Uptake of Radioactive Fission Products by Crop Plants

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The uptake of several radioactive fission products from contaminated soils by crop plants through the root system, the distribution of the absorbed radioisotopes within plants, and some factors that modify the uptake and distribution of these radioisotopes in plants are discussed. The relative order of magnitude of uptake of fission products by plants appeared to be $Sr^{89-90} \gg I^{131} > Ba^{140} > Cs^{137}, Ru^{106} > Ce^{144}, Y^{91}, Pm^{147}, Zr^{95}\text{-}Nb^{95}$. There were considerable differences in uptake among different plant species and conditions of growth. Accumulation of each of the fission products studied was greatest in leaves of plants, but comparatively low in seeds, fruits, or edible roots. Fission product contents of plants may be altered by certain soil management practices such as cultivation, fertilization, and organic matter application.

Contamination of natural environments by radioactive fission products has aroused considerable concern in relation to the health and welfare of mankind. The concern arises from the fact that sooner or later, some of these radioactive fission products will become involved with man and his food supply.

One of the important steps in the movement of radioactive fission products through the food chain to man is the transfer of these substances from contaminated soils to plants. In natural environments, these radioactive fission products can get into plants both through the aboveground parts of the plant from external surface contamination and through the roots growing in contaminated soils. Leaving aside uptake through the aboveground parts of the plants, this paper is concerned with the uptake of fission products by crop plants through the root system, the distribution of absorbed fission products in various plant parts, and certain factors that influence fission product uptake from contaminated soils.

Table I. Uptake of Fission Products by Radishes from a Soil Contaminated by Fallout from a Subsurface Detonation at Nevada Test Site

Crop No.	Harvest Time after Detonation, Days	Total Soil Activity at Harvest Time, μc./Flat[a]	Tops			Roots			Total Uptake, 10^{-3} %[b]
			Yield, g.	β-Activity, μμc./g.	Uptake, 10^{-3} %[b]	Yield, g.	β-Activity, μμc./g.	Uptake, 10^{-3} %[b]	
1[c]	48	19.1	7.0	327.0	12	6.3	322.0	11	23
2	139	8.45	23.3	95.5	26	23.3	119.0	33	59
3	216	3.25	12.1	19.5	7	11.0	20.8	7	14
4	251	2.58	23.1	5.7	5	13.6	15.9	8	13
5	296	2.15	33.5	N.S.	N.S.	13.9	N.S.	N.S.	N.S.
1[d]	48	33.8	6.6	460.0	9	4.5	427.0	6	15
2	139	15.0	7.0	155.0	7	9.3	140.0	9	16
3	216	5.77	7.5	23.2	3	4.9	10.5	1	4
4	251	4.58	11.8	4.3	1	7.4	10.8	2	3
5	296	3.81	36.7	N.S.	N.S.	14.6	N.S.	N.S.	N.S.

[a] Total surface area of the soil was 3.33 sq. feet.
[b] Per cent of total soil activity at harvest time.
[c] 12.2 miles from ground zero; initial activity, 164 μc./flat.
[d] 12.3 miles from ground zero; initial activity, 291 μc./flat.
N.S. = Not significantly above background activity.

Plant Uptake of Fission Products from Soils Contaminated by Fallout

A nuclear fission reaction produces many radioisotopes. According to Blomeke (*2*), 170 isotopes of 35 elements, ranging in mass number from Tb^{161} to Zn^{72}, are known to result from slow neutron fission of U^{235}. In addition, during nuclear detonations, radioactive elements of higher and lower atomic masses may be produced by neutron induction. Of these numerous fission products, relatively few have been studied with respect to uptake by plants. To date, most experiments have been concerned with fission products that have fairly long half lives, that represent appreciable percentages of the total fission product activity at a given time, and/or those that may have consequences biologically if present in significant concentrations.

The uptake of fission products by plants has been studied in the field and in the greenhouse. With plant samples from the field, difficulties have been encountered in differentiating between the radioactivity resulting from external surface contamination and that taken up through the roots from contaminated soils. This difficulty was encountered particularly when the radioactivity of the plant samples was low. In keeping with our objective, only data clearly showing uptake of fission products through the root system were selected for this paper.

