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Reduction of Strontium-90 Uptake by Corn and Soybeans with Deep Placement, Irrigation, and Soil Amendments[1]

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SYNOPSIS. Field experiments were initiated in 1960 in the states of Georgia, South Carolina, Iowa and Minnesota to evaluate methods of reducing uptake of Sr^{90} fallout by crops. Significant reductions in Sr^{90} content in corn and soybean grain were obtained by deep placement but not by irrigation. Calcium treatments reduced Sr^{90} in both grains in Georgia, and potassium reduced Sr^{90} in corn grain in Minnesota. The maximum reduction observed was about 50%.

RADIOACTIVE fallout from intentional or accidental nuclear explosions is a potentially serious problem. Of primary concern among long-term components of fallout is Sr^{90}, which does not occur in nature, but is produced by nuclear reactions. It has a 28-year half-life, tends to be retained by the soil, is readily available to plants grown on soils that it has contaminated, and is usually incorporated into the bodies of animals feeding on these plants. The procession of these functions can lead undesirably to the irradiation of human bones, in which Sr^{90} tends to collect; it is important, therefore, to find a way or ways of preventing Sr^{90} from reaching the human consumer. The entire problem of controlling the content of Sr^{90} in food products may be seen in sharper perspective with a knowledge of the possibilities offered by soil and crop management practices.

Factors affecting uptake of Sr^{90} by plants have been recently reviewed (5, 15). Sr^{90} uptake is inversely related to exchangeable Ca in soils (8). Therefore, liming is an appropriate method for reducing uptake from acid soils. High rates of potassium application also may reduce Sr^{90} uptake (4).

Several studies have shown that placement of Sr^{90} may affect uptake. In lysimeter cultures of barley, the uptake of Sr^{90} placed at a depth of 2 feet in the soil was approximately 10% of that placed at a 2-inch depth (17). Studies in the United Kingdom with a number of crops have shown that plowing to a depth of 12 inches led to a reduction of not more than 30% in the Sr^{89}/Ca ratio relative to a 4-inch rotary cultivation (13).

A field experiment with soybeans showed that uptake of Sr could be moderately reduced when it was placed with lime at a depth of 15 inches in the soil (9). It was speculated that uptake of the buried Sr could be further reduced if shallow root development were encouraged by applying abundant nutrients and water in the top 12 inches of soil (9).

The need for further investigation of methods for reduction of Sr^{90} contamination is pressing because of the potential hazards to human health posed by the existence of this radioactive nuclide. The present study was conducted for the purpose of partially fulfilling this need. Field experiments were carried out to evaluate the effects of deep placement, irrigation, and calcium and potassium amendments on the reduction of Sr^{90} uptake in various soils and climates. This report summarizes the results obtained with crops grown in 1960.

EXPERIMENTAL PROCEDURE

Field experiments utilizing Sr^{90} from worldwide fallout were initiated in May 1960. It was recognized that the Sr^{90} content of the crops would result from two sources, uptake from the soil and direct deposition of fallout on the plant. Estimates of the contribution from each source were derived from measurements of specific activities (Sr^{90}/Sr) in the crops and soil.

The experiments were carried out at 4 locations representing widely varying soil and climatic conditions; however, each area had been in grass at least 5 years previously. Thus, most of the Sr^{90} accumulated from previous fallout was still present in the top 4 inches of soil. The soils and locations were as follows: Cecil sandy loam, Watkinsville, Georgia; Dunbar sandy loam, Florence, South Carolina; Brookings silt loam, Morris, Minnesota; and Nicollet silt loam, Ankeny, Iowa. The experiment was planned for 3 years on the same plots, with corn and soybeans grown the

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first year, oats and wheat the second year, and adapted grasses and legumes the third year. Conventional cultural and fertilization practices were used for each crop and location, except when they conflicted with the experimental variables.

A modified split plot design was used at each location, with shallow and deep placement of the surface soil as the 2 main plots, with minimal and frequent irrigation as the 2 subplots, and with combinations of 2 levels of calcium and potassium as the 4 sub-subplots. The experiment for each crop at each location consisted of two replications.

Placement. Shallow placement was achieved by conventional plowing to a depth of about 6 inches. In deep placement, the surface 4 inches of soil was buried at a depth of 20 to 24 inches. This was achieved by excavating and replicating the soil in layers. The original 14- to 24-inch layer was replaced on top of the 0- to 4-inch layer. Finally, the 4- to 14-inch layer was replaced and became the new surface soil.

