	21.6	Fruit 2a (24 hrs.)	0.61	0.24
			Fruit 3a (48 hrs.)	0.92	0.32
Plant top:	30.0	16.4	Fruit 4a (96 hrs.)	0.91	0.35
Leaves and stem			Fruit 5a (192 hrs.)	0.81	0.24

TABLE XXII

MICROGRAMS OF STRONTIUM ABSORBED BY THE ROOTS AND TRANSLOCATED TO THE TOPS OF TOMATO PLANTS AS INFLUENCED BY TISSUE CALCIUM CONTENT AND THE CHEMICAL FORM OF APPLIED STRONTIUM

(Treatment period 8 days. Average of 4 replications.)

Plant Part	Micrograms of Sr, applied as chloride, per gram of dry tissue		Micrograms of Sr, applied as chelate, per gram of dry tissue	
	High calcium plants	Low calcium plants	High calcium plants	Low calcium plants
Leaf 1	24.3	18.2	16.1	19.1
Leaf 2	43.4	23.7	30.2	31.9
Leaf 3	35.2	46.0	36.1	44.0
Leaf 4	22.7	16.5	10.8	15.5
Leaf 5	58.8	43.8	42.0	53.1
Leaf 6	39.3	33.0	32.6	32.2
Leaf 7	38.0	20.2	27.1	25.5
Leaf 8	42.6	24.6	22.8	22.9
Leaf 9	71.4	43.8	56.7	62.5
Stem section 1, 2	30.1	22.6	19.9	33.5
Stem section 3	31.0	20.4	19.4	29.8
Peduncle	36.6	33.6	25.8	42.4
Fruit 1 (24 hrs.)	0.46	0.22	0.53	0.18
Fruit 2 (48 hrs.)	1.13	0.70	0.74	0.65
Fruit 3 (96 hrs.)	1.10	0.83	1.06	0.85
Fruit 4 (192 hrs.)	1.66	0.93	1.15	1.01

Fig. 26. Strontium accumulation by the aerial parts of tomato plants grown at two calcium levels eight days after the addition of strontium chloride to the root medium. (Mean of four plants.)

Fig. 27. Strontium accumulation by the aerial parts of tomato plants grown at two calcium levels eight days after the addition of strontium chelate to the root medium. (Mean of four plants.)