Several investigators have studied fission product uptake by plants from soils contaminated by fallout originating from nuclear detonations. Table I shows the typical results obtained by Larson *et al.* (*13*). The radioactivity of the plant material on a unit weight basis was the greatest in the first of the series of successive cropping and decreased to insignificance in the fifth crop even though the residual activity in the soil was still appreciable. The total uptake of fission products expressed as per cent of total residual activity in the soil at harvest time ranged from 0 to 0.06%. In an experiment similar to that described above, Lindberg *et al.* (*15*) studied the uptake of fission products by red clover from soil contaminated by fallout from a 500-foot tower detonation (Table II). The total uptake of fission products by clover expressed as per cent of total residual soil activity at harvest time ranged from 0

Table II. Uptake of Fission Products by Red Clover Grown on a Soil Contaminated by Fallout from a 500-Foot Tower Detonation

Distance from Ground Zero, Miles	Harvest Time after Detonation, Days	Total Soil β-Activity at Harvest Time, $\mu c./Flat^a$	Clover		
			Yield, g.	β-Activity, $\mu\mu c./g.$	Total uptake, 10^{-3} %[b]
7	41	15.53	8.0	1.62	0.08
	70	8.38	19.3	3.00	0.69
	95	5.59	21.5	3.51	1.36
	107	4.97	20.7	2.43	1.01
	133	4.66	21.2	N.S.	N.S.
	231	1.86	20.0	N.S.	N.S.
48	41	4.85	7.3	6.22	0.09
	70	2.62	13.8	3.78	1.99
	95	1.75	17.2	3.52	3.46
	107	1.55	19.2	4.60	5.70
	133	1.45	22.9	5.14	8.12
	231	0.61	18.6	N.S.	N.S.

[a] Total surface area of the soil was 1.5 sq. feet.
[b] Per cent of total soil activity at harvest time.
N.S. = Not significantly above background activity.

to about 0.008. These data showed that fission product uptake by plants grown on soils contaminated by fallout was a small percentage of the total residual activity in the soil and varied over a wide range. These variations in the uptake of fission products by plants are to be expected, because the availability of fission products to plants depends on the physical and chemical properties of fallout and on many factors involved in soil-plant interrelationships.

Some Properties of Fallout

A detailed discussion of the properties of fallout is beyond the scope of this paper, so only a brief statement will be made here. The chemical and physical properties of fallout originating from nuclear detonations are highly dependent upon the conditions of the detonation. Near-surface bursts (less than 300 feet) studied at continental test sites produced predominantly siliceous particles. This suggests the incorporation of the soil into particles. Particles from bursts at higher elevation reflected more the mass of inert material immediately surrounding the device. The median particle size of fallout generally decreased with increasing distance from ground zero. The beta radioactivity decay rate of fallout material from nuclear detonations studied at the Nevada Test Site approximated the $T^{-1.2}$ relationships to about $D + 250$ days (T refers to time after detonation and D refers to the day of detonation) and $T^{-1.4}$ relationship from $D + 250$ days to $D + 417$ days. The solubility of fallout material collected in the environs of the Nevada Test Site ranged from a trace to about 31% in distilled water, and from 2 to more than 90% in $0.1N$ HCl (*14*).

Relative Plant Uptake of Fission Products and Plutonium

Once the fallout materials become solubilized, the fission products react with the soil and become potentially available for uptake by plants through the root system. Figure 1 shows the uptake of fission products in the leaves of five different plant species grown to maturity in Hanford sandy loam (*18*). Each carrier-free radioisotope was applied individually at a dose equivalent to 100 distintegrations per second (d.p.s.) per gram of soil at the end of 120 days after planting of crops. The uptake of Sr^{90} was much greater than that of other radioisotopes. The uptake of Cs^{137} and Ru^{106} was much lower than Sr^{90}, but considerably greater than Ce^{141} and Y^{91}. The uptake of Ce^{144} and Y^{91}, being in the order of 1 to 3 d.p.s. per gram of dry plant leaves, was very small. The bars are arranged in descending order of uptake of Sr^{90} by different plant species (bean > radish > carrot > lettuce > barley). The uptake of the other isotopes did not follow the same order. For example, the uptake of Cs^{137} was about the same or greater than that of Ru^{106} in the leaves of barley, lettuce, and carrot, whereas it was lower in bean and radish leaves. Thus, although growing under identical soil and climatic conditions, at harvest time different plant species contained very different proportions of the various radioisotopes taken up from the soil. Auerbach *et al.* (*1*) have shown differences in the uptake of fission products among native plant species.

