TREATMENTS FOR FARMLAND CONTAMINATED WITH RADIOACTIVE MATERIAL

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TREATMENTS FOR FARMLAND CONTAMINATED WITH RADIOACTIVE MATERIAL

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This handbook presents information on the effectiveness and feasibility of various treatments for farmland that has been contaminated with radioactive material. Two kinds of treatments are evaluated. The first kind, which may be called decontamination, includes methods of removing radioactive material from farmland. The second kind includes methods of treating land to reduce the uptake of radioactive materials by crops without decontaminating. Alternatives to treating contaminated land are discussed to give a broader perspective on the techniques of managing contaminated land.

There are many possible sources of radioactive material that could contaminate farmland, ranging from widespread fallout from the explosion of nuclear weapons to a very limited spread from a transportation accident involving radioactive material. The explosion of nuclear weapons could result in contamination of thousands of square miles. Contamination from a very severe reactor accident might affect several hundred square miles. In transportation accidents the contaminated area would probably be less than one acre.

A decision to treat the contaminated area will require consideration of several complex factors, including (a) the immediate and long-term hazard presented by the location and nature of the radioactive material, (b) the hazard likely to remain after treatment, (c) other consequences of the treatment, such as radiation exposures to the persons carrying out the treatment and changes in productivity of the treated land, and (d) the availability of machinery and manpower for treatment. It may be unnecessary to treat contaminated land if the radioactive material is short-lived and the area can be isolated until it decays. If the area of contamination is large, the quantity of readily available resources might be lacking for desirable treatment of all areas at once. In that case, careful judgment will be required to recommend which areas should be treated first and what methods should be used.

Since the choice of treatment may depend on the objectives of treating any given area of contamination, it is necessary to define the objectives clearly. These could be one or more of the following: (a) Preventing spread of the radioactive material to other areas; (b) reducing the radiation hazard to persons who must live or work in the area; and (c) reducing the entry of the radioactive material into food products derived from the contaminated land. Some treatments are better suited to one objective than to another.

The urgency of treatment would likewise depend on the objectives. Immediate action might be essential for preventing spread of radioactivity or reducing the radiation hazard, but not for reducing the radioactivity in crops. Immediate action might increase greatly the radiation exposures to the persons carrying out the treatment. In each case of contamination, the hazards of immediate treatment should be balanced against those of delaying or forgoing treatment.

In many cases, the main objective of treating contaminated farmland would be to reduce the entry of radioactive material into food products. This would be true if relatively long-lived and biologically active radionuclides, such as calcium-45, zinc-65, strontium-89, or strontium-90, were present in appreciable quantities. In fallout from nuclear explosions the strontium radionuclides are very important (*7*).[2] Since they

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[2] Italic numbers in parentheses refer to Literature Cited, p. 15.

often constitute the main hazard, we evaluated the effectiveness of some treatments by the reduction in uptake of radiostrontium.

This bulletin describes the effectiveness and feasibility of many possible treatments of contaminated land under various soil and crop conditions. This information should allow one to choose a suitable treatment after the objectives have been decided upon. This decision must take into account the particular circumstances of each instance of contamination.

REVIEW OF RESEARCH

There is widely scattered literature concerning the treatment of radioactive contamination on land. Some of the publications are not generally available, and many of the pertinent results have not been considered in relation to agricultural areas. In this review, we have attempted to organize information about a wide variety of proposed treatments for contaminated agricultural land. References are either to original work or to critical reviews. The literature citations are selected to give pertinent results for various treatments.

The general problem of managing contaminated agricultural land has been discussed briefly in a previous publication (*31*). Experimental results that were available in 1963 concerning the removal of crops, crop residues, and surface soil, the deep placement of contaminated soil, and the application of fertilizers and soil amendments were reviewed. A Russian review of the problem has been translated and is available from the U.S. Department of Commerce (*1*). It discusses results with deep plowing, leaching, and the application of lime and fertilizer.

Many tests on the decontamination of land areas that have been conducted by the U.S. Department of Defense are relevant to agricultural decontamination. A performance summary of these tests has been published (*29*), and the application of the results in areas contaminated by fallout has been considered (*25*). These tests are particularly valuable for including techniques of snow removal and the decontamination of frozen and thawing soil that have not been studied elsewhere.

Removal of Crops and Crop Residues

A number of tests on the removal of contaminated crops and crop residues have been made by the Agricultural Research Service at Beltsville, Md. (*18*, *21*, *22*). Radioactive material was applied as a spray or as simulated dry fallout. Measurements were made of the amount of radioactive material removed as various crops or crop residues were removed from the land. The tests included removal of standing crops at various stages of maturity, removal of sod, and removal of grass or straw mulch.

Removal of standing crops from a contaminated area removed only part of the radioactive material, because much of it fell through the vegetative cover to the ground. From one-fourth to one-half of the radioactive material was usually carried on green crops removed by conventional types of forage-harvesting machinery (*21*, *22*). These included a flail-type forage chopper, a direct-cut forage harvester, and a mower, followed by a side-delivery rake and windrow pick-up baler. Crops removed by the forage chopper and harvester carried somewhat more contamination than those removed by mowing, raking, and baling. Crops providing more complete ground cover usually carried more of the radioactive material when they were removed. When rain fell or sprinkler irrigation was used after contamination and before crop removal, the amounts of contamination removed with the crops were appreciably lower.

Harvester-thresher combines were used for harvesting and threshing mature rye and soybeans. About one-tenth of the contamination was removed with the straw. The harvested grains contained less than 1 percent of the contamination in rye and less than 0.1 percent in soybeans (*18*). In these experiments, the radioactive material was carried on tiny glass spheres (20–40 μ in diam.) in order to simulate fallout occurring under dry conditions.

Cutting and removing sod removed more than 90 percent of radioactive contamination previously sprayed on the surface. The high effectiveness resulted from the fact that the root mat and some soil was removed with the sod. A road grader was also effective in removing contaminated sod. Similar tests with sod-cutting machines have been conducted by the U.S. Department of Defense, with equally effective results (*29*).