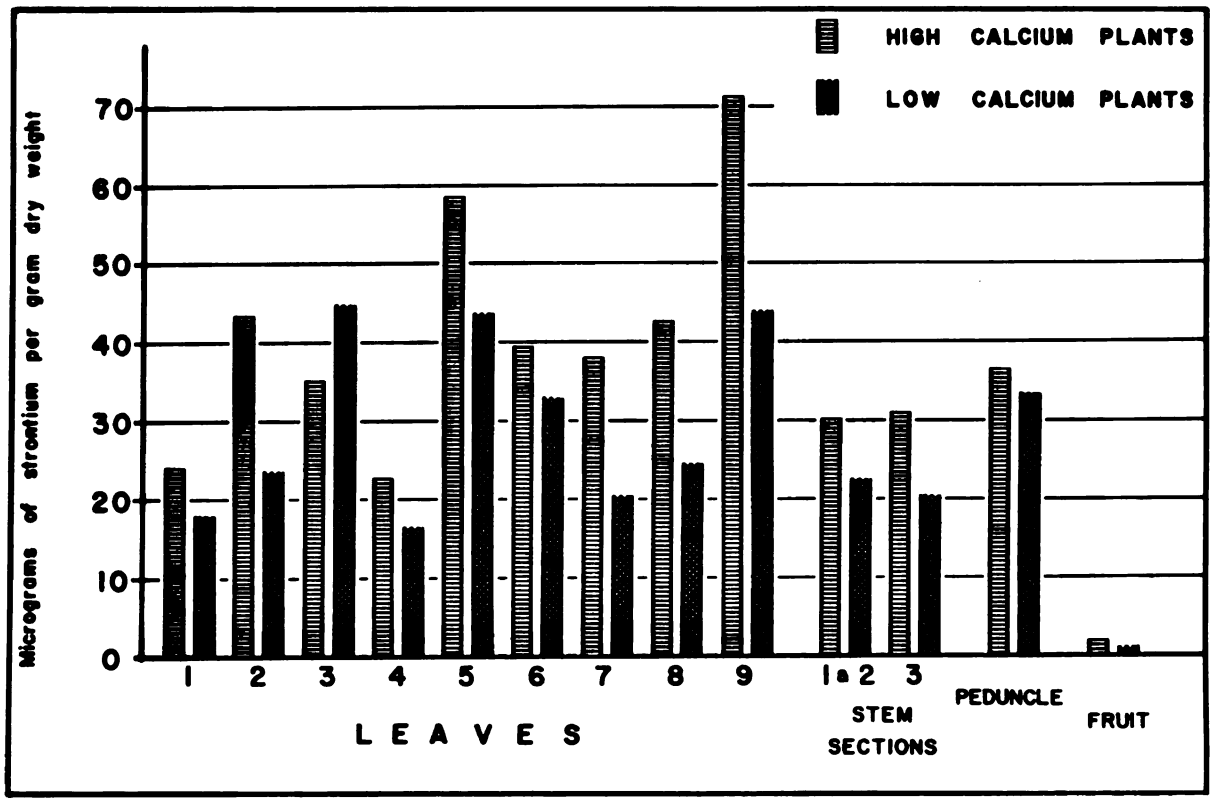

Figure 26

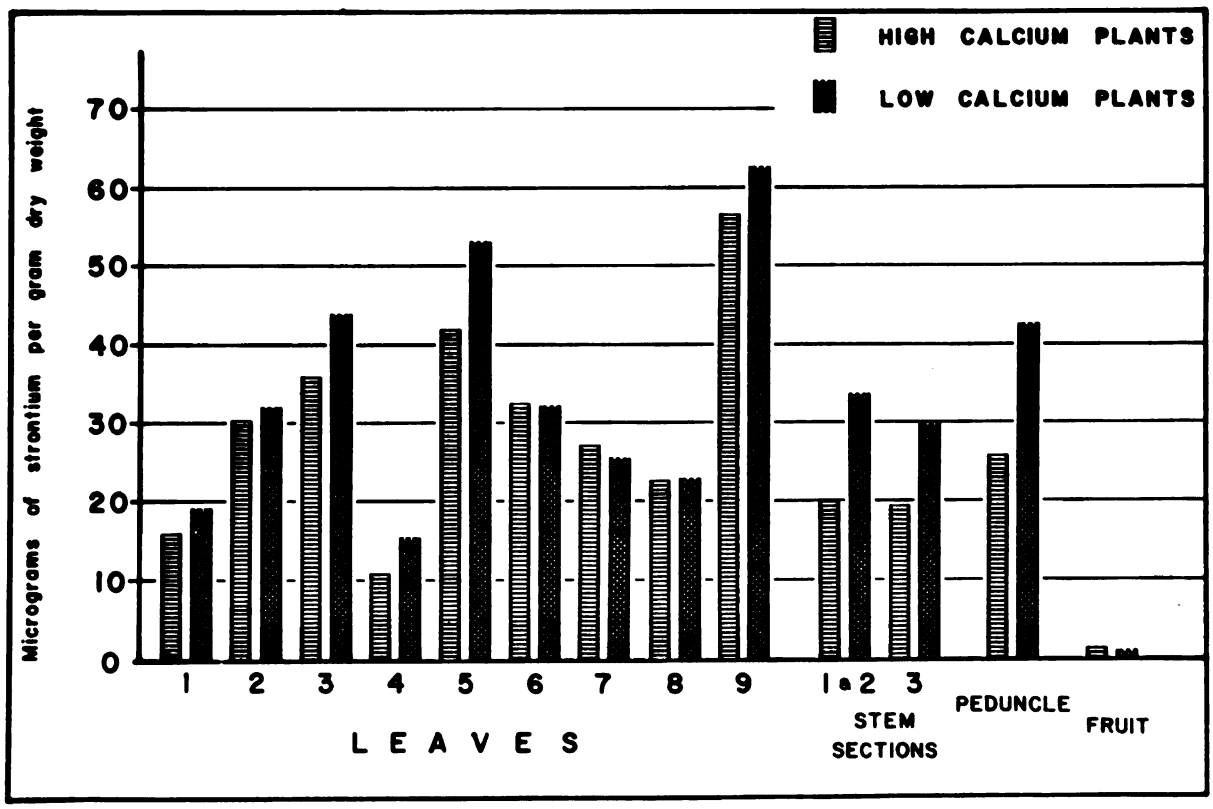

Figure 27

The accumulation of strontium in treatment #1 tomato fruits is shown in Table XXI and also in Figure 28. The time - accumulation curves in Figure 28 show that uptake is rapid at first but soon levels off. "High calcium" fruits in general absorb more than twice as much strontium as low calcium fruits. Accumulation is initially more rapid in the second cluster of fruits than in the first cluster but after eight days, first cluster fruits have a higher concentration of strontium. The decrease in strontium concentration of second cluster fruits at eight days is caused by growth dilution, that is, dry matter production exceeds strontium accumulation.

Summaries of the amounts of strontium translocated from the various treatment sites are given in Tables XXIII and XXIV for high and low calcium plants. Values for the amounts applied to fruits or leaves were determined by counting a small sample of the treated tissue, converting this to counts per minute for the whole treated portion and relating this to the counts obtained from the treating solution which had a known strontium content of 329 micrograms per milliliter. From these calculations it was found that two tomato leaves will retain from six to eight milliliters of solution from a single dip. Painting three fruits twice resulted in retention of 0.6 - 0.8 milliliters. There was detectable movement to other leaves when the two leaves above the fruit cluster were treated, and also into the peduncle when fruit #1 was injected

