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ENVIRONMENTAL MOBILITY OF CESIUM-137*

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Abstract—During a 2-year study, erosion soil losses of 53, 2·5 and 0·9 metric tons/ha were coupled with ^{137}Cs losses of 43, 19 and 7 per cent, on 2·3×2·3 m bare soil, poor meadow and good meadow plots respectively. Runoff and erosion losses of ^{137}Cs from vegetation-covered plots occurred primarily in the initial stages following the application, due to washoff from vegetation, at a rate approximately ten times greater than would be expected on the basis of soil loss alone. Evidence of ^{137}Cs redistribution was determined by sampling and analysis techniques which facilitate a fair material balance. Uptake of ^{137}Cs by new vegetation was only a small fraction of originally applied ^{137}Cs. An empirical relationship between cesium loss and soil loss of the form: $Y = A(x/b)^n$, where Y = Cs loss, x = soil loss, b = a units constant, A = a coefficient and n = an exponent, fits the data well. These results indicate that movement of radionuclides by runoff and erosion may be quite important.

Résumé—Au cours d'une étude de deux ans, des pertes de sol par érosion de 53, 2,5 et 0,9 tonnes métriques/ha ont été associées à des pertes de ^{137}Cs de 43, 19 et 7% sur 2,3×2,3 mètres d'echantillons de sol nu, de prairie pauvre et de bonne prairie respectivement. Les pertes par écoulement et par érosion de ^{137}Cs à partir des échantillons couverts de végétation se produisent aux stades initiaux à la suite du lavage de la végétation à une vitesse approximativement dix fois plus élevée que celle que l'on attend sur la base de la perte de sol seule. On met en évidence une redistribution du ^{137}Cs par des techniques d'échantillonnage et d'analyse qui facilitent une bonne balance matérielle. La prise de ^{137}Cs par la nouvelle végétation ne représente qu'une faible fraction du ^{137}Cs appliqué à l'origine. On a établi une relation empirique entre la perte de cesium et la perte de sol sous la forme: $Y = A(x/b)_2$, oú Y = la perte de Cs, x = la perte de sol, b = une constante en unités, A = un coefficient et n = un exposant. Cette relation cadre bien avec les données. Ces résultats indiquent bien que le mouvement des radionuclides par écoulement et par érosion peut être très important.

Zusammenfassung—Auf 2,3×2,3 Meter unbewachsener Erde, schlechter Wiese beziehungsweise guter Wiese wurde während einer zweijährigen Untersuchung parallel zu einem Bodenverlust durch Erosion von 53, 2,5 und 0,9 metrische Tonnen/ha Verluste an ^{137}Cs von 43, 19 und 7 Prozent beobachtet. Verluste an ^{137}Cs durch Wegschwemmen und Erosion von mit Vegetation bedeckten Stellen fanden in erster Linie in den Anfangsstadien nach der Behandlung durch Abwaschen von der Vegetation statt. Die Rate dieses Verlustes war annähernd zehnmal grösser als auf Grund des Verlustes an Erde zu erwarten war. Zur Bestimmung der Evidenz für ^{137}Cs-Wiederverteilung wurden Proben und Analysetechniken gewählt, die eine gute Materialbalance ermöglichen. Die Aufnahme von ^{137}Cs durche neues Pflanzenmaterial machte nur einen kleinen Teil des ursprünglich angewendeten

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FIG. 1. General view of study plots located at the Oak Ridge AEC Reservation in Tennessee on alluvial Captina silt loam.

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^{137}Cs aus. Eine empirische Beziehung zwischen Cäsium- und Bodenverlust der Form $y = A(x/b)^n$, wo y = Cs-Verlust, und x = Bodenverlust, b = Konstante der Einheit, A = ein Koeffizient und n = ein Exponent ist, stimmt mit den Daten gut überein. Diese Ergebnisse zeigen, dass die Bewegung von Radionukliden durch Wegschwemmen und Erosion möglicherweise sehr bedeutend ist.

INTRODUCTION

When dustfall or particulate fallout occurs, interception by plants is common. Such interception by the plant leaves is followed by foliar retention, by foliar absorption, or by washoff.[1] Nuclides which reach the soil surface are subject to further movement, either into the profile by percolating water or off the surface by runoff and erosion. The transport of radionuclides which are strongly sorbed by soils is largely determined by the movement of soil particles on the land surface; radionuclides which are not sorbed by soils follow the movement of water. Since most radionuclides are sorbed to some degree by soils, their actual behavior lies between the two extremes.

The factors affecting sorption of radionuclides by soils and intake or radionuclides by plants through foliar absorption and through roots have been reviewed by several investigators.[2–4] Movement of radionuclides into the ground, particularly radiostrontium, has been investigated both in the laboratory and in the field.[5,6] The emphasis on radiocesium, however, has been on the mechanism of fixation,[7–9] and little has been done to describe its mobility.