The effectiveness of decontamination by removing mulches differed greatly according to the type of mulch and method of contaminating it. Wheat-straw and bermudagrass mulches were spread evenly on the ground surface at rates of 2 to 5 tons per acre. Then they were contaminated and afterward removed from the plots with a side-delivery rake. When radioactive solution was sprayed onto wheat-straw mulch, more than 90 percent of the contamination was removed with the mulch (*21*). With dry simulated fallout applied on bermudagrass mulch, about 30 percent of the contamination was removed with a mulch of 2 tons per acre and 60 percent with a mulch of 5 tons per acre. The poorer decontamination with dry fallout was attributed partly to inefficient raking of the fine, short grass and partly to sifting of dry fallout through the mulch.

Removal of Surface Soil

Many common types of earth-moving equipment have been used in decontamination tests. These include graders, bulldozers, and rotary, elevating, and pan-type scrapers. In tests reported by the Agricultural Research Service (*18*, *21*, *22*), from 80 to 90 percent of radioactive surface contamination was usually removed when 2 inches of soil was removed. Although these tests were conducted at different times, there appeared to be little difference in the effectiveness of different kinds of scraping equipment.

Roughness of the soil surface apparently had some influence on the depth of cut necessary to achieve this degree of decontamination. However, the use of rollers to smooth the surface after contamination and before scraping did not increase the effectiveness of decontamination. The lack of significant results in this regard may have been due to difficulties in controlling the depth of cut, which varied with moisture content and looseness of the surface soil. The depth of cut was more easily controlled with the rotary and elevating scrapers and graders than with bulldozers and large pan-type scrapers.

Similar tests have been reported by the U.S. Department of Defense (*29*). Tilled, hard, or turf-covered soils in moist or dry condition were scraped with a pan-type scraper or with a grader followed by the scraper to pick up windrows left by the grader. The first grader cut, 2 inches deep, removed about 90 percent of the surface contamination from tilled soil, and after a second cut more than 99 percent of the initial contamination had been removed. Decontamination was even more effective with hard or turf-covered soil, or when the scraping was done with the pan-type scraper making a cut from 2 to 4 inches deep.

Street sweepers using vacuum or rotary brooms have been studied for removal of fallout contamination from soil surfaces. A small vacuum street sweeper was used to remove contamination from a clipped meadow of Kentucky 31 fescue and Ladino clover (*18*). About half of the contamination could be removed by sweeping the meadow twice, but little decontamination could be effected by further sweeping. In later experiments at Beltsville, a rotating broom sweeper with steel bristles removed about 75 percent of the contamination from a moist soil with a thin cover of fescue. A second sweeping gave almost 90 percent removal of contamination. A sweeper with plastic bristles was less effective, apparently because the plastic bristles did not cut as well through vegetation.

Some attempts have been made to bind contamination in a coating of asphalt allowed to harden on the contaminated surface. By peeling off the asphalt coating, Schulz and others (*33*) removed 97 percent of a radioactive tracer that had been sprinkled on the surface of small plots. When used on a field scale (*21*) the asphalt emulsion did not improve decontamination because mechanical scraping methods broke up the asphalt coating instead of peeling it from the surface.

Decontamination in Cold Weather

The U.S. Army Nuclear Defense Laboratory has tested methods for decontaminating various surfaces under cold weather conditions (*23*).

Treatments for frozen or thawing ground and that covered with snow or ice are of possible agricultural interest.

Mechanical snow removal was quite effective in removing radioactivity from areas where a fallout simulant had been spread on top of loose snow. Under good operating conditions, a blade snow plow or motor grader left less than 5 percent of the radioactivity, and a carryall scraper, bulldozer, or rotary snowblower left less than 15 percent. More effort was required to reach the same level of decontamination with warm, sticky loose snow than with cold snow using either a road grader or rotary snow blower.

Ice or frozen ground surface was effectively decontaminated by sweeping. Hand sweeping left less than 5 percent of the radioactivity on ice. Mechanical sweeping left less than 15 percent on a frozen ground surface. It made little difference whether the temperature was just below freezing or subzero.

Thawing ground was scraped with a carryall scraper, bulldozer, or motor grader, which left less than 10 percent of the radioactivity after one or two passes of the equipment. With additional passes it was possible to leave less than one percent of the radioactivity on the ground. About the same effort was required to scrape either a thawing soil or a warm soil.

No-tillage Management

When radionuclides are left on the soil surface by not cultivating during the planting and growth of crops, uptake by many crops is less than would be obtained with normal cultivation. For example, irrigated barley grown on a silt loam soil in central Washington (*4*) took up half as much radiostrontium when it was left on the surface as when it was thoroughly mixed through 4 inches of soil by cultivation (*4*). Similar trends were shown for wheat, barley, potatoes, and sugar beets grown in field experiments on several widely varying soil types in England (*24*). However, shallow-rooted crops such as ryegrass and kale took up twice as much radiostrontium when it was left on the surface as when it was plowed 4 inches deep.

The relative uptake of radiostrontium from no tillage, compared with normal cultivation, has varied widely in our trials at the Agricultural Research Center (unpublished data). In the no-tillage treatment, a fescue meadow was killed with herbicide, and the crops were seeded 2½ or 5 inches deep with a sod planter. On two soil types and with three crops grown in 1968, the relative uptakes were roughly as follows (normal cultivation=1.0):

Soil type	*Wheat*	*Corn*	*Bush Beans*
Elkton silt loam	1.5	[3] 1.5(1)	3
Sassafras sandy loam	2	0.2	[3] 0.6(0.3)

Although poor weed control was obtained and crop growth was generally unsatisfactory, it appears that no-tillage management reduced radiostrontium uptake only on the sandy loam with corn and beans. These crops tend to be deeper rooted than wheat. The sandy loam is better aerated and thus encourages deeper rooting than the silt loam. This factor and the minimum disturbance of the soil surface during planting are probably most important for reducing the uptake of radionuclides from the soil surface.