Irrigation. The minimal irrigation plots received only rainfall and enough sprinkler irrigation to prevent appreciable retardation of the crops due to drought. The frequent irrigation treatment called for irrigation each time the moisture deficit exceeded 1 inch of water in the top 24 inches of the soil profile. The total amounts of water received on the minimal irrigation plots during the 4 months of June through September in South Carolina, Georgia, Iowa, and Minnesota were 20.4, 16.4, 17.2, and 17.2 inches, respectively. The additional amounts of water applied in the frequent irrigation treatments were 2.2, 2.5, 4.3, and 31.9 inches, respectively.

Calcium amendment. The low-calcium plots received no lime or gypsum. The high-calcium plots were treated with finely ground limestone at rates of 3, 4, and 6 tons per acre in South Carolina, Georgia, and Iowa, respectively. Gypsum was applied at the rate of 4 tons per acre in Minnesota.

Potassium amendment. The rates for the low-potassium plots were based on conventional local fertilizer practices. They were 0, 20, 30, and 130 pounds of potassium per acre for Minnesota, Iowa, South Carolina, and Georgia, respectively. The high-potassium plots received 250, 270, 110, and 300 pounds of potassium per acre, respectively.

Soil and crop sampling. Soil samples were taken from all plots in May 1960. These samples were representative of 0- to 4-, 4- to 14-, and 14- to 24-inch layers in the soil profile before treatment. Soil samples were again collected in June 1961. Grain yields were determined at maturity and calculated on the basis of 15.5% moisture for corn and 13% moisture for soybeans. Samples of grain and lower stubble, 1–4 inches, were collected, ground, and ashed for determinations of stable Sr and Sr^{90}.

Analysis. The soils were characterized by determining pertinent physical and chemical properties. Quantities of clay were determined by a sedimentation procedure (7). Types of clay minerals were identified by the diffraction methods of Jackson (6), except that ethylene glycol was used for solvation of clays. Organic carbon was determined by the chromic acid-ferrous sulfate titration method (14). Soil pH was measured electrometrically in a 1:1 soil-water suspension. Exchangeable hydrogen was determined by the triethanolamine method (14). Other exchangeable cations were extracted with *N* neutral NH_4OAc and determined by the following methods: Ca and Mg by EDTA titration, K and stable Sr by flame photometry, and Sr^{90} by radiochemical procedures.

The plant samples were dry ashed for determination of stable Sr. The stubble ash was dissolved in dilute HCl. After removal of orthophosphate and other interfering ions by precipitation of zirconyl phosphate and hydroxide at pH 6.0 (3), the solution was analyzed by flame photometry. Since the Sr content of grain was too low for analysis by this technique, it was determined by X-ray fluorescence. Either the grain ash was analyzed directly or it was dissolved, and the analysis was made on a sulfate precipitate.

Sr^{90} in the samples was determined by separating and counting its radioactive daughter, yttrium^{90} (16). Final Sr^{90} values were calculated with efficiency corrections obtained by taking Sr^{90} standards through the same chemical and radiochemical procedures followed for the samples. Corrections were made for radioactive decay during the time between harvest in October 1960 and analysis. The error for the Sr^{90} determination is approximately $\pm$ 10%.

RESULTS

Soil properties. There was considerable variation in chemical and physical properties among the 4 different soil types, although the 2 southeastern soils resembled each other, as did the 2 midwestern soils (Table 1). The Cecil and Dunbar soils of the southeast were characterized by low values for pH, organic carbon, and exchangeable Ca. These 2 soil types, particularly the Cecil, possessed high percentages of clay below the 4-inch level. The predominant clay mineral found in the southeastern soils was kaolinite. On the other hand, the clay type of the midwestern soils was mainly montmorillonite, and the amounts were quite uniform both as to depth and in regard to each other. The Brookings and Nicollet soils had comparatively high organic carbon and exchangeable Ca contents. The Brookings silt loam had some free lime, resulting in higher pH values and possibly causing overestimation of the exchangeable Ca and Sr values.

Most of the Sr^{90} in these soils before treatment was found in the top 4 inches. When the Sr^{90} contents are expressed in terms of weight units of soil, the Sr^{90} levels are similar in all soils except in Dunbar, which is low. In volume or area units, the contents are similar in all soils except in Cecil, which is high.