In contrast to downward movement into the soil profile, radionuclides may be transported off the surface by runoff and erosion. In samples taken to determine the worldwide deposition of ^{90}Sr, special care is taken to avoid areas which show evidence of erosion or accumulation from adjacent areas;[6] hence, information on the areal distribution of ^{90}Sr is not gained from these studies, as is pointed out by the investigators. Frere and Roberts[19] reported that as much as two-thirds of the ^{90}Sr deposited by fallout on a small watershed in Ohio was lost by this mechanism. Menzel[18] found as much as 30 times more ^{90}Sr associated with soil particles in runoff from a soil plot in Wisconsin than in the original plot. Graham reported that when the rainstorm was less than 0·2 in./hr on a Putnam silt-loam soil in Missouri, no runoff was observed and, therefore, no movement of ^{90}Sr by this mode occurred.[10]

The limited amount of quantitative information on the transport of radionuclides by runoff and erosion prompted us to initiate a program to evaluate this phenomenon under field conditions. For this report, we include only the summary results of 2 years of operation of our field plots. A more detailed account of our findings will be published elsewhere.

EXPERIMENT

For our initial test, we chose to study radiocesium since this element is known to be sorbed very strongly by most soils. This high sorption suggested that radiocesium would concentrate in the uppermost layer of the surface zone, and, therefore, be more susceptible to movement by runoff and erosion. To enable comparison of the behavior of radiocesium under different vegetative-cover conditions, three plots, each 2·3 × 2·3 m, were established and their original meadow cover modified. The alluvial soil of the plots, a typic fragiudult (formerly a planosol in the Red and Yellow Podzolic region), belongs to the Captina series and has a silt-loam texture. In the first plot, plot 1—bare soil, vegetation was killed with 2-4-D and removed. In the second plot, plot 2—clipped meadow, the meadow was clipped prior to tagging and the litter was left on the ground. In the third plot, plot 3—good meadow, the meadow was fertilized at the rate of 300 kg/ha of nitrogen, as ammonium nitrate, and allowed to grow tall. The vegetative cover consisted of a mixture of crabgrass and meadow fescue with crabgrass predominating.

In Fig. 1 a general view of the experimental area is shown. Each plot was enclosed by a metal strip sunk into the ground to prevent surface losses to the outside. The study was conducted on the first three plots (on the right side of Fig. 1), and the fourth plot was kept in reserve for future use. At the lowest corner of

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each plot, a runoff-catchment sink was cemented in place and connected to the runoff-collection pans shown in the lower left of Fig. 1. Each pan was equipped with calibrated drums and water-level recorders. A recording rain gauge was installed in the experimental area. The information from the recording rain gauge on duration, intensity, and amount of rainfall for each storm was used in computing the erosion index value. It was also correlated with the runoff rates, and the amounts and starting times obtained with the water-level recorders for each plot.

Application of ^{137}Cs was carried out using a modified orchard sprayer at constant pressure of 50 psi. Five millicuries of ^{137}Cs were diluted to four liters in a weak HCl solution (pH = 4). This quantity was sufficient for five complete spray passes. Alternate sprayings were made in the direction at right angles to the previous application. Cesium-137 tag was applied under dry-soil conditions; the first rain was recorded 6 days after tagging.

After each storm the runoff collected was sampled and the concentration of ^{137}Cs on the solid and in the liquid determined. Detailed area, soil and plot descriptions, as well as tagging and sampling procedures, have been reported previously.[11]

BASIC CONCEPTS OF EROSION

Following washoff from the vegetation, movement of radionuclides in a soil will depend on the interaction of primary causative agents, such as rain, with the radionuclides and with the physical and chemical characteristics of a given soil material. Although this study was concerned with the movement of ^{137}Cs on a Captina soil in East Tennessee, similar principles may well be applied to other radionuclides and in other areas.

The universal soil-loss-estimating equation of WISCHMEIER and SMITH was used.[12,13]

$$S = K \times EI \times \Lambda \times C \qquad (1)$$

where

S = soil loss (g/m²),
K = soil erodibility constant (g/m²/dyn/sec),
EI = erosion index, equal to the product of storm energy and its maximum 30-min intensity (dyn/sec),

and Λ and C are dimensionless correction factors for the topography and vegetative cover, estimated by

$$\Lambda = (\lambda/2212{\cdot}85)^{0{\cdot}5}(0{\cdot}52 + 0{\cdot}36\,s + 0{\cdot}052\,s^2)/8 \qquad (2)$$

and

$$C = \frac{S/EI}{K\Lambda} \qquad (3)$$

where

s = average plot gradient (per cent),
λ = average slope length (cm).