Deep Placement of Contaminated Soil

Field plot experiments have usually shown reductions in the uptake of radiostrontium when it was placed deeper in the soil than it would be with normal cultivation. Deep placement has been accomplished in several experiments by excavating and refilling field plots. Placement of strontium-89 in a layer 15 inches deep in a silt loam soil at Beltsville, Md. did not reduce uptake by soybeans compared with rotary tillage into the top 6 inches of soil (*17*).

In other experiments, placement treatments were combined factorially with lime, irrigation, and potassium fertilizer treatments to test for effects on root distribution that might increase the benefit from deep placement. No such effects were found. With various soil types and climatic conditions in several states, the lowest strontium-90 content of corn, soybean, oats, or wheat grain with deep placement was about 40 percent of that with normal plowing (*8*). The reduction in up-

[3] Relative uptake values in parentheses are from planting 5 inches deep. Otherwise, uptake was the same from both depths of planting.

take from deep placement of strontium-90 varied considerably with different crops and locations.

In similar experiments carried out in Russia, the uptake of mixed fission products was compared from placements 30 and 60 or 70 cm. (12 and 24 or 28 in.) beneath the surface of a soddy leached soil (*10, pp. 204–208*). This type of soil encourages shallow rooting of plants. Several crops were grown in 3 or 4 successive years on the same plots. The results with each crop varied greatly from year to year. In general, the uptakes from the deeper placements were about one-tenth of those from the shallow placement. The reduction from deep placement was least with oats and barley, intermediate with peas, and greatest with vetch.

Field tests with varying depths of plowing to reduce radiostrontium uptake have been reported from England (*24*) and Russia (*13*). Deep plowing to 50 cm. (20 in.) on a leached chernozem soil in Russia reduced average uptake of strontium-90 by oats to 60 percent of the uptake after disking 10 cm. (3.9 in.) deep. The uptake by individual plants was highly variable, perhaps because plowing tended to band the surface-applied strontium-90. In England, studies on widely varying soil types showed that, in general, the deepest plowing (12 inches) resulted in least uptake for shallow-rooted crops such as ryegrass and a grass-clover pasture. However, plowing depths to 12 inches had little effect on the strontium-89 uptake by deep-rooted crops.

Various herbicides and inorganic chemicals were used in greenhouse and field experiments to limit uptake from a buried soil layer containing strontium-85 (*19*). When sodium carbonate was placed with the contaminated layer at the rate of 10 tons per acre, the uptake of strontium-85 was less than one-tenth of that without sodium carbonate, but crop yields were only slightly reduced. Seven other inorganic chemicals and seven herbicides did not reduce strontium-85 uptake as effectively and tended to give greater yield reductions. But this limited experience does not establish that sodium carbonate is the best material to use as a root inhibitor. A long-lasting, immobile material that will stop root growth into the contaminated soil volume without reducing crop yields is needed.

In a subsequent experiment on an irrigated silty clay loam in Texas, sodium carbonate at the same rate of application was plowed to a depth of 3 feet with contaminated surface soil (*20*). A 36-inch moldboard plow with an attached grader blade was used to push a 2-inch layer of topsoil into the furrow behind the moldboard. Nearly all (95 percent) of the contaminated surface soil was placed deeper than 24 inches beneath the plowed surface. The uptake of strontium-85 by Sudan grass, sugarbeets, soybeans, and cabbage was from one-fourth to one-half as much as with rotary tillage to a 6-inch depth. When sodium carbonate was applied with deep plowing, the uptake of strontium-85 was only one-fifth as much as without sodium carbonate. On this rather tight, deep, fertile soil, crop yields were increased markedly by deep plowing. They were not measurably affected by the application of sodium carbonate.

Heating contaminated soil to immobilize strontium-90 has been tried in conjunction with deep placement (*2*). Uptake of strontium-90 with four soil types that had been heated to 800° C. ranged from one-eighth to one-half as much as with no heating. In all cases, the contaminated soil was placed 25 cm. (10 in.) deep for measuring plant uptake. Extractability investigations suggested that less uptake would be obtained if the soil were heated to 1,000° C. or higher.

Irrigation and Leaching

Controlled applications of water to contaminated land might be used to leach radionuclides out of the rooting zone of crops or to modify the rooting depth of the crops. Until now, the reported attempts to use irrigation have had little success toward either objective.

Leaching of radioactive strontium through soils with water of dilute solutions is very slow. When columns of various soils were leached with 30 inches of water, the maximum penetration of strontium-89 was 4.3 inches (*26*). In the same experiment, leaching with 0.005 N $CaCl_2$ increased the penetration, but the average strontium-89 movement in one soil was only 3 inches after application of 16.4 inches of solution. With the other soils, more solution (up to 250 inches) was required to give the same average strontium-89 movement. Leaching with dilute solutions of complexing agents, such as ethylenediaminetetraacetic acid, has also shown little advantage for removing radioactive strontium (*27*).

Acids and salts also have been applied to contaminated soil surfaces in order to increase the movement of strontium-90 during leaching (*33*). Hydrochloric acid and ferric chloride, at rates of 15 and 22 tons per acre, respectively, were most effective. When these treatments were followed by leaching with 5 feet of irrigation water, about 20 percent of the strontium-90 remained in the top foot of a fine sandy loam, and about 60 percent in the top foot of a loam. In addition to being expensive and rather ineffective, the latter two treatments would leave an infertile soil.

A series of field experiments have been reported (*8*) in which irrigation was used in an attempt to modify the uptake of strontium-90 from deep or shallow placement in the soil. No modifying effect of irrigation could be detected.