Besides Sr^{90}, Cs^{137}, Ru^{106}, Ce^{141}, and Y^{91}, the uptake of several other fission products has been studied. In a comparative study of Pm^{147}, Ce^{144}, and Y^{91} at our laboratory, using contaminated Hanford sandy loam and the five plant species (bean, radish, carrot, lettuce, and barley), the uptake of Pm^{147} was found to be of the same order of magnitude or less than that of Ce^{144} or Y^{91}. Jacobson and Overstreet (*10*) grew dwarf peas for 3 months in a contaminated sandy soil and found that the amount of Zr^{95}-Nb^{95} in the leaves was much less than Ce^{144} or Y^{91}. Rediske, Cline, and Selders (*24*) grew barley seedlings in several different soils by a modified Neubauer technique and found that the uptake of Zr^{95}-Nb^{95} was about equal to Ce^{144} or less. Their results also indicated that the uptake of Ba^{140} was less than I^{131} which in turn was less than Sr^{90}.

Although Pu^{239} (half life, 2.4 × 10^4 years) is not a fission product, its uptake by plants has been studied because it may be produced by neutron induction of uranium, or it may be dispersed in an unfissioned form during a nuclear detonation. At our laboratory, ladino clover was grown in soil contaminated with fallout containing Pu^{239} and was found to contain only trace amounts of Pu^{239} in the above ground parts. Selders, Cline, and Rediske (*31*) grew beans, barley, tomato plants, and Russian thistle in soils that were contaminated by fallout from an atomic detonation, and observed a trace amount of translocation of alpha activity in tomato plants [< 1 distintegration per minute (d.p.m.) per gram], but none in the other plants, although the soil contained 35 d.p.m. of alpha activity per gram. Jacobson and Overstreet (*10*) studied the uptake of Pu^{239} using barley seedlings in contaminated bentonite suspensions for a 24-hour absorption period. Their results showed that, although very small, some activity was translocated to the leaves. The accumulation occurred primarily in or on the surface of the roots. The amount adsorbed on the clay or taken up by the plant depended on the valence state of Pu^{239}.

In general, these and other available data in the literature (*1*, *3*, *8*, *9*, *27*) show that the relative order of magnitude of uptake of fission products and plutonium by plants from contaminated soils is $Sr^{89-90} >> I^{131} > Ba^{140} > Cs^{137}$, $Ru^{106} > Ce^{141}$, Y^{91}, Pm^{147}, Zr^{95}-$Nb^{95} > Pu^{239}$. Where difficulty was encountered in determining the relative order of magnitude of uptake, commas are inserted among the isotopes.

Variation in Uptake Associated with Soil Type

At comparable dose levels in a particular soil, the relative order of uptake of radioisotopes by plants does not vary much, but the absolute magnitude of uptake may vary considerably with different soils. Figure 2 illustrates the relative difference in fission product uptake by barley plants grown in different soils. The bars represent the radioactivity of a unit weight of plant material. The numbers above the bars represent concentration factors. A concentration factor is obtained by dividing the radioactivity of a unit weight of dry plant material by that of a unit weight of soil. The factor gives an indication of the availability of different radio-

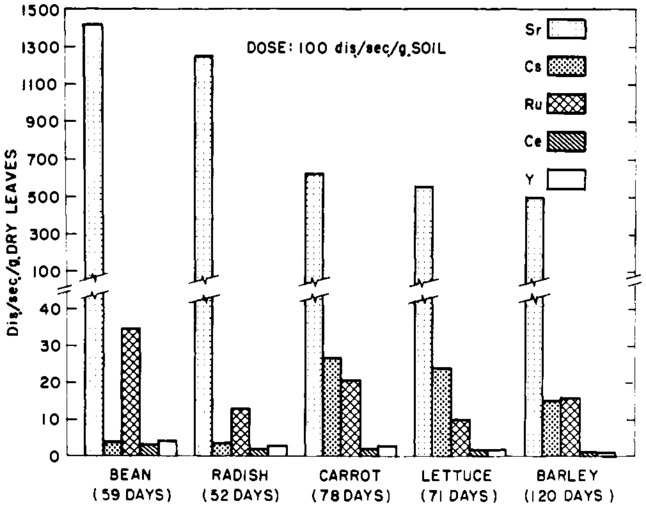

Figure 1. Accumulation of Sr^{90}, Cs^{137}, Ru^{106}, Ce^{144}, and Y^{91} in leaves of five crop plants grown in contaminated Hanford sandy loam