The values of factor K are calculated for a unit plot, defined by Wischmeier and Smith as a plot 2212·85 cm (72·6 ft) long, having a uniform slope of 9 per cent.[12]

The value of K for Captina soil, listed in Table 1, was determined from the least-squares fit of EI and soil loss on bare soil plot 1. The available data for 44 out of 50 storms, with EI as the independent variable, were used. Of the six storms omitted in computation of K plugging of the exit drain was observed on three, no runoff on one, and unaccountable high soil loss and very high EI value on the remaining two, respectively. The value for K of $1{\cdot}96 \pm 0{\cdot}19$ (g/m²)/(dyn/sec) obtained by us agrees closely with the estimated value of 1·98 (g/m²)/(dyn/sec).[14]

Under bare-soil conditions of plot 1, vegetative cover correction factor C is unity. The values of factor C, computed using equation (3) for meadow plots, are given in Table 1, A low value of C for plot 3 reflects a heavy meadow stand during the 2-year-study period. A high value of C for plot 2 is indicative of a poorer stand and the unfavorable initial conditions.[11]

To compute annual EI values for an area, WISCHMEIER and SMITH recommend using the data from storms larger than 1·27 cm.[13] On our small plots, runoff was produced even by minor storms (<1·27 cm), particularly in the winter and spring months. This is not unusual for small plots. The EI values used here represent, therefore, the EI for all the rains that occurred during the 2-year-study period.

The values of average slope (s) and average

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Table 1. Area, slope (s), *slope length* (λ), *slope, slope-length correction factors* (Λ), *cover correction factors* (C) *and soil erodibility factor* (K), *on the three radionuclide movement study plots on alluvial Captina si. l. soil in Tennessee**

Plot†	Area, m^2	s, %	λ, m	Λ	C	K, $g/m^2/dyn/sec$‡
1	5·5	3·2±0·2	1·8±0·2	0·08	1·000	1·96±0·19
2	5·3	4·6±0·3	1·9±0·2	0·12	0·040	
3	5·4	7·8±1·0	2·2±0·2	0·26	0·006	

*Correction factors (Λ) were computed from equations given on page 153 of Wischmeier and Smith,[13] our equation (2). Soil erodibility factor (K) was computed from equation (1) and least squares fit of soil loss as g/m^2 vs. EI in dyn/sec, using C value of 1·0. Cover factors for plots 2 and 3 were computed from equation (4), using observed soil loss values, observed EI values and K and Λ values listed above. Values of K and C are based on 2 years of data.

†Plot 1, bare soil; plot 2, clipped meadow; plot 3, good meadow.

‡Conversion factors are as follows: 224·2 g/m^2 = 2242 kg/ha = 1 ton/acre; 0·4728 dyn/sec = 0·4728 $(ergs/cm^2)/(cm/sec)$ = 1 (ft-ton/acre) (in./hr); 4·74 $(g/m^2)/(dyn/sec)$ = 1 (ton/acre)/(100 ft-tons/acre) (in./hr).

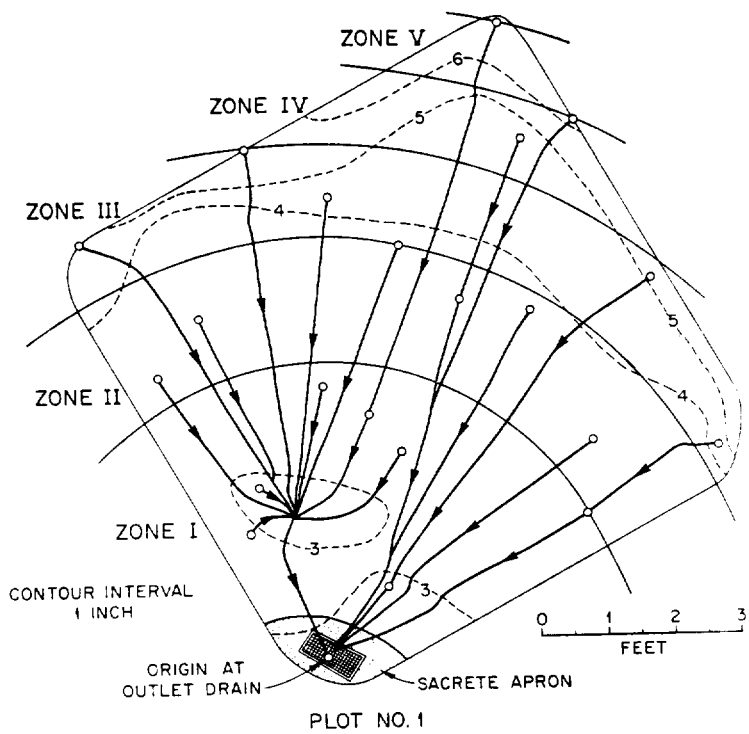

FIG. 2. Network of points and resulting surface streamlines used for computation of slope and slope length, superimposed on the contour lines of bare soil plot 1.