Applications of Lime, Fertilizers, and Other Soil Amendments

Soil amendments have been used to reduce the uptake of radionuclides in different ways. Calcium- and potassium-bearing materials provide cations that compete, respectively, with strontium and cesium and thus reduce their entry into plants. Soluble phosphates added in large amounts precipitate strontium so that less of it may enter plants. Additions of materials with a high cation exchange capacity, such as peat, compost, or clay minerals, may also reduce the amounts of radionuclides taken up by plants.

Many experiments have shown that applications of lime or gypsum to acid soils reduce the uptake of radioactive strontium by plants grown on these soils (*1*, *4*, *10*, *14*, *17*, *24*). The reduction depends upon increasing the available calcium supply of the soil, so that little effect is seen on soils already well supplied with calcium. Even on very acid soils, application of lime or gypsum does not usually reduce uptake of radiostrontium to less than one-third of the uptake from the untreated soil.

Potassium fertilizers reduce the uptake of radioactive cesium from soils (*1*, *17*). This is similar to the effect of lime on uptake of radioactive strontium. Potassium also reduces the uptake of radioactive strontium, but to a much smaller degree than applications of lime or gypsum (*1*, *6*, *8*).

Nitrogen fertilizers tend slightly to increase the uptake of radioactive strontium and cesium from soils (*1*).

Phosphate fertilizers added to soils at the usual agronomic rates have shown little effect on uptake of radionuclides (*10*, *pp. 197–200*). However, large additions of soluble phosphates have resulted in very striking reduction in the uptake of radioactive strontium (*16*). When diammonium or tripotassium phosphates were added in amounts equivalent to the cation exchange capacity of the soil (4 to 12 metric tons per hectare, or 2.2 to 6.5 avdp. tons per acre), the uptake of radioactive strontium was reduced to one-tenth of that without these materials. The treatment was more effective in soils with a higher pH value. At the higher rates of application, some difficulty with plant growth was noted.

Materials with a high cation exchange capacity have reduced uptake of radioactive strontium when they were added to soils. Decomposing organic materials or compost have reduced uptake as much as a factor of five when mixed with mineral soils in amounts greater than 2 parts per 100 of soil (*10*, *pp. 170–180; 17*). Clay minerals such as kaolinite and montmorillonite have also reduced uptake of radioactive strontium when added to a sand culture (*11*) or soils (*28*).

FEASIBILITY OF TREATMENTS FOR CONTAMINATED AREAS

Treatments for land areas that are contaminated with radioactive materials will not be feasible unless the following requirements are met. First, the treatment must make a significant reduction in the radiation hazard, either by removing the radioactive material or by reducing its uptake into crops. Second, it must leave the land in a productive state for agricultural use. Third, equipment and materials for the treatment must be available. Finally, the treatment should meet the other requirements with no more than a reasonable effort. Treatments that are feasible in one situation may not be in another.

In some cases it may be impractical, or even impossible, to treat contaminated land because of the condition of the land. An obvious limitation would exist if the radiation level were high enough to endanger workers in the field. The existence of heavy vegetative or snow cover, or of a frozen surface soil, would preclude the use of most kinds of scraping equipment. Soil characteristics such as surface roughness, shallowness of fertile soil, or the presence of stones might greatly increase the effort needed to reach the desired effectiveness, or even prevent some treatments.

In order to compare the feasibility of various treatments, their important characteristics are given in tables 1, 2, 3, and 4. These characteristics include the effectiveness of the treatment, the effort required for treatment and for disposal of contaminated material, and the productivity of treated land. Because soil and crop conditions vary so widely, we attempt only the qualitative evaluation of these characteristics. For example, the effectiveness of a treatment is judged good if test results generally showed more than 95 percent of surface contamination was removed, poor if less than 75 percent was removed, and fair if the amount removed was intermediate. Few data are available for estimating effort required for treatment or disposal, or predicting the productivity of treated land. Evaluations of these characteristics are based on existing data, supplemented by qualitative observations of test procedures and general agricultural experience.

We found that machinery must be operated with care to obtain clean removal of contami-

TABLE 1.—*A comparison of methods for removing contaminated crops or mulches from land*

Type of vegetation	Implement	Removal of radioactivity [1]	Effort required— For removal [2]	Effort required— For disposal [3]
Soybeans, 12" high	Mower	Poor	Poor	Fair.
Soybeans, 12" high	Flail harvester	Poor	Fair	Good.
Soybeans, full growth	Flail harvester	Poor	Poor to fair	Good.
Soybeans, full growth	Forage harvester	Poor	Poor to fair	Good.
Soybeans, mature	Combine, straw removed	Poor	Poor	Fair.
Fescue-clover meadow	Forage harvester	Poor	Poor to fair	Good.
Sudan grass, 12" high	Mower	Poor	Poor	Fair.
Sudan grass, 12" high	Flail harvester	Poor	Fair	Good.
Rye, full growth	Mow, rake and bale	Poor	Poor	Good.
Rye, full growth	Forage harvester	Poor	Poor to fair	Good.
Rye, mature	Combine, straw removed	Poor	Poor	Fair.
Wheat, mature	Combine, straw removed	Poor	Poor	Fair.
Corn, full growth	Forage harvester	Poor	Poor	Fair.
Mulch, 5 tons wheat straw/acre	Side-delivery rake	Good	Poor	Fair.
Mulch, 5 tons bermudagrass hay/acre	Rake and bale	Poor	Poor	Good.

[1] Rating of removal of radioactivity: Good—>95 percent removal.
Fair—75 to 95 percent removal.
Poor—<75 percent removal.

[2] Rating of removal effort: Good—>5 acres per hour.
Fair—1 to 5 acres per hour.
Poor—<1 acre per hour.

[3] Rating of disposal effort: Good—additional loading and hauling effort minimal.
Fair—considerable effort in loading and hauling.
Poor—very great loading and hauling effort.

nated soil or vegetation. This means that more effort may be required than in normal operations with the same types of machinery.