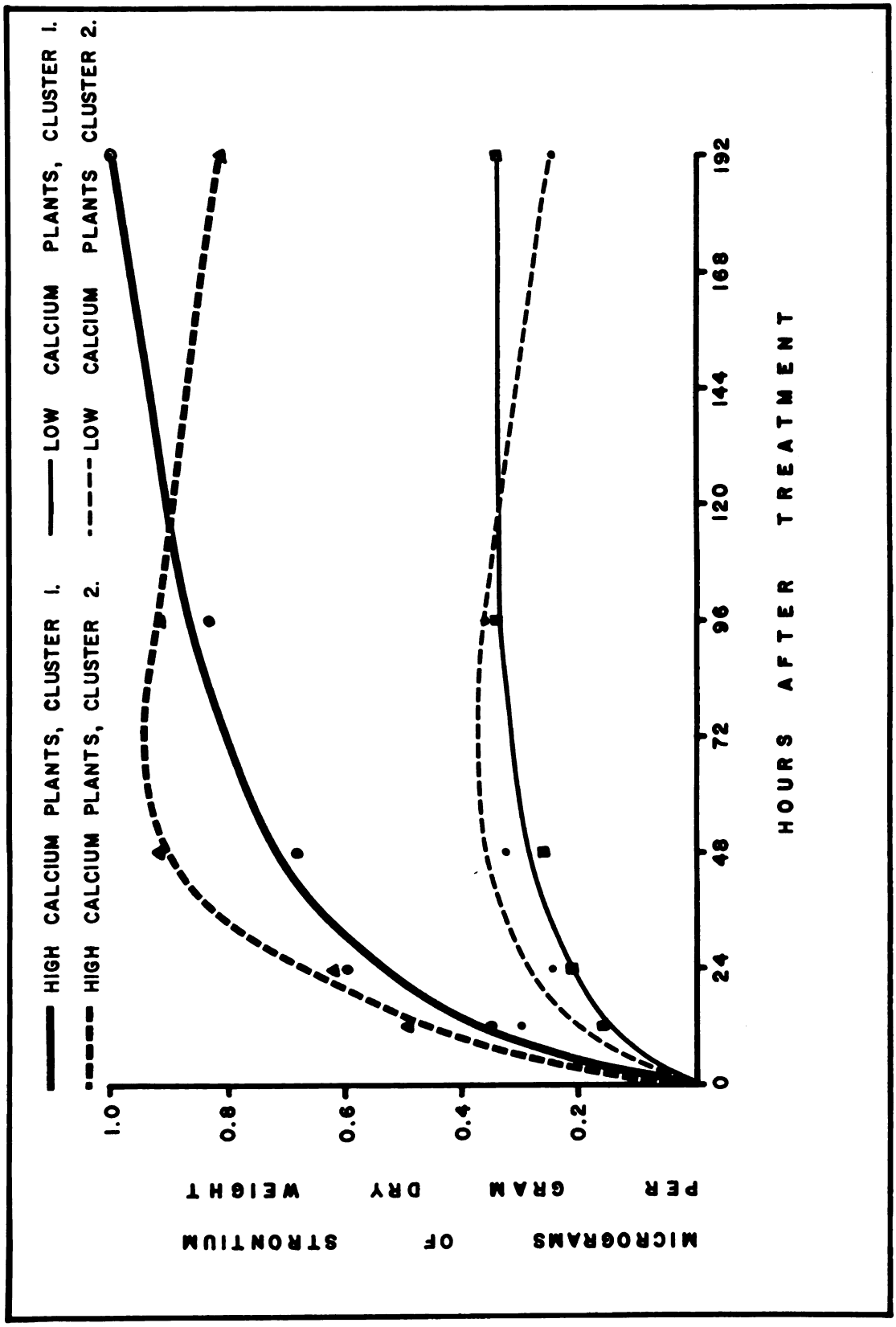

Fig. 28. Rates of strontium accumulation in tomato fruits following application of Sr^{90} to the root growing media of plants high and low in calcium.

TABLE XXIII

SUMMARY OF STRONTIUM TRANSLOCATION IN TOMATO PLANTS FROM ROOT, FRUIT AND LEAF APPLICATIONS TO PLANTS HIGH IN TOTAL CALCIUM

(Mean of four replications)

	Treatment	Form of Sr applied	Sr applied (micrograms)	Sr translocated to untreated parts (micrograms)	Location of translocated strontium	Percent of Sr application translocated
1.	Root application	Chloride	9858	2565	All parts of plant top	26.02
2.	Root application	Chloride	4929	1694	All parts of plant top	34.37
3.	Root application	Chelated	4929	1318	All parts of plant top	26.74
4.	Fruit #1 injected	Chloride	365	0.144	Pedumcle	0.04
5.	Fruit #1 injected	Chelated	398	None	----	----
6.	Fruits 2, 3, 4 painted	Chloride	265	None	----	----
7.	Fruits 2, 3, 4 painted	Chelated	216	None	----	----
8.	Leaves 7, 8 dipped	Chloride	2202	0.163	Leaves 4, 5, 6, 9	0.007
9.	Leaves 7, 8 dipped	Chelated	2404	0.244	Leaves 1, 2, 3, 4, 5, 6	0.010
10.	Leaves 5, 6 dipped	Chloride	2222	None	----	----
11.	Leaves 5, 6 dipped	Chelated	2505	None	----	----

TABLE XXIV

SUMMARY OF STRONTIUM TRANSLOCATION IN TOMATO PLANTS FROM ROOT, FRUIT AND LEAF APPLICATIONS TO PLANTS LOW IN TOTAL CALCIUM

(Mean of four replications)

	Treatment	Form of Sr applied	Sr applied (micrograms)	Sr translocated to untreated parts (micrograms)	Location of translocated strontium	Percent of Sr application translocated
1.	Root application	Chloride	9858	1960	All parts of plant top	19.88
2.	Root application	Chloride	4929	924	All parts of plant top	18.76
3.	Root application	Chelated	4929	1098	All parts of plant top	22.28
4.	Fruit #1 injected	Chloride	356	0.149	Peduncle	0.04
5.	Fruit #1 injected	Chelated	411	None	----	---
6.	Fruits 2, 3, 4 painted	Chloride	234	None	----	---
7.	Fruits 2, 3, 4 painted	Chelated	192	0.055	Peduncle, leaf 6	0.03
8.	Leaves 7, 8 dipped	Chloride	2343	None	----	---
9.	Leaves 7, 8 dipped	Chelated	2121	0.137	Leaves 1, 2, 3, 4, 5, 6	0.006
10.	Leaves 5,6 dipped	Chloride	2081	None	----	---
11.	Leaves 5, 6 dipped	Chelated	2303	None	----	---

with strontium chloride. Tables XXIII and XXIV show that these amounts were no more than traces and they represent a very small percentage of the strontium applied. Other than these occasional traces detected, there was no movement of strontium away from the site of foliar or fruit applications.