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length of slope (λ) listed in Table 1 are different from those reported previously.[11] The average predominant land-slope and slope-length criteria applicable to agricultural fields[12] were not considered suitable for small-plot studies. In the context of the small-plot study, doubts arose regarding selection of deposition areas and of easily definable drainage channels.[12] When cover factor C for good meadow turned out to be lower by $\frac{1}{3}$ than the lowest value in use, the procedure described below was developed to obtain the average slopes and slope lengths of our small plots.

The procedure makes use of a set of points, Fig. 2, distributed uniformly per unit of plot area but in random directions with respect to the exit sink. Uniform distribution is obtained by inscribing the plot in a circle with the origin at the exit sink and dividing it into a number of equal annular zones.[15]

A number of points proportional to the area of the zone occupied by each plot segment are assigned in random directions[16] and located on the imaginary subannular arcs within each zone segment. The points are connected with the exit sink by surface streamlines which cross the equipotential 1-in. contour lines at right angles. The slopes at each location are calculated from elevations with respect to the sink and the length of surface streamlines. The average, listed in Table 1, is taken as plot slope (s), and the average length of streamlines is taken as the slope length (λ). The same set of points was used for each of the other plots (plots 2 and 3); the values of s and λ obtained are listed in Table 1, along with the computed Λ a slope, slope-length topographic correction factor.

RESULTS AND DISCUSSION

Cesium-137 leaching from vegetation

After ^{137}Cs was applied on the plots with vegetation (plots 2 and 3), it was found that practically all the cesium was on the plant and litter material. In Fig. 3 the percentage concentration of ^{137}Cs in the dead vegetation for selected sampling dates following application is shown as a function of rain. The results show

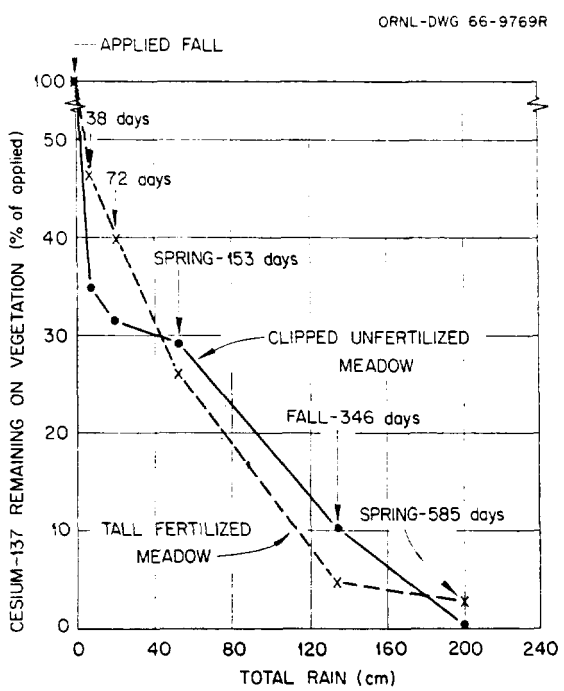

FIG. 3. Cesium-137 (%) remaining on the vegetation as a function of rain (cm).

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that, during the first 153 days following application, about three-fourths of the ^{137}Cs originally present on vegetation was washed off, and that after 585 days practically all of it was gone. Limited data in Fig. 3 also indicate that the initial decline in concentration in the clipped-meadow plot was more rapid. The reason for the lower loss from the good meadow could be that the pathway for leached ^{137}Cs is partly along the blade of grass for the tall meadow vegetation which would tend to slow the transfer of ^{137}Cs to the soil.[1]

Samples taken after 2 years (737 days) confirmed the total loss of ^{137}Cs from vegetation: 0·3 and 0·1 per cent were found in the vegetation of plots 2 and 3, respectively. These values and those reported for the 585-day samples were corrected for the additional vegetation due to new growth.

Cesium–soil loss relationship

The relationship of ^{137}Cs loss to soil loss was found to fit the logarithmic curve of the type,