Exposure of Workers

It is doubtful whether the treatment of agricultural land would be so urgent as to justify exposing workers to possibly disabling amounts of radiation. Disabling illnesses are not likely to occur if radiation doses to humans are limited to less than 100 rems (*9, p. 591*). Different ways may be used to limit radiation doses, depending on whether intense local contamination or widespread fallout are present.

In cases of localized contamination, it should be possible to limit exposures by evacuating residents and using teams of workers to remove the contamination. Each team might work only a short time in areas of high radiation intensity. Specially shielded or radio-controlled equipment could be brought to the contaminated area to reduce further the exposure of workers. Concentrated effort would be needed to remove con-

TABLE 2.—*A comparison of methods for removing soil surface contamination in warm weather*

Condition of surface	Implement	Removal of radioactivity [1]	Effort required—		Effect on soil productivity [4]
			For removal [2]	For disposal [3]	
Bluegrass sod	Sod cutter 12″ wide	Good to fair	Poor	Fair	Good to fair.
Fescue-clover meadow	Vacuumized sweeper	Poor	Poor	Good	Good.
Fescue meadow	Rotating-broom sweeper	Fair	Fair	Good	Good.
Fescue-clover meadow	Motor grader	Fair	Poor	Poor	Good to fair.
Fescue-clover 12″ high	Motor grader	Good to fair	Poor	Poor	Good to fair.
Soybean stubble	Motor grader	Fair	Poor	Poor	Good to fair.
Soybean stubble	Constant-draft scraper	Fair	Poor	Poor	Good to fair.
Wheat stubble	Vacuumized sweeper	Poor	Poor	Good	Good.
Corn stubble	Motor grader	Poor	Poor	Poor	Good to fair.
Plowed	Motor grader	Fair	Poor	Poor	Good to fair.
Plowed	Bulldozer	Good	Poor	Poor	Good to fair.
Plowed	Self-loading scraper, 1 cu. yd.	Fair to good	Poor	Fair	Good to fair.
Plowed	Pan-type scraper, 8 cu. yd.	Good	Poor	Fair	Fair.
Disked	Motor grader	Fair to poor	Poor	Poor	Good to fair.
Disked	Rotary scraper	Fair to good	Poor	Fair	Good to fair.
Disked	Elevating scraper	Fair	Poor	Fair	Good to fair.
Seedbed	Motor grader	Good to fair	Poor	Poor	Good to fair.
Seedbed	Bulldozer	Good to fair	Poor	Poor	Good to fair.
Seedbed	Self-loading scraper	Fair	Poor	Fair	Good to fair.
Seedbed	Pan-type scraper	Good	Poor	Fair	Fair.

[1] Rating of removal of radioactivity: Good—$>$ 95 percent removal.
Fair—75-95 percent removal.
Poor—$<$ 75 percent removal.

[2] Rating of removal effort: Good—$>$ 5 acres per hour.
Fair—1 to 5 acres per hour.
Poor—$<$ 1 acre per hour.

[3] Rating of disposal effort: Good—additional loading and hauling effort minimal.
Fair—considerable effort in loading and hauling.
Poor—very great loading and hauling effort.

[4] Rating of effect on soil productivity: Good—Increases or does not change productivity.
Fair—Reduces productivity $<$ 20 percent.
Poor—Reduces productivity $>$ 20 percent.

tamination quickly or prevent its spreading to other areas.

In case of widespread contamination after a nuclear attack, decontamination effort should be concentrated in densely populated areas. For the population as a whole, this would give the greatest reduction in radiation dose, which would come primarily from external gamma radiation. Fallout on sparsely populated farmland would contribute relatively little external gamma radiation to the whole population. It would contribute more radiation internally through the entry of strontium-90 and other fission products into the food chain. Thus, the probable pur-

TABLE 3.—*A comparison of methods for removing soil surface contamination in cold weather*

Condition of surface	Implement	Removal of radioactivity [1]	Effort required—		Effect on soil productivity [4]
			For removal [2]	For disposal [3]	
Loose snow 2 to 7'' deep	Motor grader	Poor to good	Fair	Fair	Good.
Do.	Carryall scraper	Fair	Fair	Good	Good.
Do.	Bulldozer	Fair	Fair	Fair	Good.
Do.	Rotary snow blower	Fair	Poor	Fair	Good.
Loose snow 7 to 12'' deep	Snow plow	Good	Good	Poor	Good.
Do.	Motor grader	Good	Fair	Poor	Good.
Do.	Carryall scraper	Fair	Fair	Fair	Good.
Do.	Rotary snow blower	Poor to good	Poor	Poor	Good.
Packed snow	Motor grader	Fair	Fair to poor	Fair	Good.
Do.	Rotary-broom sweeper	Fair	Fair to poor	Good	Good.
Do.	Vacuumized sweeper	Poor to fair	Poor	Good	Good.
Loose snow on packed snow.	Motor grader	Poor to fair	Poor	Fair	Good.
Frozen loose snow on packed snow.	Snow plow	Poor	Good	Fair	Good.
Frozen ground	Motor grader	Poor	Poor	Fair	Good.
Do.	Rotary-broom sweeper	Fair to good	Poor to fair	Good	Good.
Do.	Vacuumized sweeper	Poor to fair	Poor to fair	Good	Good.
Thawing ground	Motor grader	Good	Poor	Poor	Good to fair.
Do.	Carryall sweeper	Good	Poor	Fair	Good to fair.
Do.	Bulldozer	Good	Poor	Poor	Good to fair.
Do.	Rotary-broom sweeper	Poor	Fair	Good	Good.

[1] Rating of removal of radioactivity: Good—$>$ 95 percent removal.
Fair—75 to 95 percent removal.
Poor—$<$ 75 percent removal.

[2] Rating of removal effort: Good—$>$ 5 acres per hour.
Fair—1 to 5 acres per hour.
Poor—$<$ 1 acre per hour.

[3] Rating of disposal effort: Good—additional loading and hauling effort minimal.
Fair—considerable effort in loading and hauling.
Poor—very great loading and hauling effort.