Yield of corn and soybean grain. The growth of both corn and soybean plants was reduced throughout the season as a consequence of the deep-placement treatments. The average yield of corn grain was reduced about 40% and that of soybeans about 10% (Table 2). These reductions were statistically significant at the 0.99 probability level for corn and 0.90 for soybeans. At individual locations, the reductions were not statistically significant because the experimental design gave so few degrees of freedom for estimating variances.

Calcium application was the only other treatment to cause significant yield effects. It resulted in about 10% decrease in corn yield in Georgia, and about 10% increases in soybean yields in Georgia and South Carolina. These relatively small differences were significant because more degrees of freedom were available for estimating variances than were available for placement comparisons. Irrigation, which was tested with the same degrees of freedom as placement, and potassium application, which was tested with the same degrees of freedom as calcium, had no significant effects.

Concentration of Sr^{90} in grain. The concentration of Sr^{90} in soybean grain exceeded that in corn grain about 50-fold. The average for all plots of corn was 1.4 picocuries per kilogram (pc./kg.); the average for all plots of soybeans was 75 pc./kg. (Table 2). Such differences were not unexpected because similar differences exist in the calcium concentrations in the two grains (2).

Table 1. Chemical and physical properties of the soils at 4 field locations before treatment.

Depth in.	Clay <2 μ %	Org. C %	pH	Exchangeable cations: Ca (me./100 g.)	Mg	K	H	Total	Sr mg./kg.	Sr^{90} pc./kg.	Sr^{90} μc/A.
Cecil sandy loam, Watkinsville, Georgia											
0-4	13	2.0	4.8	1.5	0.6	0.2	10.4	12.7	1.3	162.7	99.5
4-14	44	0.5	4.9	1.1	0.4	0.1	10.5	12.1	0.7	6.6	9.4
14-24	55	0.2	5.1	0.7	0.8	0.1	11.3	12.9	1.6	*	*
Dunbar sandy loam, Florence, South Carolina											
0-4	9	1.5	5.2	1.7	0.5	0.2	6.6	9.0	2.7	117.0	70.2
4-14	26	0.4	5.1	1.6	0.8	0.1	6.2	8.7	2.5	8.0	11.9
14-24	31	0.3	4.8	1.0	0.7	0.1	7.6	9.4	2.6	1.4	2.2
Brookings silt loam, Morris, Minnesota											
0-4	25	4.4	6.8	20.6	8.7	0.6	8.8	38.7	86.8	178.9	69.4
4-14	23	2.1	7.0	18.1	8.8	0.4	5.7	33.0	91.8	2.0	2.2
14-24	22	0.7	7.8	15.3	7.4	0.3	3.5	26.5	85.2	*	*
Nicollet silt loam, Ankeny, Iowa											
0-4	20	3.1	5.6	8.6	3.4	0.6	10.2	22.8	10.5	161.1	73.9
4-14	22	2.1	5.5	8.4	3.2	0.4	9.9	21.9	11.4	8.0	10.6
14-24	22	1.4	5.8	8.3	3.8	0.3	7.3	19.7	12.7	*	*

* Not determined.

Table 2. Yields and Sr^{90} concentrations in corn and soybean grain at 4 locations and influenced by soil management treatments.

Treatment and level	Grain yields, kg./A. Ga.	S.C.	Minn.	Iowa	Aver.	Sr^{90} concentration, pc./kg. Ga.	S.C.	Minn.	Iowa	Aver.
					Corn grain					
Placement										
Shallow	3021	1728	771	3715	2309 **	2.8	1.8	0.9	0.7	1.6 x
Deep.	2059	762	635	2150	1402	1.2	1.2	1.1	0.6	1.0
Irrigation										
Minimal	2540	1207	626	2831	1801	2.0	1.5	1.3	0.7	1.4
Frequent	2540	1284	780	3030	1909	2.0	1.4	0.7	0.6	1.2
Calcium										
Low	2699 *	1306	694	2944	1909 t	2.4 **	1.6 x	1.0	0.7	0.4 t
High	2386	1184	712	2921	1801	1.7	1.4	1.0	0.6	1.2
Potassium										
Low	2431	1202	689	2976	1828 t	2.2 x	1.4	1.2 *	0.6	1.4 t
High	2649	1288	717	2885	1882	1.9	1.5	0.8	0.7	1.2
					Soybean grain					
Placement										
Shallow	871	1075	290	1111	835 x	170	113	26	30	85 **
Deep	753	1061	268	821	726	146	72	20	15	63
Irrigation										
Minimal	794	1098	236	912	762	172	90	23	24	77
Frequent	830	1039	317	1021	803	144	95	23	21	71
Calcium										
Low	771 *	989 *	290	934	748 t	202 **	98	24	23	87 t
High	853	1148	263	998	816	115	87	22	22	62
Potassium										
Low	803	1034	281	956	771 t	165	92	22	22	75 t
High	821	1148	272	975	794	151	92	24	23	72

x, *, ** Significantly different from each other at 0.90, 0.95, and 0.99 probability levels, respectively. t Not tested statistically.