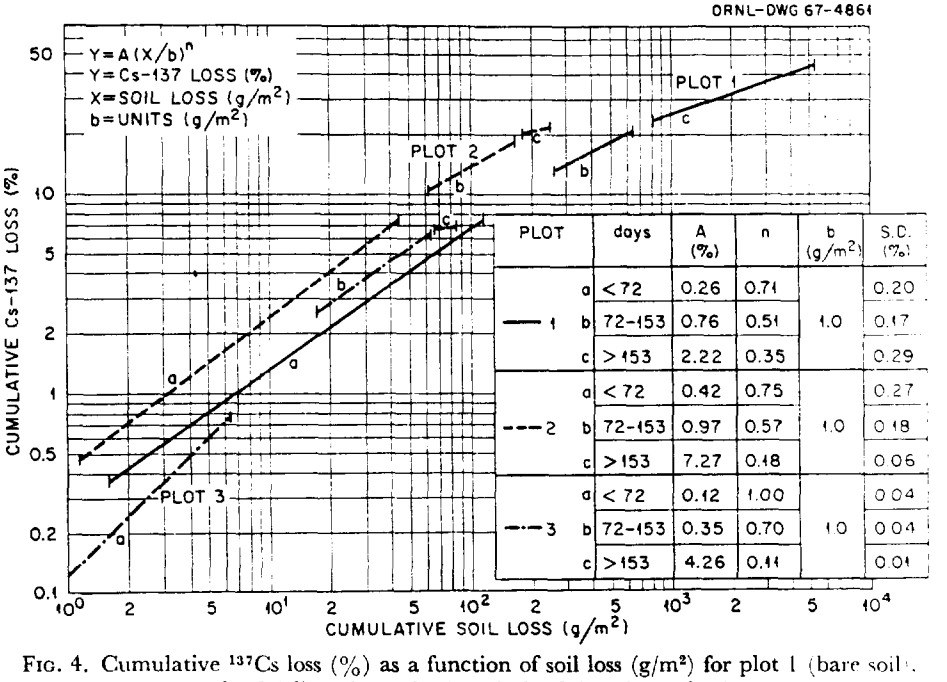
$$Y = A(X/b)^n \qquad (4)$$

where

Y = cumulative per cent of ^{137}Cs loss,
X = cumulative soil loss (g/m²)
b = units constant = 1·0 g/m²,
n = exponent ($0 > n > 1$),
A = coefficient.

When the data obtained over a 2-year period were used, the best least-squares fits of equation (4) were obtained by splitting the data into three distinct time phases—early, transition, and equilibrium—and by treating each plot separately.

In Fig. 4 the respective time-phase graphs for the bare soil (plot 1), clipped meadow (plot 2) and good meadow (plot 3) are shown in the logarithmic form. The time phases for this study refer to the number of days after the application of radiocesium. The time phases chosen here were based on information derived from empirical field data. The early phase, 'a' in Fig. 4, occurred during the first 72 days; transition phase 'b' took place in the 72–153-day period; and the equilibrium phase 'c' was considered to apply to the data in the 153–



PLOT		days	A (%)	n	b (g/m²)	S.D. (%)
—— 1	a	< 72	0.26	0.71	1.0	0.20
	b	72–153	0.76	0.51		0.17
	c	> 153	2.22	0.35		0.29
--- 2	a	< 72	0.42	0.75	1.0	0.27
	b	72–153	0.97	0.57		0.18
	c	> 153	7.27	0.18		0.06
-·- 3	a	< 72	0.12	1.00	1.0	0.04
	b	72–153	0.35	0.70		0.04
	c	> 153	4.26	0.11		0.01

FIG. 4. Cumulative ^{137}Cs loss (%) as a function of soil loss (g/m²) for plot 1 (bare soil), plot 2 (clipped meadow) and plot 3 (good meadow).

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730-day period. The values of coefficient A, exponent n, and standard deviation of Y (SD) are shown in the insert of Fig. 4.

When equation (4) is plotted on the log–log scale (Fig. 4), exponent n becomes the slope, and coefficient A is the Y-axis intercept at $X = 1{\cdot}0$ g/m^2.

From Fig. 4 we see that the ratio of ^{137}Cs loss to soil loss is linear on the logarithmic scale. The exponent n will be referred to as 'rate of loss' in the following discussion. Since n is obtained from least-squares fit of log data, it is not defined for $X = 1{\cdot}0$ g/m^2; the Y-intercept at $X = 1$ will be referred to as the 'initial loss'.

The rate of ^{137}Cs loss by runoff and erosion, as would be expected, decreased with time for all plots. This was due to the depletion of ^{137}Cs on the surface due to runoff and erosion, as well as movement of ^{137}Cs into the profile. During the first two phases, 'a' and 'b' in Fig. 4, the rate increased with the amount of cover, higher rate being observed on the good-meadow plot 3 than on the clipped, poor-meadow plot 2, which had a slightly higher rate than bare-soil plot 1. This increase could be related to a washoff contribution from vegetation, the increase due to washoff per unit weight of eroded material being greater from standing meadow (plot 3) than from clipped litter lying on the ground surface (plot 2), although in both meadow plots ^{137}Cs was being added to runoff and eroded sediment through washoff at a rate greater than could be added by erosion of contaminated soil from bare-soil plot 1. After 153 days, the rate of ^{137}Cs loss decreased with the amount of vegetation. By this time, on the average, only 27 per cent of the originally applied ^{137}Cs remained on the dead vegetation (Fig. 3), and the new vegetation had taken over. The new vegetation cover was heavier on plot 3, which was fertilized the preceding fall, than on plot 2; the corresponding decrease in runoff and erosion rate of soil is, therefore, reflected by the decreased ^{137}Cs loss rate.

