



Radiocesium in Montana soils and applications for soil erosion measurement
by Olafur Gestur Arnalds

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Soils
Montana State University

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Abstract:

Radiocesium levels in soils were measured at eleven sites throughout Montana. Cesium was mostly confined to the top of the soil profile. Both lateral and vertical displacement of cesium was attributed to mechanical movement of soil particles. The areal activity of cesium was strongly correlated to annual precipitation ($R^2 = 0.92$). An equation is given to predict cesium activity from annual rainfall.

Methods of calculating soil erosion and deposition are discussed and performed for a wind erosion study site in Pondera County and a small watershed in Teton County. The results indicate that deposition at the wind erosion study site can be quantified. Soil deposition of 70 to 1290 $\text{m}^3 \text{ha}^{-1}$ was measured on the leeward sides of a fence and tree windbreaks while an average of 450 m^3 was lost from the windward sides. An average of 740 $\text{m}^3 \text{ha}^{-1}$ was lost since 1962 from an adjacent wind eroded field. This amounts to 34.8 $\text{Mg ha}^{-1} \text{yr}^{-1}$.

Soil loss since about 1962 ranged from 300 to 820 $\text{m}^3 \text{ha}^{-1}$ within the upper areas of the watershed studied. A pond at the outlet of the watershed and deposition areas at the toeslope accounted for a relatively small fraction of the soil loss within the watershed. Most of the losses are likely to be from wind erosion. Length of slopes or position within the field were more related to erosion than was steepness of slopes. Estimates of erosion rates based on ^{137}Cs ranged from 16.5 $\text{Mg ha}^{-1} \text{yr}^{-1}$ at the summit of the watershed to 45.1 $\text{Mg ha}^{-1} \text{yr}^{-1}$ at the midslope. Predictions by conventional methods (wind erosion equation and the Universal Soil Loss Equation) agreed rather closely with the estimates from ^{137}Cs .

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of
Master of Science
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Soils

MONTANA STATE UNIVERSITY
Bozeman, Montana

May 1984

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APPROVAL

of a thesis submitted by

Olafur Gestur Arnalds

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citation, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Radiocesium levels in soils were measured at eleven sites throughout Montana. Cesium was mostly confined to the top of the soil profile. Both lateral and vertical displacement of cesium was attributed to mechanical movement of soil particles. The areal activity of cesium was strongly correlated to annual precipitation ($R^2 = 0.92$). An equation is given to predict cesium activity from annual rainfall.

Methods of calculating soil erosion and deposition are discussed and performed for a wind erosion study site in Pondera County and a small watershed in Teton County. The results indicate that deposition at the wind erosion study site can be quantified. Soil deposition of 70 to 1290 $\text{m}^3 \text{ha}^{-1}$ was measured on the leeward sides of a fence and tree wind-breaks while an average of 450 m^3 was lost from the windward sides. An average of 740 $\text{m}^3 \text{ha}^{-1}$ was lost since 1962 from an adjacent wind eroded field. This amounts to 34.8 $\text{Mg ha}^{-1} \text{yr}^{-1}$.

Soil loss since about 1962 ranged from 300 to 820 $\text{m}^3 \text{ha}^{-1}$ within the upper areas of the watershed studied. A pond at the outlet of the watershed and deposition areas at the toeslope accounted for a relatively small fraction of the soil loss within the watershed. Most of the losses are likely to be from wind erosion. Length of slopes or position within the field were more related to erosion than was steepness of slopes.

Estimates of erosion rates based on ^{137}Cs ranged from 16.5 $\text{Mg ha}^{-1} \text{yr}^{-1}$ at the summit of the watershed to 45.1 $\text{Mg ha}^{-1} \text{yr}^{-1}$ at the midslope. Predictions by conventional methods (wind erosion equation and the Universal Soil Loss Equation) agreed rather closely with the estimates from ^{137}Cs .

CHAPTER 1

INTRODUCTION

In a world of increasing food demand there is a growing concern for soil conservation. Decline and downfall of ancient civilizations have been related to improper soil management and erosion (Brown, 1982). The problem of controlling soil erosion involves quantification of soil loss. Models have been developed to estimate erosion by wind and water (Wischmeier and Smith, 1978; Woodruff and Siddoway, 1972), but erosion is not often measured directly under field conditions. A method based upon radioactive fallout from nuclear testing provides a potential way of quantifying erosion.

From the early fifties to 1963, the USA and USSR conducted numerous experiments with nuclear weapons in the atmosphere and the pollutants have been falling down on earth ever since as worldwide nuclear fallout. One of the radioactive isotopes that has thereby accumulated on earth is radiocesium (^{137}Cs). It is formed from uranium and has a half life of 30 years. Cesium is tightly adsorbed on soil materials due to its chemical and physical properties. Once adsorbed on soil, it is relatively immobile unless some external forces move the soil. Cesium is primarily moved with soil by physical processes such as erosion.

The objectives of the study described herein were as follows:

1. To investigate the pattern and levels of ^{137}Cs fallout in Montana soils, and
2. To investigate the use of ^{137}Cs redistribution as a tool to quantify erosion.