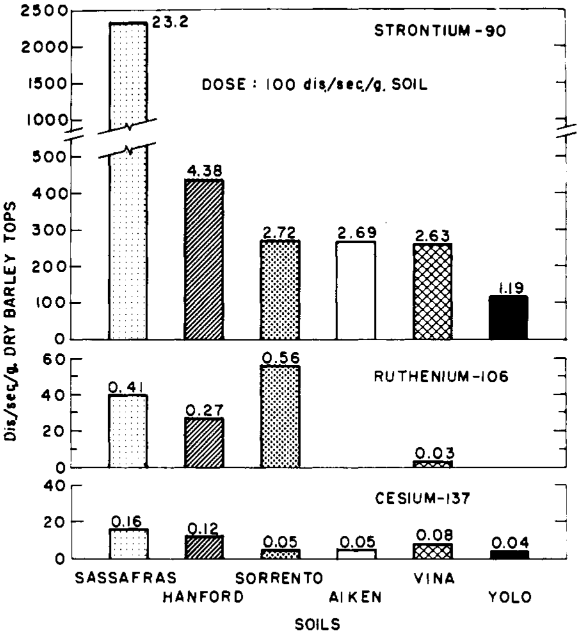

Figure 2. Uptake of Sr^{90}, Ru^{106}, and Cs^{137} in above-ground part of barley grown in different soil types

isotopes to plants grown under similar conditions. The uptake of Sr^{90} by the plants from the soils is arranged in decreasing order—i.e., Sassafras > Hanford > Sorranto, Aiken, Vina > Yolo. The concentration factor for Sr^{90} ranged from about 23 for Sassafras down to about 1 for Yolo. The order of uptake of Ru^{106} and Cs^{137} with respect to soils was not the same as for Sr^{90}. The greatest uptake of Ru^{106} by the plants was from the Sorrento soil. The uptake of Cs^{137} was greater from Vina than from Sorrento or Aiken soil. As shown in Figure 3, these variations result from the differences in the reaction of these radioisotopes with different soils *(21)*. For example, the water-soluble fraction (52%) of Sr^{90} in the Sassafras soil was much greater than that (<8%) in the other soils studied. Except in Sassafras soil, the water-soluble fraction of Ru^{106} was greater than that of Sr^{90} or Cs^{137} in the various soils. The water-soluble fraction of Cs^{137} was very low. The exchangeable fraction of Cs^{137} was much greater than that of Ru^{106}, but was considerably less than that of Sr^{90}. In general, the nonextractable fractions of Cs^{137} and Ru^{106} were much greater than that of Sr^{90}. Thus, the chemical properties of the radioisotopes as well as those of the soils influence the uptake of mineral ions by plants.

Distribution of Fission Products in Plant Parts

Only certain parts of many crop plants are used as food. Therefore, knowledge of the distribution of fission products in different plant parts is necessary in order to assess the potential hazards that might arise from eating plant produce grown in heavily contaminated areas. External surface contamination of plant foliage by radioactive fallout is an important means by which fission products are transferred from plants to animals in the food chain leading to man *(15, 29)*. Aside from the external surface contamination of the various plant parts, the distribution of fission products in the plant following uptake through the root system will be discussed.

Table III illustrates this distribution of fission products within some crop plants. The table presents a composite of typical results obtained by various investigators under different conditions of plant growth such as different soils, contamination doses, methods of growth, and climatic conditions. Although the amount of Sr^{90} accumulated varied markedly with plant species and the conditions of growth, the greatest accumulation of Sr^{90} invariably occurred in the leaves. The accumulation of Sr^{90} in the fruits was comparatively low, and its accumulation in the seeds was much less than it was in the other parts. The Sr^{90} contents of edible roots of the root crops studied were considerably lower than that in the tops of the same plants. As for Cs^{137}, the greatest accumulation occurred in the stems of some plants, but in most cases it was the greatest in the leaves. Cesium-137 appeared to be more uniformly distributed among the different plant parts than Sr^{90}. A greater proportion of the absorbed Cs^{137} accumulated in the edible roots and the fruits of plants in comparison to leafy tissues than was observed for Sr^{90}. In general, Ru^{106}, Ce^{144}, Y^{91}, and Zr^{95}-Nb^{95} also accumulated in the leaves in the greatest amount relative to fruits and stems.