The initial loss in phase 'a' was highest on the clipped, poor-meadow plot 2, containing large amounts of loose dead-plant material in contact with the soil, followed by bare-soil plot 1 and good-meadow plot 3. Results in the last colunm of Table 2 show highest loss of ^{137}Cs in solution on plot 2. The results also indicate highest first

Table 2. Annual and total precipitation, runoff, infiltrate, energy-intensity index EI, *soil and ^{137}Cs loss on three radionuclide movement study plots on alluvial Captina si. l. soil in Tennessee*

Plot*	Year	Rain†, cm	Runoff, l/m^2	Infiltrate, l/m^2	EI‡, $\times 10^3$ dyn/sec	Soil loss§, g/m^2	^{137}Cs loss, %	
							Soil	Solution
1			780	568		2023	30·33	0·39
2	1	135	523	825	15·7	206	18·35	0·54
3			251	1096		72	6·37	0·36
1			711	388		3235	12·14	0·18
2	2	110	260	839	14·6	44	0·52	0·05
3			152	948		13	0·07	0·04
1			1491	956		5258	42·29	0·57
2	Total	245	783	1664	30·3	250	18·82	0·59
3			403	2044		85	6·44	0·40

*Plot 1, bare soil; plot 2, poor meadow; plot 3, good meadow.

†Normal (1931–1960) rain is 139 cm/year, U.S. Department of Commerce, 1966; Local Climatological Data, Annual Summary, Oak Ridge, Tennessee; 1 cm of rain = 10 l/m^2 of rain.

‡Expected EI for the area is $9{\cdot}9 \times 10^3$ dyn/sec/year, Soil loss estimation in Tennessee,[14] where 0·4728 dyn/sec = 1 EI (ft-tons/acre) (in/hr).

§Where 224·2 g/m^2 = 2242 kg/ha = 1 ton/acre.

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year adsorption at the surface of plot 2.* In addition infiltration measurements showed that the average infiltration rate during the first five months was lowest on the clipped-meadow plot 2. The resulting high concentration at the eroding surface could, therefore, explain the high initial loss value for plot 2. Higher loss per unit weight might be expected on the bare soil than on good meadow because of the higher surface concentration on plot 1, while ^{137}Cs was still being leached off from the vegetation on plot 3.

Under the equilibrium conditions, 'c' in Fig. 4, inspection of the coefficients suggests two conclusions. First, the initial losses of ^{137}Cs per unit weight of soil would have been relatively higher if ^{137}Cs was in the equilibrium phase, since little or no net movement into the soil would have taken place. Second, the highest value on plot 2 could be indicative of the highest potential concentration of ^{137}Cs at the surface of the soil in the litter layer relatively more susceptible to losses by erosion than surface soil. This observation complements the adsorption data presented in Table 2.

A summary of the yearly values of runoff, infiltrate, *EI* and soil loss, in addition to ^{137}Cs concentrations in the soil and liquid portions of runoff, is presented in Table 2. The higher soil loss on the bare plot in the second year did not result in an increase in ^{137}Cs loss; this was likely due to mixing of contaminated soil material with the uncontaminated one from the lower zone of soil. Movement of contaminated soil particles down the profile is probably the mechanism of mixing, as the high adsorption of ^{137}Cs exhibited by the soil virtually precludes movement by desorption. Since ^{137}Cs in the runoff is on the solids, percolating water, like runoff, should also contain solids bearing ^{137}Cs which move downward until filtered by the mass of soil. In the second year, very little ^{137}Cs was lost from the vegetation-covered plots; though the soil loss decreased by a factor

*Adsorption coefficients, K_d computed as the ratio of per cent loss per gram of soil to per cent loss per milliliter of solution from columns 4, 7, 8 and 9 of Table 2 were approximately 3×10^4, 9×10^4 and 6×10^4 ml/g for plots 1, 2 and 3 respectively.