VI. DISCUSSION

During the course of this investigation it was found that large amounts of strontium can be absorbed by plant roots and translocated to the above ground plant parts. Biddulph and Cory (4), Jacobson and Overstreet (29) and Neel et al (38) also found appreciable plant absorption of strontium. In contrast, they report other nuclear fission products to be only sparingly translocated upwards in plants. The quantitative effect of plant calcium content upon strontium absorption was also studied. The limited absorption and translocation from plant leaves and fruits was demonstrated in several experiments.

According to Comar (13) there are three basic types of doses that can be administered to an organism: (a) tracer dose, where the amount of substance administered is small compared to the normal intake; (b) physiological dose, when the administered amount is of the same magnitude as the normal intake; and (c) massive dose, one in which the administered amount exceeds the normal intake. He stated that the first two dosage types are usually the more desirable. Massive doses may cause abnormal distribution due to mass action or upset metabolism. Although there is no established "normal intake" of strontium for plants, most experimental applications

made in this study may be considered as tracer doses. In the first two experiments the root applications probably fall in the category of "massive" doses. These two differ in that the first experiment treatment period was short while in the second experiment the treatment period was long enough for for plant composition to come to equilibrium with the nutrient solution.

In Experiment 1 it was found that tomato plants take up more strontium than beet plants during a four day period. Both plants accumulated more strontium in the roots than in the tops. It should be noted, however, that neither of these statements held true when the treatment period was extended to several weeks (Experiment 2). Rediske and Selders (45) also found higher accumulation in roots than in leaves. They demonstrated that most strontium associated with plant roots grown in solution culture was adsorbed on the roots rather than absorbed into them. Calcium content of tomato and beet plants had a very different effect on strontium uptake by these two crops. Tomato plants high in calcium took up more strontium than those low in calcium, while with beet plants a low calcium content accelerated strontium uptake. Tomato plants high in calcium translocated a greater proportion of the absorbed strontium to the upper leaves and stem.

In Experiment 2 tomato and beet plants were grown for 46 and 90 days respectively in nutrient solutions containing

various amounts of calcium, strontium, or combinations of the two. The highest concentrations in the nutrient solutions were eight milliequivalents per liter (160 ppm Ca or 352 ppm Sr). These long treatment periods allowed plant accumulation to come to equilibrium with the nutrient solution strontium.

Tomato and beet plants will accumulate nearly as much strontium from high strontium nutrient solution as calcium from a high calcium solution. The actual maximum accumulations found, measured in milliequivalents per gram of dry tissue, were: tomato tops, .712 Ca, .531 Sr; tomato roots, .245 Ca, .232 Sr; beet tops, .915 Ca, .679 Sr; beet roots, .095 Ca, .172 Sr. These maximum accumulations of strontium were accompanied by severe toxicity symptoms and much reduced growth. When less strontium was accumulated growth was more nearly normal. Tomato plants had less tolerance for strontium than beets. With tomatoes the highest strontium level caused the death of most leaves and a 75 percent reduction in dry matter; while the same treatment to beets resulted in greater accumulation of strontium but no leaf necrosis and only 54 percent reduction in dry weight. Hurd-Karrer (27) noted that strontium injury to plants is always more pronounced in tops than in roots. Such was the case here. This may be the effect of lower accumulation by roots. Both tomato and beet roots normally contain much less calcium than their respective tops. Root accumulation of strontium was

correspondingly low. However, when strontium toxicity reduced the dry weight of plant tops it reduced the dry weight of roots proportionally. This is shown by the lack of variability in the dry weight Top/Root ratios. The difference in growth and mineral content also had no appreciable effect on the percent dry weight of the various tissues.

There were no visual symptoms of strontium toxicity on tomato plants for the first twenty days and on beets for the first thirty days. Symptoms were different for the two crops. The pattern of tomato leaf chlorosis and subsequent necrosis was unusual since it developed from the leaflet bases toward the tips on older leaves and in the opposite direction on younger leaves. The youngest leaves were unaffected until they became two to three inches long. The highest strontium treatments eventually caused complete death of all older leaves. Beet leaves were not killed by the highest strontium treatments but they changed to a dark red color, were smaller and rigidly erect. The youngest beet leaves were not affected until they became one to two inches long.

Rediske and Selders (45) found that strontium accumulation in bean plants was proportional to its concentration in the nutrient solution up to 100 ppm, their highest level. Results here with tomato and beet indicate that this relation is still generally true up to 350 ppm of strontium in the nutrient solution. Beet roots were an exception in that maximum accumulation of strontium occurred at 175 ppm.

Calcium absorption from these various nutrient solutions was also proportional to its concentration in the solution except where no calcium was added. Here there was still a small amount of calcium detectable in the plant tissues. Normal appearance and growth of both tomato and beet plants in the nutrient solution with no calcium and no strontium was rather unexpected. Apparently impurities in nutrient salts and the distilled water furnished enough calcium for normal growth and therefore, calcium can not be considered a limiting factor for plant growth in any of the treatments.