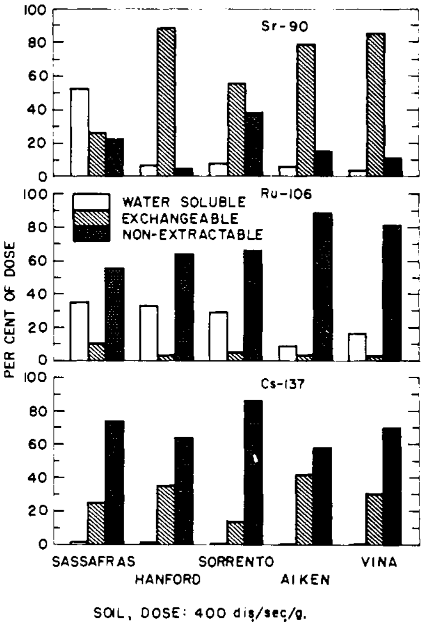

Figure 3. Water-soluble, exchangeable, and nonextractable Sr^{90}, Ru^{106}, and Cs^{137} in contaminated soils

The data of Table III show the composition of the mature plants only. The content of the fission products will vary with the stage of plant development. Working with bean plants, Romney *et al.* *(28)* found that Sr^{90}, Ru^{106}, and Ce^{144} increased steadily in the leaves during the plant development. In the stems, these radioisotopes increased rapidly during the first 20 days and then remained fairly constant during the remaining growth period of 60 days. The Cs^{137} content increased rapidly in both the stems and the leaves for the first 20 days and then remained fairly constant during the remaining growth period. Working with rye, Russell *et al.* (*30*) found that on all occasions the Sr^{90} content greatly exceeded that of the other fission products, but with the passage of time, the content of Ru^{106} and Ce^{144} increased relative to Sr^{90}. This effect was much greater with Ce^{144} than with Ru^{106}.

Since soils react chemically with radioactive contaminants and influence their uptake by plants, it is of interest to compare the distribution of fission products taken up through the root systems with and without the influence of the soil system. Data in Table IV reported by Klechkovsky and Gulyakin (*12*) show that, in all cases, the uptake of Sr^{89-90}, Cs^{137}, Ru^{106}, and Zr^{95}-Nb^{95} was greater from water culture than from soil, but that the relative distribution of these radioisotopes within the plant was similar in the two media. In water culture the uptake of Cs^{137} was greater than Sr^{90}, whereas it was much less than Sr^{90} from the soil system. Thus, the uptake of Cs^{137} was more strongly influenced by the soil than was Sr^{90}. The accumulation of Ru^{106} and Zr^{95}-Nb^{95} in the aerial parts was very small whether the plants were grown in the soil or in water culture. The largest percentage of these radioisotopes was in or on the surface of the roots, whereas comparatively large proportions of Cs^{137} and Sr^{90} were translocated to the aboveground parts of the plant. These results, aside from the modifying effect of the soil, further illustrate that uptake of radioisotopes by plants may be greatly influenced by the chemical properties of the individual element.

Table III. Distribution of Fission Products in Different Parts of Crop Plants

Plant Parts	Dose in Soil, µc./Kg.	Radioisotope, D.P.S. per Gram						Ref.
		Sr^{90}	Cs^{137}	Ru^{106}	Ce^{144}	Y^{91}	Zr-Nb^{95}	
Maize								
Leaves	243	4,683	...	5.0	16.7	...	...	(*13*)
Stems		633	...	1.7	1.7	...	...	
Panicle		1,023	...	3.0	3.3	...	...	
Husk		220	...	0.3	1.7	...	...	
Cob		283	...	0.5	3.3	...	...	
Grain		18	...	0.17	...	...	...	
Wheat								
Leaves	156	11,422	63.3	...	11.7	...	...	(*10*)
Stems		1,817	18.3	...	3.3	...	...	
Grain		638	10.0	...	1.7	...	...	
Pea								
Leaves	[a]	2,605	...	...	17.0	10.0	7.09	(*11*)
Stems		1,905	...	...	3.68	1.55	2.30	
Pods		1,115	...	...	1.98	0.80	2.28	
Seeds		73	...	...	0.13	0.02	0.30	
Roots		3,530	...	...	662.0	385.0	418.0	
Bean								
Leaves	2.7	1,945	13	67	10	6	...	(*32*)
Stems		1,002	7	3	3	2	...	
Fruits		320	13	6	3	2	...	
Lettuce								
Leaves	2.7	757	65	9	2	3	...	
Stems		424	29	2	1	1	...	
Radish								
Leaves	2.7	1,813	22	9	10	5	...	
Roots		455	21	4	6	7	...	
Carrots								
Leaves	2.7	910	20	73	2	4	...	
Roots		297	24	1	1	3	...	