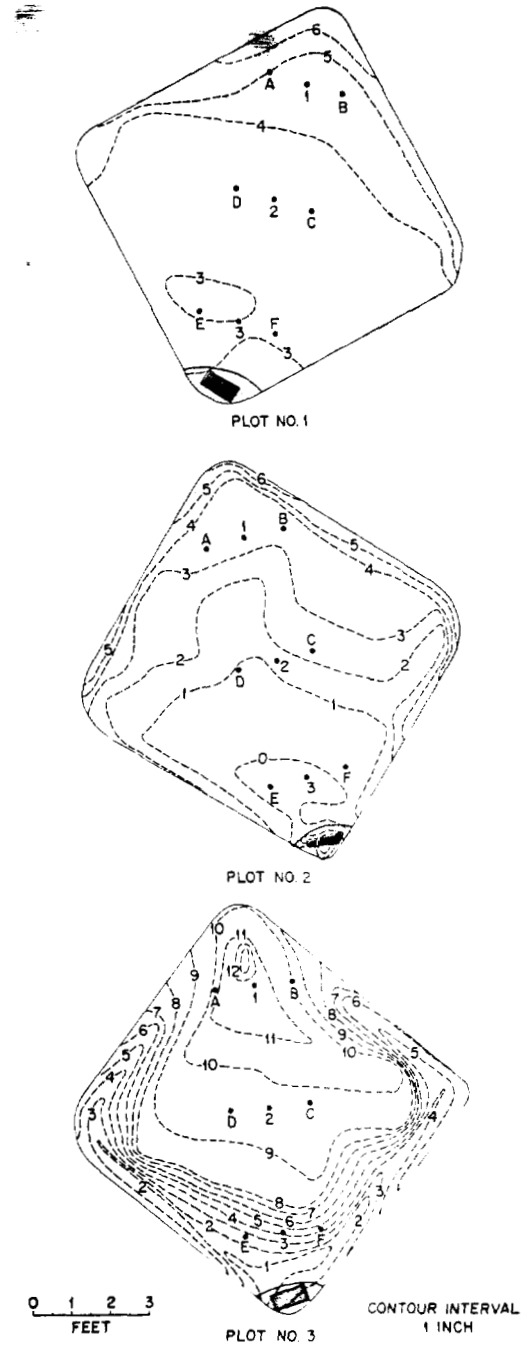

FIG. 5. Location of core samples taken after 1 year an after 2 years following application of ^{137}Cs on bare sc (plot 1), clipped meadow (plot 2) and good meado (plot 3).

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of 5 from the first year, the ^{137}Cs loss decreased by factors of 35 and 90 for plots 2 and 3, respectively. Hence, once the ^{137}Cs reaches the soil, losses by runoff and erosion are greatly reduced through protection afforded by plant cover.

Distribution of ^{137}Cs in the soil

In Table 3, ^{137}Cs distribution on the study plots is given, both for the first year and the second year; in Fig. 5 the respective locations of sampled cores are shown. To avoid disturbing the erosion characteristics of these small plots, only a limited number of cores could be taken. The results show that most of the ^{137}Cs is in the 0–3 cm depth; however, considerable redistribution of applied ^{137}Cs within the plots becomes apparent from the results in Table 3. Considering the 0–3 cm layer, this is true of cores *E* on plots 1 and 2. A glance at Fig. 5 will show that these cores were taken from depressions close to the exit drain. Excessive accumulations, corresponding to core *D* on plot 2 and core *C* of plot 3 could have been caused by almost flat microtopography and heavy cover in the immediate vicinity. Areas of excessive accumulation are further complicated by the nature of meadow growth and litter accumulations during the successive growing seasons.

In the 3–30 cm layer, in general, the amount of ^{137}Cs was highest on the bare-soil plot, lowest on the good-meadow plot. During dry spells in the 2-year-study period, the soil surface on plot 1 (bare soil) and, to a lesser extent, on plot 2 would become extensively cracked. This cracking could have aided in subsequent mechanical washing of fine clay with adsorbed ^{137}Cs into deeper portions of the profile. However, high adsorptive capacity of the organic material proportional to the amount of cover and effectively absent on bare-soil plot 1 should be taken into consideration.[17]

The average concentration of ^{137}Cs in the soil was determined after 2 years of operation. The average percentages were adjusted for the area of depressions around *E* cores in plots 1 and 2. (See Fig. 5.) Values for plots 2 and 3 were not corrected for high values of cores *D* and *C*. The results are summarized in Table 3. The highest concentration remaining in the soil is in plot 3 with 87·6 per cent. To these values one might add the ^{137}Cs found in runoff and erosion and on vegetation. Contribution by vegetation, including new vegetation, after 2 years was 0·4 per cent for plot 2 and 0·5 per cent for plot 3; contribution by runoff and erosion amounted to 43·4, 20·0 and 7·2 per cent for plots 1, 2 and 3, respectively. The total ^{137}Cs accounted for

Table 3. Average percentage concentrations of ^{137}Cs in the soil after 2 years and concentrations at several locations at two depths on the study plots† 1 year and 2 years after the application of radionuclides*

Year (date)	Location	Plot 1		Plot 2		Plot 3	
		0–3 cm	3–30 cm	0–3 cm	3–30 cm	0–3 cm	3–30 cm
				Per cent of applied			
1	1	43·1	10·4	17·3	0·9	68·9	9·6
8 Oct., 1965	2	93·5	11·1	49·4	3·9	32·5	1·9
	3	25·8	10·6	44·9	2·0	128·6	10·0
2	A	23·0	9·1	66·3	4·8	85·6	9·1
15 Oct., 1966	B	24·1	12·1	12·4	2·4	43·8	2·7
	C	61·8	25·6	13·8	8·5	139·5	7·1
	D	32·6	4·2	121·2	11·3	59·0	4·1
	E	122·0	124·0	163·9	65·6	91·8	7·1
	F	22·7	5·9	56·4	5·9	73·9	1·7
Average		35·6	14·8	59·6	9·6	82·3	5·3

*Respective locations shown in Fig. 5.
†Plot 1, bare soil; plot 2, clipped meadow; plot 3, good meadow.