The Sr^{90} concentration in the corn and soybean grain varied among the different locations. The concentration in corn that was grown in the southeast was about twice that in corn grown in the midwest. The corresponding difference in soybeans was usually greater than fourfold. These differences are probably related to differing contents of exchangeable calcium in the soils (5, 8, 9). It is also recognized that varietal differences among locations may have contributed to differing Sr^{90} concentrations (18).

An analysis of variance of the combined data from all locations showed significant reduction in Sr^{90} content in both corn and soybean grain (Table 2) from deep placement but not from frequent irrigation. The last column of Table 2 is an arithmetic average of locations, but the variance was analyzed on logarithms of the original data to obtain homogenous error variance. The calcium and potassium variables were not tested in the combined data because these variables had been adequately tested within each location. Calcium treatments were found to have significantly reduced Sr^{90} in both grains in Georgia and in corn in South Carolina. Potassium significantly reduced Sr^{90} in corn grain in Georgia and Minnesota.

DISCUSSION

Contribution of direct deposition of Sr^{90}. When the experiment was designed it was recognized that the Sr^{90} content of the grain would result from two sources, soil uptake and direct deposition of fallout on the plant. Two approaches have been used to estimate the contribution of the direct deposition of Sr^{90} on the plant. Since fallout is essentially a carrier-free source of Sr^{90}, it should be possible to determine fallout contribution to the total Sr^{90} on grain by comparing the specific activity (Sr^{90}/Sr) in the grain with that in another plant part not exposed to fallout, or with that of the soil. Secondly, the amount of Sr^{90} retained on the crop and that subsequently translocated to the grain may be estimated from the amount of fallout deposited during the growing season.

Specific activities. Specific activities of the grain, stubble, and soil were calculated (Table 3). If the Sr^{90} in the stubble came only from the soil, then the stubble specific activity should represent an integrated soil specific activity available to the plant over the growing season. Furthermore, any increase in specific activity in the grain over that in the stubble should result from direct deposition of Sr^{90} on the plant.

Table 3. Specific activity of Sr in corn and soybean crops grown with shallow placement compared with that of the soil at the 4 locations.

Location	Specific activity, pc. Sr^{90}/ mg. Sr. Soil*	In corn Stubble	In corn Grain	In soybeans Stubble	In soybeans Grain
Georgia	30	7	44	20	32
S. Carolina	8	3	19	48	28
Minnesota	< 1	1	2	10	8
Iowa	4	3	9	8	8

* Weighted average for 0-20" layer calculated from values given in Table 1.

It is probably incorrect to assume that soybean stubble received no fallout Sr^{90}, because the stubble specific activity is higher than that of the corresponding grain or soil at all locations except Georgia. It is pertinent to note that the soybean stems from Georgia were washed with tap water before analysis. Thus, external contamination could have been removed. On the other hand, the specific activity of the corn stubble is much lower than that of the 0- to 20-inch soil layer except for the calcareous soil at Minnesota.

The discrepancy between corn stubble and soil specific activities cannot be explained at present. Since the specific activity in the soil is not uniform, perhaps changing pattern of root distribution during plant growth result in nonuniform specific activity in the mature plant. If the specific activity of the 0- to 20-inch soil layer is used to calculate the soil contribution to Sr^{90} content in corn grain grown with shallow placement, values ranging from 20% at Minnesota to 70% at Georgia were found. These values are compatible with the observed reductions in Sr^{90} content from the soil management treatments.

Amount of fallout deposited during the growing season. In June 1961, the Sr^{90} contents of the 0- to 4-inch layers from the deep placement plots ranged from 11 to 15 μc./A. In May 1960, from 1 to 5 μc./A. was present in the corresponding layers (40% of the 4- to 14-inch layers in Table 1). The difference of approximately 10 μc./A. represents the deposition of Sr^{90} in fallout. This amount agrees reasonably well with measured depositions at the AEC fallout collection stations nearest to the experimental fields. These depositions ranged from 6.4 μc./A. at Columbia, S. C., to 10.8 μc./A. at Vermillion, S. Dak. (19). The amount deposited at the experimental fields during the 1960 growing season is estimated by linear interpolation with rainfall to be from 3 to 4 μc./A.