[4] Rating of effect on soil productivity: Good—Increases or does not change productivity.
Fair—Reduces productivity $<$ 20 percent.
Poor—Reduces productivity $>$ 20 percent.

pose of treating farmland after contamination with widespread fallout would be to reduce uptake of fission products by plants.

Removal of Crops and Mulches

The presence of a crop would affect the choice of treatments for a contaminated area. A heavy crop would intercept part of any contaminating material that was deposited from the air, such as fallout. Thus, removal of the crop would partly decontaminate a land area. However, crop removal would generally be inadequate. In some cases, crops might have to be removed before other, more effective treatments could be carried out.

The feasibility ratings of methods for removing crops and mulches are summarized in table 1. Most common types of crop-harvesting machinery are compared on crops ranging from meadow to full-grown corn.

With one exception, none of the methods removed more than 75 percent of simulated fallout from a contaminated area. The exception is that taking off a heavy mulch of wheat straw gave good decontamination. This test was run with liquid droplet contamination, which apparently adhered to the straw. Dry fallout contamination

TABLE 4.—*A comparison of soil management methods for reducing strontium-90 uptake from contaminated soils.*

Method	Reduction in Sr-90 uptake [1]	Effort required [2]	Effect on soil productivity [3]
Minimum tillage	Poor to fair	Good	Good to poor.
Plowing, 7″ deep	Poor	Good	Good.
Plowing, 12″ deep	Poor	Fair	Good.
Plowing, 36″ deep	Fair to poor	Poor	Good to poor.
Plowing, 36″ deep with root inhibition.	Good to fair	Poor	Good to poor.
Irrigation	Poor	Fair to good	Good.
Leaching	Poor	Fair	Poor.
Lime application, 2 to 10 tons/acre.	Poor to fair	Good	Good.
Nitrogen fertilizers, 100# N/acre.	Poor	Good	Good.
Phosphate fertilizers, 100# P/acre.	Poor	Good	Good.
Potassium fertilizers, 500# K/acre.	Poor	Good	Good.
Organic compost, 5 to 20 tons/acre.	Poor	Fair	Good.
Clay minerals, 5 to 20 tons/acre.	Poor	Fair	Good to fair.
Ammonium or potassium phosphates, 2 to 5 tons/acre.	Fair	Fair	Fair to poor.

[1] Rating of reduction in Sr-90 uptake: Good—$>$ 95 percent reduction.
Fair—75 to 95 percent reduction.
Poor—$<$ 75 percent reduction.

[2] Rating of effort required: Good—Not significantly more than normal field practices.
Fair—Extra equipment, materials, or labor required.
Poor—Very great requirement of equipment, materials, or labor.

[3] Rating of effect on soil productivity: Good—Increases or does not change productivity.
Fair—Reduces productivity $<$ 20 percent.
Poor—Reduces productivity $>$ 20 percent.

might sift through the straw, resulting in poor decontamination as was achieved with the bermudagrass hay mulch.

In view of the rather poor removal of radioactivity, crop removal would probably be used only as a necessary preliminary to some soil treatment that would be more effective. For example, a bulky crop would interfere with the loading of scrapers, and cause excessive spillage from the blades of graders or bulldozers. Such crops would have to be removed before the land could be decontaminated by scraping. Even then, roots that could not be cut might decrease the effectiveness of scraping. Areas with trees probably could not be decontaminated effectively.

Crop removal requires considerable time. The most rapid methods will clear little more than one acre per hour.

The problem of disposal of contaminated plant material has received little attention. It consists of reducing bulk of the material, hauling it, and storing it in a safe manner. For the ratings in table 1, it was considered that crop disposal would be easier than disposal of surface soil, since the weight of material to be hauled would be much less. Methods that remove and load the plant material for hauling in one operation are generally less time consuming than those that do not. Disposal might be in pits or isolated stacks or buildings.

The removal of crops and mulches would have no detrimental effect on soil productivity.

Removal of Surface Soil

Decontamination of farmland is easier if the contaminated surface soil can be removed before the soil has been cultivated. Penetration of surface contamination into soil by leaching or erosion is minor compared to that in cultivation. Thus, removal of a few centimeters of surface soil will give a high degree of decontamination unless the soil has been disturbed by cultivation or the surface is so rough that some of the exposed soil is not removed by shallow scraping.

Feasibility ratings are summarized in table 2 for various methods of removing unfrozen contaminated surface soil. The equipment ranges from sweepers, which would remove a minimal thickness of soil, to heavy earth-moving equipment. Soil conditions vary from a rough plowed surface to light vegetative covers, which are not expected to interfere with soil removal.

Scraping operations usually remove more than 75 percent of the radioactive contamination on a soil surface. The removal of radioactivity is likely to be better from a smooth seedbed than from a corn stubble or other rough soil surface.

Decontamination with scrapers is ineffective on stony soils. Scrapers cannot cut at shallow depths when large stones lie at the soil surface. Even small stones, a few centimeters in diameter, may cause the scraper blade to roll over considerable quantities of fine soil containing the radioactive material. Thus, it would be necessary to scrape repeatedly, or to greater depth, to achieve a high degree of decontamination.

Rough soil surfaces are common in pastures and cultivated fields. Freshly plowed surfaces and row-crop ridges often have differences in elevation of several inches between the highest and lowest surface. Land that has been bedded for furrow irrigation presents even greater extremes. Since a greater amount of soil would have to be removed for effective decontamination, rough surface areas would require extra effort for soil removal and disposal.

Measurements of the time required for soil removal and disposal were made in the U.S. Department of Defense tests (*29*) and in some of our unpublished studies. Bulldozers, road graders, and scrapers required more than one hour of equipment time per acre of surface soil removed. It usually required more time to haul the soil to a disposal pit or pile than it did to scrape the surface.