The three treatments with both calcium and strontium in the nutrient solution were interesting. The tops of tomato and beet plants grown in these solutions contained more calcium than those grown in the same amount of calcium alone, and also contained more strontium than those grown in the same amount of strontium alone. Thus it appears that calcium and strontium mutually increase the accumulation of each other in plant tops rather than depress it as reported by Haselhoff (22). However, beet root accumulation of strontium does appear to be inhibited by nutrient solution calcium. Strontium toxicity symptoms are greatly decreased when calcium is present in the nutrient solution in spite of the increase in plant strontium content. McCool (34) noted that potassium, magnesium and sodium as well as calcium could suppress strontium toxicity. The data presented here indicate that this effect

of calcium is a suppression of symptoms rather than a suppression of absorption.

Several investigators, McNargue (36), Scharrer and Schropp (49) and Walsh (63), found a growth stimulation by strontium provided adequate calcium was present. In this study an appreciable increase in beet plant dry weight was found in certain calcium-strontium mixtures. Tomato plants showed no such increase, probably because of their greater sensitivity to strontium.

Chemical analyses for several other elements were made to determine whether strontium accumulation in the plant had any effect on absorption of these elements by tomato and beet plants. In general, the substitution of strontium for calcium in the nutrient solution had no effect on potassium or copper content. It caused a significant increase in phosphorus, magnesium and manganese content. The substitution of strontium for calcium had no effect on boron in roots but caused a significant boron increase in tomato and beet tops. It had no effect on iron content at high strontium concentrations, but at low strontium concentrations iron increased in the plant tissues.

Analysis of field grown plants indicate there was no appreciable strontium in plant tissues collected in this area. Calcium analysis of these plants showed field grown plants to have about the same calcium content as plants grown in nutrient solutions. Newton (39) reported that plants grown in

solution culture often contain larger amounts of nutrient elements than plants grown in soil. Therefore, where possible, the plant composition values determined in this study were checked against those compiled by Beeson (2) and Goodall and Gregory (18). Potassium values determined here were somewhat higher than found elsewhere but all other elements were very similar to values given in the literature.

Autoradiographic studies of root absorption by bean, tomato and beet plants showed that radiostrontium, radiocalcium and radiobarium are translocated to all parts of these plants. This is in contrast to the wheat plants studied by Spinks et al (53). They found wheat plants absorb radiostrontium only into the first two leaves. Strontium and barium exhibited a tendency to accumulate in the leaf veins. This was also noted in the dwarf pea by Jacobson and Overstreet (29). Autoradiograms of median transverse and longitudinal sections of fleshy beet "roots" showed that strontium and calcium concentrate in the true root portion and the stem plate. The main paths of upward transport were the central zone of primary and secondary vascular tissues and tertiary vascular tissue just under the periderm. Autoradiograms of transverse sections of tomato fruits eighty hours after a soil application of $Sr^{90}Cl_2$ showed strontium concentrated in or near the vascular strands. There was no movement of strontium into tomato seeds. The very limited movement of strontium

into seeds has been noted in barley by Walsh (63), in dwarf pea by Jacobson and Overstreet (29), and in barley and bean by Neel et al (38).

Four day treatments of tracer amounts of radiocalcium, radiostrontium and radiobarium to beet plant root media indicated a much greater equivalent absorption of strontium and barium than of calcium. This is undoubtedly due to the rapid uptake of ions not initially present in the plant. Twice as much strontium as barium was translocated to the beet leaves while only half as much accumulated in, or possibly on, the roots. The concentration of all three elements was about twice as high in young leaves as in old leaves. A fundamental difference in the treatments to "high calcium" and "low calcium" beet plants was the calcium content of their respective nutrient solutions. In the former the nutrient solution contained 160 ppm of calcium while the nutrient solution of the latter contained no calcium. In spite of this difference, beet plants took up approximately the same amount of treatment calcium, strontium and barium from both solutions. Both Collander (12) and Hurd-Karrer (27) concluded from their investigations that plants are unable to distinguish between calcium and strontium and therefore absorb them in proportion to their presence in the nutrient solution. This conclusion is generally in agreement with the results of this investigation when plants were harvested after a comparable long period of treatment (Experiment 2). However, with beets when the treatment period was short, absorption of strontium and barium appeared independent of nutrient solution calcium content.

Leeper (31) and Jacobson and Overstreet (28) have suggested that soluble complexes or chelates may be important in cation absorption and exchange by plants. A chelated form of strontium was prepared to determine what effect chelation would have on strontium absorption. The complexing agent used was ethylene diamine tetraacetic acid. In all experiments up to this time strontium chloride applications to the roots had resulted in greater strontium uptake by tomato plants high in calcium. When chelated strontium was applied to tomato roots, plants low in calcium accumulated more strontium in the leaves and stem than plants high in calcium. This indicates there may be a real difference in response of the root absorption mechanism depending on the form of strontium presented to the root surface. This difference in plant absorption did not extent to fruit accumulation of strontium. Fruits of high calcium plants contained more strontium irrespective of the form in which strontium was applied.