In field measurement with various crops (10, 11, 12), up to 40% of the fallout deposit has been retained on plant foliage. Other work (1) has shown that less than 0.003% of the Sr^{85} activity applied to individual leaves of corn and snap beans is translocated to the grain. Assuming Sr^{90} fallout of 4 μc./A., retention of 40% on foliage, and translocation of 0.003%, the Sr^{90} in the grain that was derived from deposition on the leaves should have been less than 5×10^{-5} μc./A. By analysis, the corn grain contained from 10^{-3} to 10^{-2} μc./A. and the soybean grain contained from 10^{-2} to 10^{-1} μc./A. Thus, the actual contents of Sr^{90} in both grains are much greater than are estimated as coming from leaves. This does not preclude an appreciable contribution from direct deposition because deposition on the flowers and corn silk may be more readily translocated to the grain. However, it is improbable that the twofold variation among locations for Sr^{90} content in corn grain and fourfold variation for soybeans would be explained by the contribution from direct deposition when there was only about a 40% difference between locations in the amount of fallout deposited.

Obviously, there is no accurate way of separating the contributions from the two sources of Sr^{90}. The best estimate appears to be that the direct fallout contribution was less than 50% with shallow placement and somewhat more with deep placement of Sr^{90}. The direct fallout contribution probably is largely independent of soil treatments and would add more or less uniformly to the Sr^{90} concentration in the grain regardless of soil treatment. Thus, the observed effects of soil treatments (Table 2) would be smaller than the true effects.

Main effects and interactions of treatments. Uptake of Sr^{90} from about 20 inches below the soil surface was less than that from the conventional plow layer. The observed average reduction in Sr^{90} concentration in grain from deep placement was about 30%. If, on the average, direct fallout contributed nearly half of the Sr^{90} concentration in grain from the shallow placement, and the same concentration from deep placement, the reduction in Sr^{90} uptake from the soil was about 50%.

Yield of corn was sharply reduced by the deep placement treatment (Table 2). This results in larger reductions in Sr^{90} uptake on an area basis. However, the additional reduction would be of no value toward the objective of minimizing contamination in feed.

Application of calcium reduced Sr^{90} concentration at the Georgia location about 30% in corn grain and 40% in soybean grain. The correction for direct fallout is estimated from specific activity measurements to be about 30% of the observed concentration in the shallow placement treatment. Thus, the corrected concentrations indicate that calcium application reduced Sr^{90} uptake about 50% in corn and 60% in soybeans.

Application of calcium at other locations was much less effective, as were the treatments with irrigation and application of potassium.

Few of the treatment interactions were statistically significant. Eleven treatment interactions were tested with each crop and location, giving a total of 88 interactions. One interaction was significant at the 99% level and 12 were significant at the 95% level. Several of these could have arisen by chance. The most frequently occurring significant interactions were: Placement × irrigation × Ca application—Georgia corn (90%), Iowa corn, Minnesota corn and soybeans; placement × Ca application—Georgia corn, Minnesota corn, South Carolina soybeans; irrigation × K application—Georgia corn, Iowa corn, South Carolina corn.

Nearly all of the significant treatment interactions were negative. That is, the effect of combinations of treatments were less than additive. For example, the Sr^{90} concentration in soybeans grown at the South Carolina location with shallow placement was reduced from 126 to 100 pc./kg. by application of calcium. But with deep placement, application of calcium raised the concentration from 70 to 73 pc./kg.

SUMMARY

Field experiments were initiated in 1960 to evaluate methods of reducing Sr^{90} uptake under 4 widely varying soil and climatic conditions. The locations included Georgia, South Carolina, Minnesota and Iowa. Each experiment consisted of a modified split-plot design with factorial combinations of shallow and deep placement, minimal and frequent irrigation, no calcium and high calcium amendments, and normal potassium and high potassium amendments.

A significant reduction in Sr^{90} content in both corn and soybean grain was obtained by deep placement, but not by irrigation. Calcium treatments reduced Sr^{90} in both grains in Georgia, and potassium reduced Sr^{90} in corn grain in Minnesota. The maximum reduction was only about 50%, which is far from adequate decontamination. Foliar deposition probably contributed about one-half of the total content of Sr^{90} in corn and soybean grain.

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