Feasibility ratings for disposal (table 2) are based on the mass of soil to be moved and the loading effort required after decontamination. After scraping with a motor grader or bulldozer, the removed soil must be loaded for hauling to a disposal area. The sweepers and other scrapers are loaded during decontamination. The mass of soil to be hauled is much greater with the scrapers than with sweepers.

Studies on removal of surface soil have often shown some loss in soil productivity (*3*, *34*). The loss in productivity will vary according to the depth of fertile soil originally present, and the amount of soil removed. Restoring the productivity of the treated area requires improvements in the physical structure and in the nutrient supply of the remaining soil. Additions of lime, fertilizers, manure, and mulches help to restore productivity.

Decontamination in Cold Weather

Subfreezing weather and the possibility of snow cover exist for part of the year on large acreages of farmland in the United States. In cold weather, the removal of surface contamination would usually be more difficult than in warm weather. If the soil surface were frozen, it could not be removed by scraping. Vacuum or sweeping machines might be useful unless the contaminant had been frozen into the surface.

A snow cover would present different problems, depending on whether the contaminant was beneath it, mixed with it, or deposited on top of it. In the first case, the snow cover would have to be removed before the contaminant on the soil surface could be treated. If additional hazard would be created by contaminant carried in the runoff from melted snow, it might be desirable to remove the snow cover in spite of the extra effort required. In case the contaminant was in or on top of the snow, the area could be decontaminated by removing only the snow. However, the presence of crop residues in the snow cover would interfere with snow removal and could seriously reduce the effectiveness of decontamination.

Studies on the decontamination of land that was frozen or covered with ice or snow have been made by the U.S. Army Nuclear Defense Laboratory (*23*). Feasibility ratings derived from their data are given in table 3 for methods that may be applicable under some farmland conditions.

Several methods removed 75 percent or even 95 percent of the contaminant that had been deposited on the snow or ground surface. Since tests were carried out at varying temperatures and textures of the snow, differences between implements in effectiveness of removal of radioactivity may not be significant. The texture of the snow, which varied with the recent temperature history, affected the removal of radioactivity.

The effort required for removal of radioactive contaminants in cold weather was not excessive under the conditions of the tests, which were run on paved or smooth ground areas. On rough land areas, the rate of travel would be much slower. A longer time would be required for decontamination in such circumstances, even assuming that the snow cover permitted effective decontamination.

Ratings for disposal effort are based on the weight of materials to be moved, and whether or not an extra loading operation would be necessary. However, the disposal of contaminated snow could be very difficult because of its great bulk. It should be piled so that the contaminant would not spread by wind, rain, or runoff from melting snow. If one could let the snow melt while retaining the contaminant, there would be much less material for disposal.

No effect on soil productivity would be expected from snow removal, and removal of thawing ground should have an effect comparable to that of removal of surface soil.

No-tillage Management

Where the soil surface contains most of the radioactive contamination, its uptake by crops could be lessened by growing deep-rooted crops under conditions of no-tillage. The feasibility of no-tillage management has been established for economic production of certain crops (*5*), but its possible usefulness as a treatment for contaminated land has not been established. It would have the advantage of keeping the radioactive material mostly on the surface, where it could later be removed or otherwise treated. Estimated feasibility ratings for no-tillage management are given in table 4.

Deep Placement of Contaminated Soil

Contaminated surface soil may be buried by plowing. With common farm tractors and plows, the depth of plowing is limited to about 12 inches.

Large moldboard or disk plows are available in limited numbers. Some of these plows might not give efficient burial of contaminated soil (*15*). The uptake of radioactivity is much less when sodium carbonate is placed on the contaminated soil before deep plowing.

Feasibility ratings for plowing treatments are summarized in table 4. Plowing to 7 or 12 inches deep could be carried out with common farm plows, but it has little effect on uptake of radioactive strontium. If the hazard were from external gamma radiation from uptake of radioactivity into plants, plowing would reduce the hazard very greatly. Plowing 36 inches deep requires special machinery, and the effects on strontium uptake may vary greatly with different soils and crops. Only by using some material or technique to stop root growth into the contaminated soil volume can a highly effective reduction in uptake be achieved.

The effort required for plowing increases sharply with increasing depth of plowing. Two large crawler tractors were required to pull the plow 36 inches deep in Pullman silty clay loam (*12*). About one acre was plowed per hour of operating time. Two tractor drivers and one man at the controls of the plow were used. During large field operations, the rear tractor driver could possibly control the plow. However, it was convenient to station an extra man on the front tractor to warn its driver in case of equipment breakdown. Thus, from 2 to 4 man-hours were required per acre plowed.

Many soils would produce poor crops after deep plowing. This could result from low fertility, high acidity, soluble salts, or poor texture or structure of the soil brought to the surface. Fertility and acidity problems could be corrected by mixing fertilizers and lime into the new topsoil. Correcting poor soil structure is more difficult since it may require large additions of sand, compost, or manure, and long periods of time for the improvement of structure. These measures would add to the already great effort of deep plowing. Soils with deep, fertile subsoils would be most likely to produce good crops after deep plowing. Some impervious soils are benefited by improved water infiltration after deep plowing (*30*, *32*).

Irrigation and Leaching

The effectiveness, effort, and productivity ratings of irrigation and leaching treatments for contaminated land are listed in table 4. Irrigation does not reduce uptake of radioactive strontium. Leaching removes little radioactive strontium from the soil profile unless large quantities of chemicals are added to increase the movement of strontium. Therefore, irrigation and leaching would not be feasible treatments for contaminated soils, even though little extra effort might be needed in some irrigated areas to change the frequency of irrigation or to leach with large amounts of water. Soil productivity would be lowered by leaching because essential nutrient elements would be removed with the strontium.