The distribution of strontium in a large tomato plant after eight days of root treatment was of some interest. There was considerable variability in the amount of strontium accumulated by the leaves. The oldest seven or eight leaves contained less strontium than the next seven or eight leaves and the youngest leaves were again somewhat lower. The stem sections and peduncles were fairly uniform in strontium content and the amount was about equal to that of leaves. Fruit

strontium content was about one-twentieth that of the vegetative plant parts. This low strontium content of fruits is consistent with their low calcium requirement. When fruits were harvested from two clusters at various time intervals (1/2, 1, 2, 4, 8 days) it was found that initial uptake is rapid and then the rate of accumulation decreases. Second cluster fruits contained a higher concentration of strontium than first cluster fruits at the earlier harvests but by the end of eight days the first cluster fruits had the higher concentration.

In contrast to the free movement upwards and the high accumulation from a soil application, the movement of strontium from the site of a foliage application is very limited, never amounting to more than a trace of the quantity applied. Rediske and Selders (45) treated bean roots with radiostrontium for a period of time and then withdrew the strontium supply. They found that once strontium has been deposited in a tissue such as a leaf, there is no significant redistribution even when a comparatively high concentration gradient exists. This also appears to be the case when strontium is applied directly to a leaf. Foliage applications of calcium and barium as well as strontium were made in several experiments; all with very similar results. There was little movement away from the site of application. Autoradiograms indicated that bean and beet plants may translocate small amounts of calcium, strontium or barium downward into the untreated portions of

the plant, while tomato plants showed no translocation at all. More precise measurements using an autoscaler indicated that in a few cases strontium did move in tomato plants but only in trace amounts.

Both autoradiograms and radioactive counting data indicate strontium can be absorbed into tomato fruits through the intact skin but can not move out of the fruit. Even injecting strontium directly into a fruit does not facilitate appreciable movement to other parts of the plant.

Chelation of strontium had an effect on root absorption but had no effect on foliar absorption and translocation. Counting data indicate that chelated strontium was just as immobile as strontium chloride.

An additional observation was made concerning blossom-end rot of tomato fruits. Raleigh and Chucka (44) found blossom-end rot to be correlated with a low calcium content in the fruit. In the present investigation blossom-end rot soon began to appear on tomato fruits when calcium was withheld from the nutrient solution. As soon as calcium was returned to the nutrient solution, the increase in "diseased" fruits was arrested. It would be of interest, in future work, to determine whether strontium might also prevent the developement of blossom-end rot when calcium is limited.

VII. SUMMARY

The results of this investigation have led to several conclusions concerning the qualitative and quantitative aspects of strontium absorption by certain horticultural plants.

Strontium applied to the roots of bean, tomato and beet plants was absorbed by the roots and translocated to all above ground plant parts. It is generally absorbed in proportion to its presence in the nutrient solution. Strontium can be accumulated in tomato and beet tissues in amounts almost equivalent to the normal calcium content. At such high concentrations it is toxic to both plants but the adverse effects are greater on tomato than beet. Strontium and calcium in the same nutrient solution mutually favor the absorption of each other but the presence of adequate calcium in plant tissues largely masks the toxic effect of strontium. Plant tissue analysis for several nutrient elements demonstrated that a high strontium and low calcium concentration in the plant tissues, as contrasted to high calcium and no strontium, had no effect on potassium or copper content, nearly always caused an increase in phosphorus, magnesium and manganese and sometimes favored an increase in boron and iron.

Samples from field grown plants contained no appreciable strontium. The calcium content of these plants was about the same as the calcium content of greenhouse grown plants.

Autoradiographic studies indicated that radiocalcium, radiostrontium and radiobarium are translocated to all parts of the plant from root application. Strontium and barium tend to accumulate in the vascular tissues. The distribution of radiostrontium in beet roots and tomato fruits was also studied. Strontium did not move into maturing tomato seeds.

The absorption of calcium, strontium and barium applied to the roots of beet plants for four days was independent of plant calcium content and nutrient solution calcium content. On the other hand with longer treatment periods calcium and strontium were absorbed in proportion to their presence in the nutrient solution.

Tomato plants high in calcium always absorbed more strontium than tomato plants low in calcium when strontium was applied as the chloride. When applied in a chelated form the low calcium plants had a greater strontium uptake. Plant calcium content had little effect on strontium absorption by beets.

In contrast to the free movement upwards and high accumulation of strontium from a root application, the movement of strontium from a foliage application was very slight. Bean and beet plants showed a somewhat greater movement than tomato plants, but in neither was the amount translocated more than a trace of that applied. This was likewise true of calcium and barium. Chelation of strontium did not increase translocation away from treated tomato leaves or fruits. By means

of autoradiography it was demonstrated that radiostrontium can penetrate the intact skin of a tomato fruit and accumulate in the inner tissues.

VIII. LITERATURE CITED

1. Association of Official Agricultural Chemists. 1950. Official Methods of Analysis. Seventh Edition.

2. Beeson, Kenneth C. 1941. The mineral composition of crops with particular reference to the soils in which they were grown. U. S. Dept. Agr. Misc. Publ. No. 369.

3. Bibliography of the Literature on the Minor Elements and Their Relation to Plant and Animal Nutrition. Fourth Edition. 1948. Chilean Nitrate Educational Bureau, Inc., New York City, New York.

4. Biddulph, O, and R. Cory. 1952. The relationship between Ca^{45}, total calcium and fission product radioactivity in plants of Portulaca oleracea growing in the vicinity of the atom bomb test sites on Eniwetok Atoll. United States Atomic Energy Commission Report:UWFL-31.