[a] Dose in soil (µc./kg.): Sr^{90} = 244, Ce^{144} = 233, Y^{91} = 216, and Zr-Nb^{95} = 180.

Table IV. Comparison of Distribution of Fission Products in Parts of Wheat Plants Grown in Soil and Water Cultures (*12*)[a]

Plant Part	Sr^{89-90}[b]		Cs^{137}		Ru^{106}		Zr-Nb^{95}	
	Soil	Water	Soil	Water	Soil	Water	Soil	Water
	10^3 Counts per Minute							
Straw	1.65	54.1	0.28	208.4	0.08	1.13	0.04	0.36
Chaff	0.65	16.9	0.08	143.6	0.03	0.95	0.01	0.13
Grain	0.08	2.3	0.02	29.1	0.00	0.03	0.00	0.02
Roots	0.73	56.3	7.80	807.1	1.10	368.5	0.18	31.6

[a] Contamination level was 50 µc./liter of solution or 50 µc./kg. of soil.
[b] Sr^{90} was used in soils; Sr^{89} in water cultures.

Some Factors That Influence Uptake

While the relative uptake and distribution of fission products generally may be expected to follow patterns similar to those described, the absolute amount of uptake through the roots depends on a number of modifying factors, which may either enhance or inhibit uptake. Thus far, it has been shown that the uptake of fission products by plants varies with the physicochemical properties of the ions, the plant species, and the soil type under which the plants grow. Besides soil type, there are other environmental factors that influence the uptake of mineral ions by plants. The environment of living organisms is so complex that it is extremely difficult to make a complete analysis of these modifying factors. Thus, further discussion in this paper is restricted to certain soil factors that influence the uptake of fission products by plants and that may be changed quite readily by certain soil management practices such as the addition of organic matter, mineral fertilizers, and other amendments to soils.

Fertilizers are added to soil to replenish mineral nutrients exhausted by heavy cropping or leaching by rain or irrigation. Other amendments may also be applied to alter the natural mineral nutrient content in order to bring about a nutrient balance in the soil that is more conducive to crop production. When mineral elements with similar chemical properties are introduced into the soil exchange complex, they tend to compete with each other for the same chemical reactions and often can replace each other to a limited extent in this category; the cations of these elements are termed "complementary ions." Based on the premise that an excess of one of two complementary ions would tend to suppress the entry of the other into a given chemical reaction, a number of investigations have been conducted to study the influence of stable calcium and potassium on the transfer of Sr^{90} and Cs^{137}, respectively, to plants through the root system. Several investigators (*4*, *6*, *7*, *12*, *26*, *32*) have shown that the application of Ca amendments [$Ca(NO_3)_2$, $Ca_3(PO_4)_2$, $CaCO_3$ or $CaSO_4$] to acidic soils low in available Ca reduced the uptake of Sr^{90} by plants; however, these treatments did not effectively reduce Sr^{90} uptake from soils that contained sufficient levels of available Ca for good crop growth. Romney *et al.* (*26*) found that the application of $CaCO_3$ and $CaSO_4$ at levels equivalent to 2 to 5 tons per acre reduced to about one fifth the transfer of Sr^{90} to beans from an acidic soil low in available Ca. Although there were some differences due to accompanying anions, Ca appeared to be primarily responsible for reduced uptake of radioactive Sr (*26, 32*).

The application of K to soils showed analogous effects on the uptake of radioactive Cs. The added K inhibited the Cs^{137} uptake by plants from soils low in available K, but it had no appreciable effect in reducing the uptake of Cs^{137} from soils that contained high levels of available K (*5, 22*). In untreated soils, Menzel (*16*) found the transfer of Cs^{137} to plants was inversely correlated with the level of available K. In agreement with this result, Nishita *et al.* (*22, 23*) found that the uptake of Cs^{137} increased as the potassium was depleted in the contaminated soil by prolonged cropping.