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each plot is 93·8 per cent for plot 1, 89·6 per cent for plot 2, and 95·3 per cent for plot 3; the differences from 100 per cent are unaccounted for.

Comparison with findings of others

We compare now the observed ^{137}Cs losses with the findings of others. Direct comparisons are difficult, since experimental conditions differ. However, they are informative. Comparing our initial results with those of GRAHAM[10] for two rains of consequence with similar runoffs (about 19 and 41 per cent vs. 29 and 63 per cent, respectively, of Graham's), we found that ^{137}Cs loss on our bare plot was 1·8 per cent in contrast to Graham's strontium loss of 0·7 per cent. It should be pointed out that Graham's fallow plot was kept clean by frequent cultivation and the soil remained loose and free of weeds. On our bare-soil plot it was not necessary to cultivate and a surface seal was allowed to develop. These differences could account for lower losses from Graham's plot because cultivation promotes both infiltration and mixing.

Our highest single loss of ^{137}Cs was 5·6 per cent with 77 per cent runoff from the bare plot; this value may be compared with over 25 per cent loss of deposited radiostrontium from corn and oat plots in Wisconsin for samples taken in June 1957 by MENZEL.[18] In Menzel's results, each loss was based on the fallout occurring during a specified period. If we consider loss from our good-meadow plot (plot 3) for one rainstorm, the highest was observed on 9 January, 1965, and amounted to 1·92 per cent. The ^{137}Cs-loss data obtained up to this date revealed that the ^{137}Cs loss per gram of soil loss was 0·12 per cent and was probably decreasing with increasing soil loss. Using this value for the specific loss, we obtain 1·27 per cent as the value anticipated for 10·6 g of soil loss in this storm. (The observed value was 1·92 per cent.) Sampling of the vegetation on 22 March, 1965, showed that 13·3 per cent of the ^{137}Cs on vegetation had been washed off since 31 December, 1964. During this period 34 cm of rain was recorded, of which 8·2 cm fell on January 9. Based on a semilogarithmic relationship of ^{137}Cs loss from vegetation and rainfall, one calculates approximately that the 13·3 per cent was washed off from vegetation in the rain of January 9. If we consider the runoff loss of 0·65 per cent observed on that day (1·92–1·27 per cent = 0·65 per cent) as being contributed by washoff from vegetation, we conclude that approximately 13 per cent [$(0{\cdot}65/5) \times 100$ = 13 per cent] of the ^{137}Cs washed from vegetation was lost in runoff as a result of this rain. This value, though lower than the 25 per cent observed by Menzel for corn and oat plots, is higher than the 1 per cent loss he observed for the clover plot. Similar calculations for the clipped-meadow plot (plot 2) showed that 0·64 per cent was unaccountable by soil loss alone; but since only 2·3 per cent (in contrast to 13·3 per cent) of ^{137}Cs was washed off from the vegetation during this period, the possible contribution to runoff from vegetation washoff is approximately 80 per cent for the rain on 9 January, 1965.

FRERE and ROBERTS[19] report that $\frac{1}{3}$–$\frac{2}{3}$ of ^{90}Sr deposited by fallout up to 1960 was lost from cultivated watersheds in Ohio with an average slope of 13 per cent. These values are higher than ours and possibly reflect the effects of cultivation, steeper slopes, and higher degree of washoff from vegetation. Interestingly, the watershed used as a reference for the above study was reported to have no recorded soil loss and the average ^{90}Sr content was slightly higher than surrounding areas; this observation implies that ^{90}Sr losses are associated with soil losses (erosion) and not necessarily with runoff only. This corroborates our findings with ^{137}Cs.

SUMMARY

On the basis of the 2-year study, we conclude that ^{137}Cs loss by runoff and erosion can be considerable, particularly from the exposed bare-soil areas. Runoff and erosion losses of ^{137}Cs from the vegetation-covered plots occurred primarily in the initial stages following the application and were due to washoff from vegetation.

Cesium-137 loss was dependent on soil loss, and empirical logarithmic equations described the relationship. It was found that considerable redistribution within a plot occurred and that

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the uptake of ^{137}Cs by new vegetation constituted only a small fraction of the total ^{137}Cs applied. Most of the applied ^{137}Cs that had not been eroded was found in the 0–3 cm layer of the soil.

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