5. Bledsoe, R. W., C. L. Comar, and H. C. Harris. 1949. Absorption of radioactive calcium by the peanut fruit. Science 109:329-330.

6. Blume, J. M. 1952. Radiation effects on plants grown in soil treated with fertilizer containing P^{32}. Soil Sci. 73:299-303.

7. Brenchley, W. E. 1927. Inorganic Plant Poisons and Stimulants. Second Edition Cambridge University Press.

8. Brown, J. G., O. Lilleland, and R. K. Jackson. 1948. The determination of calcium and magnesium in leaves using flame methods and a quartz spectrophotometer. Proc. Amer. Soc. Hort. Sci. 52:1-6.

9. _____, _____, and _____. 1950. Further notes on the use of flame methods for the analysis of plant material for potassium, calcium, magnesium and sodium. Proc. Amer. Soc. Hort. Sci. 56:12-22.

10. Churchill, J. R. 1944. Techniques of quantitative spectrographic analysis. Ind. and Eng. Chem., Anal. Ed. 11: 653-670.

11. Colin, H., and Lavison, J. 1910. Absorption comparée des sels de Baryum, de Strontium et de Calcium par la plante vivante. Rev. Gén. Bot. XXII:337-344.

12. Collander, R. 1941. Selective absorption of cations by higher plants. Plant Physiol. 16:691-720.

13. Comar, C. L. 1948. Radioisotopes in nutritional trace element studies I. Nucleonics 3: No. 2. 32-45.

14. Daubeny, C. 1835. Memoir on the degree of selection exercised by plants with regard to the earthy constituents presented to their absorbing surfaces. Trans. Linn. Soc. XVII:253-266.

15. _____. 1861. On the power ascribed to the roots of plants of rejecting posonous or abnormal substances presented to them. Jour. Chem. Soc. of London. XIV:209-230.

16. Downes, J. D. 1954. Growth and certain aspects of the chemical composition of the onion as influenced by nutrition. Ph. D. Thesis, Michigan State College.

17. Evans, T. C. 1948. Selection of radioautographic technique for problems in biology. Nucleonics 2: No. 3. 52-58.

18. Goodall, D. W., and F. G. Gregory. 1947. Chemical Composition of Plants as an Index of Their Nutritional Status. Tech. Comm. No. 17. Imperial Bureau of Horticulture and Plantation Crops, Aberystwyth, Wales.

19. Guettel, C. L. 1944. Emission spectrographic equipment used in quantitative analysis. Ind. and Eng. Chem., Anal. Ed. 11:670-675.

20. Hance, F. E. 1933. Less common elements in soils and fertilizers. Hawaiian Sugar Planters' Assoc., Proc. 53rd. Ann. Meeting. 46-63.

21. Harris, H. C. 1949. The effect on the growth of peanuts of nutrient deficiencies in the root and the pegging zone. Plant Physiol. 24:150-161.

22. Haselhoff, E. 1893. Versuche über den Ersatz des Kalkes durch Strontium bei der Pflanzenernährung. Landw. Jahrb. 22:851-861.

23. Haynes, J. L. and W. R. Robbins. 1948. Calcium and boron as essential factors in the root environment. Jour. Am. Soc. Agron. 40:795-803.

24. Hinsvark, O. N., S. H. Wittwer, and H. M. Sell. 1953. Flame photometric determination of calcium, strontium and barium in a mixture. Anal. Chem. 25:320-322.

25. Hoagland, D. R. and D. I. Arnon. 1950. The water culture method for growing plants without soil. Calif. Agr. Exp. Sta. Cir. 347.

26. Hodgman, Charles D., Editor. 1952-53. Handbook of Chemistry and Physics. 34th Edition. Chemical Rubber Publishing Co., Cleveland Ohio.

27. Hurd-Karrer, Annie M. 1939. Antagonism of certain elements essential to plants toward chemically related toxic elements. Plant Phsiol. 14:9-29.

28. Jacobson, L., and R. Overstreet. 1947. A study of the mechanism of ion absorption by plant roots using radioactive elements. Amer. Jour. Bot. 34:415-420.

29. _____ and _____. 1948. The uptake by plants of plutonium and some products of nuclear fission adsorbed on soil colloids. Soil Sci. 65:129-134.

30. Kamen, M. D. 1951. Radioactive Tracers in Biology. Academic Press, New York.

31. Leeper, G. W. 1952. Factors affecting availability of inorganic nutrients in soils with special reference to micro-nutrient metals. Ann. Rev. Plant Physiol. 3:1-16.

32. Loew, O. 1898. Über die Physiologischen Functionen der Calciumsalze. Botanisches Centrblt. Bd. LXXIV.

33. _____. 1903. The physiological role of mineral nutrients in plants. U. S. Dept. Agr. Bur. Pl. Ind. Bull. 45.

34. McCool, M. M. 1913. The action of certain nutrient and non-nutrient bases on plant growth. I. The antitoxic action of certain nutrient and non-nutrient bases with respect to plants. Cornell Univ. Agr. Exp. Sta. Mem. 2. 121-170.

35. _____. 1913. The Action of certain nutrient and non-nutrient bases on plant growth. III. Toxicity of various cations. Cornell Univ. Agr. Exp. Sta. Mem. 2. 201-216.

36. McHargue, J. S. 1919. Effect of certain compounds of barium and strontium on the growth of plants. Jour. Agr. Res. 16:183-194.