Klechkovsky and Gulyakin (*11*) reported that the addition of nitrogen (as NH_4NO_3) to soil increased the accumulation of Sr^{90} and Cs^{137} in the straw and grain of oat plants. This effect was much less on Sr^{90} uptake than on Cs^{137}. The addition of P[as $Ca\,(H_2PO_4)_2$] reduced the uptake of Cs^{137} and increased the uptake of Sr^{90} in the straw, but had no appreciable effect on their accumulation in the grain. Under the influence of these fertilizers, the straw/grain ratio of Cs^{137} was markedly lowered, whereas the straw/grain ratio of Sr^{90} was greatly increased. Thus, by adding certain amendments to the soil, the relative amounts of radioisotopes distributed in different plant parts may be altered.

Several investigators conducted experiments with the premise that the addition of a stable isotope of a radioisotope to soils would dilute the amount of radioisotope available to the plant by mass action effect and thereby reduce its uptake. Contrary to expectation, the addition of moderate amounts of stable Sr to soil did not reduce Sr^{90} uptake significantly, but rather, in several cases, caused a slight increase in the amount of Sr^{90} uptake through the roots. The addition of small amounts of stable Cs markedly increased the uptake of Cs^{137} by plants (*5, 22*). This effect was still apparent even when the amount of stable Cs applied was toxic to plants. This increased uptake of Sr^{90} and Cs^{137} from the addition of carrier to the soil is attributable largely to the increased displacement of Sr^{90} and Cs^{137} from the exchange complex into the soil solution by the stable element where they could be more readily absorbed by the plant (*22, 25*). The reduction of the uptake of radioisotope by plants could be achieved by adding relatively high levels of its stable isotope to the soil (*4, 25*); however, these levels are economically impractical for Sr, and for Cs these levels are definitely toxic to plants.

In adding stable Sr to soils, several anionic forms have been used. As might be predicted from the solubility of the salts, Uhler (*32*) found that the availability of radioactive Sr from the slightly soluble forms [SO_4^{-2}, $C_2O_4^{-2}$, F^-, OH^-, CO_3^{-3}, HPO_4^{-2}] was less than one tenth of that from the soluble forms (Cl^- and NO_3^-). In the calcareous soils studied, the relative order of availability of radioactive Sr was $Cl^-, NO_3^- >> SO_4^{-2}, C_2O_4^{-2} > F^- > OH^- > CO_3^{-3}, > HPO_4^{-2}$. In an acidic soil, the availability of radioactive Sr from the slightly soluble forms studied was not significantly different.

Another factor that may influence the uptake of fission products is the soil organic matter with its associated microorganisms. The number of studies of the influence of the addition of organic matter to soils on the uptake of fission product by plants is quite limited. Nishita *et al.* (*19*), in a short term experiment, found that the addition of dry, nondecayed ground lettuce at a level of 1% by weight of soil reduced by 12% the Sr^{90} uptake by barley seedlings grown by a modified Neubauer technique. Progressively higher levels of organic matter reduced the uptake of Sr^{90}. The addition of dry, nondecayed lettuce at a level of 10% by weight reduced the uptake of Sr^{90} about 78%. In a longer term experiment, in which tomato plants were grown in pots, the addition of organic matter up to about 2% by weight increased the uptake of Sr^{90} and then decreased it upon further addition of organic matter (*20*). From a practical point of view, the point to note here is that large amounts of organic matter were required to reduce the uptake of Sr^{90}. One per cent by weight represents roughly 10 tons per acre (mineral soil) of dry organic matter. Another effect of organic matter was observed by Milbourn, Ellis, and Russell (*17*). They found 25% greater uptake of Sr^{89} by sugar beet, rye, and barley when the land was under stubble at the time of contamination than when it was bare. It appeared that the applied Sr^{89} adsorbed on herbage which was subsequently plowed into the soil was more readily available to plants than contamination applied directly to the bare soil.

Inasmuch as the distribution of fission products in the soil profile may be altered by mechanical movement, cultivation and plowing are other common soil management practices that may affect plant uptake of fission products. Milbourn, Ellis, and Russell (*17*) showed that the effect of cultivation on the plant uptake of Sr^{89} from contaminated soils depended on the depth of cultivation, plant species, and kind of soil. In general, deep plowing (12 inches) was more effective than shallow cultivation. The variable effect of cultivation on different plant species was considered to reflect differences in the depths of their absorbing roots.