Applications of Lime, Fertilizers, and Other Soil Amendments

The effectiveness, effort, and productivity ratings of various soil amendments are also given in table 4. Unfortunately, none of the soil amendments are highly effective in reducing uptake of radioactive strontium. Large applications of ammonium or potassium phosphates and, on very acid soils, the application of lime, will reduce the uptake of radioactive strontium by 75 percent. With lime, this is about the maximum reduction that can be achieved, and it has been observed only on soils that were initially very low in exchangeable calcium. With the phosphates, reductions in the range of 75 to 95 percent have been observed on a number of soil types in the greenhouse, but phosphates are much less readily obtainable than lime, and detrimental effects on plant growth have been observed. Field tests have not been made with the phosphates.

Applications of soil amendments could be made more easily than most other treatments for contaminated land. They would be limited mainly by the availability of the materials, the effort required to spread them on the land, and response of the soil to the amendment. Optimum use of lime and fertilizers for economic crop production gives nearly as much reduction in radiostrontium uptake as can be achieved with heavier applications of these materials.

ALTERNATIVES TO TREATING CONTAMINATED SOIL

In the event of widespread radioactive contamination, such as after a nuclear attack, much of the contaminated farmland could be needed for crop production before it could be treated. Since the major hazard from farmland contamination arises from the entry of radionuclides, especially strontium, into human food, some alternatives to soil treatment have been suggested. Among these are using contaminated land to grow crops that contribute lesser amounts of radionuclides to the human diet; using contaminated pastures for beef or mutton instead of dairy production; and removing radionuclides from milk and other products by treatment in processing. The main characteristics and limitations of these alternatives are important in determining the feasibility of treating contaminated soil.

Some crops would contribute little or no radioactive material to the human diet, even if they were grown on highly contaminated soils. Fiber crops, such as cotton and flax, are obvious examples. Sugar and oil crops would have most of the radioactive materials removed from the refined products that are part of the human diet. However, in case byproducts, such as cottonseed meal or sugarbeet pulp, are fed to animals, the indirect contribution of radionuclides to the human diet would have to be considered. Since corn has one of the lowest mineral contents of any grain, its content of radionuclides such as strontium is very low. Other essential food crops, especially those that contribute important minerals to the diet, would have to be grown on land with lesser amounts of contamination. Such crops would include most fruits and vegetables.

Meat and eggs would contribute little radioactive strontium to the human diet. Thus, when the most hazardous contaminating material was strontium, using the land for beef, pork, mutton, or poultry production would be advantageous. This may not be true when other radionuclides constitute the main hazard. For example, meat contributes almost as much cesium-137 to the diet as does milk (*36*).

Ion-exchange treatment of milk could reduce its strontium-90 content perhaps more effectively than decontamination or soil management treatments on hay and pasture land. In full-scale tests of ion-exchange treatment in a milk-processing plant, from 90 to 97 percent of the strontium-90 was removed from the milk (*35*). Similar treatment may be possible with vegetable and fruit juices and purees, but experimental tests have not been made.

If the alternatives to treating contaminated soil were used fully, land for nutritionally critical crops could be treated preferentially. Critical crops might vary, depending on what crops were normally produced in the highly contaminated areas and the possibility of transporting substitutes from other areas. In subsequent years, more land could be treated for producing critical crops.

In some situations, it might be possible to use very highly contaminated land by treating the soil and then using one of the above alternatives.

CONCLUSIONS

Land that has been contaminated with radioactive materials may be treated to remove the contaminant or to reduce its entry into food products. Because these treatments usually require great effort, the objectives and feasibility of various treatments need to be carefully evaluated for each contamination incident. Indiscriminate use of ineffective treatments could be very costly without much reduction in the radiation hazard to the population.

Treatment objectives may vary according to the type and extent of contamination. If accidental contamination is confined to a limited area, it may be removed to prevent its spread to other areas. In such cases, an existing or potential radiation hazard may be removed without undue hazard to the decontamination workers. If the contamination is widespread radioactive fallout, it may be physically impossible to remove the entire hazard. Nevertheless, the proper choice of treatments and land areas to be treated could reduce significantly the entry of radionuclides into the human food chain.

Scraping off the surface soil is the most ef-

fective method of removing a surface deposit of radioactive material. More than 95 percent may be removed if scraping is carefully done. Scraping should be done before the contaminated soil has been cultivated. Even in favorable circumstances, about one hour of equipment time per acre is required for soil removal and disposal. Scraping rough or stony soil, or that covered by coarse vegetation, is less effective and requires more effort. Various kinds of scraping machinery could be used, but those providing easy depth control and self-loading reduce the effort of soil removal and disposal. Scraping treatments may also be effective for contaminated snow surfaces.

A rotary-brush street sweeper removes more than 75 percent of radioactive particles that have been deposited on a relatively hard, smooth soil surface. Two or three passages of the sweeper remove additional contamination, and the amount of soil to be disposed of is much smaller than with scraping equipment. This treatment may also be effective on ice or frozen soil surfaces.

Vegetative cover would intercept part of a deposit of radioactive material, and removing the vegetation might remove up to half of the radioactive material. Removal of vegetation might be a necessary preliminary to a more effective treatment such as scraping. Conventional forage-harvesting machinery could be used to remove vegetation.

Lime, fertilizer, or other amendments may reduce the entry of radionuclides from contaminated soils into crops. Use of lime and fertilizers for optimum economic return often gives the best reduction in radionuclide uptake. Hence, although the reduced uptake may be 70 or 80 percent of that with no treatment, it can be obtained at no cost. Some other amendments, including large applications of ammonium phosphate or sodium carbonate (the latter plowed deeply with the contaminated soil), may reduce radionuclide uptake much more effectively. However, the reduction in uptake is less than would be obtained by scraping a suitable soil surface, and the treatments would probably be more costly than scraping.

Alternatives to decontamination and soil management treatments should be considered, especially if the radioactive material is widespread, because of the great effort required for effective treatment of contaminated land. Some alternatives are growing crops that take up small amounts of radionuclides and removing radionuclides from milk and other products by treatment during processing. The treatment of contaminated land might then be limited to those areas needed for the production of certain vegetable or fruit crops.

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