37. Mitchell, R. L. 1948. The Spectrographic Analysis of Soils, Plants and Related Materials. Technical Communication No. 44, Commonwealth Bureau of Soil Science, Harpenden, England.

38. Neel, J. W., B. E. Gillooly, J. H. Olafson, H. Nishita, A. J. Steen, and K. H. Larson. 1953. Soil-plant interrelationships with respect to the uptake of fission products. I. The uptake of Sr^{90}, Ca^{137}, Ru^{106}, Ce^{144} and Y^{91}. United States Atomic Energy Commission Report: UCLA - 247.

39. Newton, J. D. 1928. The selective absorption of inorganic elements by various crop plants. Soil Sci. 26:85-91.

40. Norton, R. A. 1954. The absorption, translocation and distribution of mineral nutrients in the strawberry as indicated by radioactive isotopes. Ph. D. Thesis, Michigan State College.

41. Odum, H. T. 1951. Notes on the strontium content of sea water, celestite Radiolaria, and strontianite snail shells. Science 114:211-213.

42. _____. 1951. The stability of the world strontium cycle. Science 114:407-411.

43. Osterhout, W. J. V. 1907. On nutrient and balanced solutions. Univ. Cal. Pubs., Bot., 2. No. 15. 317-318.

44. Raleigh, S. M. and J. A. Chucka. 1944. Effect of nutrient ratio and concentration on growth and composition of tomato plants and on the occurrence of blossom-end rot of the fruit. Plant Physiol. 19:671-678.

45. Rediske, J. H., and A. A. Selders. 1953. The absorption and translocation of strontium by plants. Plant Physiol. 28:594-605.

46. Ririe, D., and S. J. Toth. 1952. Plant studies with radioactive calcium. Soil Sci. 73:1-10.

47. Russell, E. J. 1950. Soil Conditions and Plant Growth. Eighth Ed. Jarrold and Sons, Ltd., The Empire Press, Norwich, England.

48. Rygh, O. 1949. Trace Elements. I. Importance of strontium, barium and zinc in the animal organism. Bull. Soc. Chem. Biol. 31:1052-1061.

49. Scharrer, K. and W. Schropp. 1937. The effects of strontium and barium ions upon the growth of some plants. Bodenkunde und Pflanzenernähr. 3:369-385. Seen in abstract only. Bibliography of the Literature on the Minor Elements and Their Relation to Plant and Animal Nutrition. Fourth Edition. Chilean Nitrate Educational Bureau Inc., New York City, New York.

50. Schweitzer, G. K., and B. K. Stein. 1950. Measuring solid samples of low-energy beta emitters. Nucleonics 7:65-72.

51. Siegel, J. M. 1946. Nuclei formed in fission: Decay characteristics, fission yields, and chain relationships. Issued by the Plutonium Project. Jour. Amer. Chem. Soc. 68:2411-2442.

52. Siri, William E. 1949. Isotopic Tracers and Nuclear Radiations with Applications to Biology and Medicine. McGraw-Hill Book Company, New York.

53. Spinks, J. W. T., E. Cumming, K. L. B. Irwin, and T. J. Arnason. 1948. Lethal effect of absorbed radioisotopes on plants. Canadian J. Research, 26 C:249-262.

54. Spooner, M. A. 1949. Observations on the absorption of radioactive strontium and yttrium by marine algae. Jour. Marine Biol. Assoc. United Kingdom 28:587-625.

55. Stiles, W. 1923. Permeability. New Phytol. 22:128-149.

56. _____. 1946. Trace Elements in Plants and Animals. The MacMillan Company, New York.

57. Stout, P. R., and K. Overstreet. 1950. Soil chemistry in relation to inorganic nutrition of plants. Ann. Rev. Plant Physiol. I., 305-342.

58. Suzuki, V. 1900. Can strontium and barium replace calcium in phanerogams? Bull. Coll. Agr. Tokyo 4:69-79,

59. Ticknor, K. L. 1953. The entry of nutrients through the bark and leaves of deciduous fruit trees as indicated by readioactive isotopes. Ph. D. Thesis, Michigan State College.

60. Vlamis, J. and H. Jenny. 1948. Calcium deficiency in serpentine soils as revealed by adsorbent technique. Science 107:549.

61. Voelcker, J. A. 1915. The influence of strontium salts on wheat, Jour. Roy. Agr. Soc. England. 76:344-351.

62. Voinar, A. O. and L. I. Lazovekaya. 1942. The biochemistry of strontium and barium. Biokhimiya 7:244-254. Seen in abstract only. Bibliography of the Literature on the Minor Elements and Their Relation to Plant and Animal Nutrition. Fourth Edition. Chilean Nitrate Educational Bureau, Inc., New York City, New York.

63. Walsh, T. 1945. The effect on plant growth of substituting strontium for calcium in acid soils. Proc. Roy. Irish Acad. 50B:287-294.

64. Wittwer, S. H., and W. S. Lundahl. 1951. Autoradiography as an aid in determining the gross absorption and utilization of foliar applied nutrients. Plant Physiol. 26: 792-797.

65. _____ and H. B. Tukey. 1954. Chap. 15. Radioisotopes in research on nutrition of fruit crops. Childers, N. F., Editor. Mineral Nutrition of Fruit Crops. Horticultural Publications, Rutgers University, New Brunswick, N. J. Pp. 758-774.

66. Wolf, B. and S. J. Cesare. 1952. Response of field-grown peaches to strontium sprays. Science 115;606-607.