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Absorption of Radionuclides by Aboveground Plant Parts and Movement within the Plant

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The aboveground parts of plants readily absorb radionuclides from external spray applications. Entry occurs through the leaves, stem, fruit, and bark. The rate of absorption, extent of subsequent transport, and pattern of distribution within the plant is dependent upon the nature of the radionuclide and many internal and external factors. Not only are radionuclides absorbed by aboveground plant parts, but they may be lost therefrom into the external environment from leaching induced by rain and dew. Both acropetal and basipetal transport occur following application of P^{32}, K^{42}, Rb^{86}, and Cs^{137} to aerial plant parts. This is in marked contrast to Ca^{45}, Sr^{89}, Sr^{90}-Y^{90}, Ru^{103}, and Ba^{140}. These latter radionuclides do not move freely from the absorbing aerial organ (leaf, fruit), and basipetal transport is negligible. The hazard exists that fission product radionuclides may be directly incorporated into plant tissues.

THE ROOT is commonly accepted as the principal nutrient-absorbing organ of the plant. However, Mayer (*25*) as early as 1874 demonstrated that ammonia was absorbed directly by the foliage of plants and influenced growth. Sulfur is absorbed as sulfur dioxide (*29*) from the atmosphere by leaf surfaces and is translocated and readily converted to organic forms (*40*).

A few years ago a very simple yet significant experiment was conducted in which bean seedlings were grown to maturity in solution cultures of only distilled water (Figure 1). The sole supply of nutrients for the plants was in solutions applied to the foliage. The life cycle of the bean plant was completed with all mineral nutrients being supplied through the foliage.

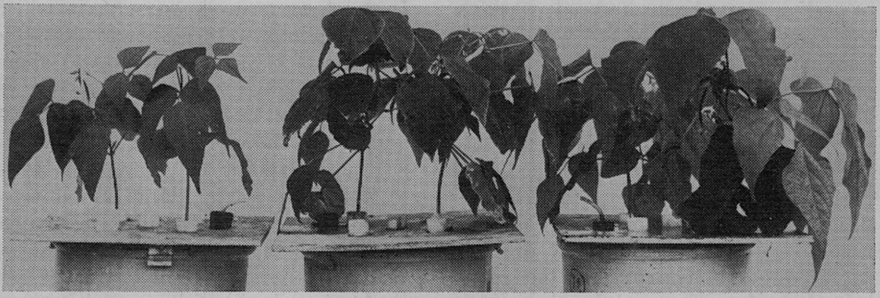

Figure 1. Bean plants grown with mineral nutrients supplied solely by foliar or nonroot feeding, as compared to root feeding

Left. Foliage sprayed weekly with a complete nutrient solution
Center. Sprayed daily with a complete nutrient solution
Right. Plants supplied with a complete nutrient solution (containing 1/10 the concentration of nutrients sprayed on foliage) through roots
Roots of plants in left and center cultures grown in distilled water

Recently, with the use of radioactive isotopes, it has been conclusively demonstrated that not only the leaves but also the bark and even the fruit can absorb nutrients (*42*). Fallout products from a nuclear detonation may be deposited upon the aboveground parts of plants and be absorbed by them, and therefore, it becomes of some concern to determine how and to what degree these contaminate materials may enter a plant, the nature and the amount of movement of these substances within the plant, and the extent to which they may be leached from plants once they are absorbed.

The Leaf as an Organ of Absorption

The cuticle of the leaf is composed of a framework of cutin within which flat platelets of wax are embedded (*23*). The structure has been likened to a rubber sponge of cutin in which the holes are filled with wax. In a heavily cutinized leaf with unbroken cuticle, this layer is not easily penetrated by materials in solution (*45*). In some species of plants a heavy wax is extruded onto the leaf surface which may act as a significant barrier to penetration (*34*).

Such complete barriers to penetration, however, seldom exist in nature. Cracks and imperfections appear in the cuticle. Hydration of the cuticle causes expansion in which the wax platelets are spread apart so that permeability of the cuticle is increased. Hairs and other specialized epidermal cells overlie veins, and there are specialized surface veins in the leaf which are made up of parenchyma tissue with thin-walled cells which extend into the epidermis and provide excellent conduction into the leaf. Cuticular areas have been observed over the anticlinal walls of epidermal cells which are preferentially penetrated by water-soluble substances (*9*). In fact, in very young leaves, cutin may be absent over these areas. The damaging of epidermal hairs by brushing lightly with a soft brush or eroding the leaf surface by rubbing gently with a glass rod markedly increases penetration (*38*).

In addition, Roberts *et al.* (*31*) have shown from microchemical examination of McIntosh apple leaves that there is a relationship of cell wall constituents to penetration of water-soluble materials