Samples were obtained from various undisturbed native sites in Montana to study areal and profile distribution of ^{137}Cs . Radiocesium levels were used to study wind erosion at a site in Pondera County and both water and wind erosion within a watershed in Teton County.

Methods of calculating soil erosion from levels of ^{137}Cs are discussed and comparison made with methods used by the Soil Conservation Service in Montana to predict soil erosion.

CHAPTER 2

LITERATURE REVIEW

Fallout and Radiocesium

Radiocesium is introduced into the environment by man generated nuclear fissions. The probability of forming 137 mass product in a fission of uranium is about 6%. Iodine 137 is the main decay product from which ^{137}Cs is formed. The decay of ^{137}I to the stable isotope, barium 137, is as follows (Katcoff, 1960):

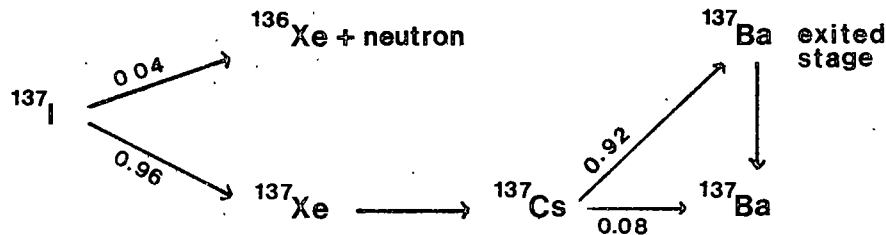


Figure 1. Decay of ^{137}I .

The scheme shows how ^{137}Cs is formed by decay from the initial fission product.

Tremendous heat is produced in nuclear explosions within a small fraction of a second. The nuclear fuel and the immediate surroundings are raised to a temperature of several million degrees, vaporized, and form a bright fiery ball of gases called the "fireball." As the fireball rises, gradual cooling occurs, allowing the vaporized materials to condense into small droplets which solidify to form small particles that eventually fall back on earth (Whicker and Schultz, 1982).

The larger particles are deposited within a few hundred kilometers of the explosion site and constitute the local fallout. Smaller particles may be injected into the troposphere

or stratosphere and constitute the worldwide fallout. The major deposition will however take place in the same hemisphere as the site of explosion (Pentreath, 1980; Whicker and Schultz, 1982). Fallout from the troposphere usually reaches the earth's surface within a month. The majority of the worldwide fallout produced has been stratospheric. The radionuclides, including cesium, are mainly brought to earth by precipitation, either as dust suspended in rain or dissolved in the water (Arnold and Martell, 1959; Pentreath, 1980; Syers et al., 1972). Some radionuclides may be settled out by dry deposition, especially in arid regions (Pentreath, 1980). Mean residence time of radioactive debris in the stratosphere may range from less than a year to 5 years (Arnold and Martell, 1959; Whicker and Schultz, 1982). The halflife of cesium is approximately thirty years.

Retention of Cesium in Soils

Cesium is a monovalent ion in Group I of the Periodic Table. Its chemical properties are like those of the other alkali metals (Whicker and Schultz, 1982). Cesium forms solution complexes rarely and appears in solutions predominantly as Cs^+ . The main soil and rock reaction with cesium is expected to be ion exchange (Onishi et al., 1981). Distribution coefficients for cesium adsorption are generally large so that little of this nuclide remains long in solution (Onishi et al., 1981). Gillham et al. (1980) and Onishi et al. (1981) reported that ion exchange reactions for cesium were rapid; sorption of cesium was observed to reach steady state in relatively short time (hours).

Cesium is preferentially adsorbed and strongly retained by soil particles. The Lyotropic series for the order of monovalent cation preference by soil colloids is: $\text{Cs} > \text{Rb} > \text{K} > \text{Na} > \text{Li}$ (Gast, 1977). According to Samoilov (1965) cesium has negative hydration. As cesium closely approaches soil surfaces, Coulomb attraction forces become strong. Differential thermal curves of trioctahedral vermiculite show little water of hydration when cesium saturated (Douglas, 1977). Cesium has been shown to be preferably adsorbed by

kaolinites in the presence of NaCl and CaCl₂ solutions (Kormanej, 1978). Sandy materials have also been reported to have a substantial capacity to retard migration of cesium (Gillham et al., 1980).

Many researchers have discussed the strong retention of cesium by mica-like or illite and vermiculite clay minerals (Coleman et al., 1963a; 1963b; Coleman and LeRoux, 1965; Frances and Brinkley, 1976; Lomenic and Tamura, 1965; Onishi et al., 1981; Sawhney, 1965; Schultz et al., 1960; Tamura, 1964). Due to this strong adsorption, Cs is not released from minerals in the presence of large concentrations of other ions, like Ca⁺⁺ or Na⁺. Cesium "fixation" involves adsorption on the ion edges of mica-like crystals or its entrapment in positions between the layers such as those occupied by potassium in micas (Coleman and LeRoux, 1965). Douglas (1977) noted that cations with low hydration energies, such as Cs⁺, cause interlayer dehydration and are therefore fixed in interlayer positions of vermiculite, where bonds may be satisfied over the shortest distance. Larger ions, such as Ca⁺⁺ and Mg⁺⁺, that later enter the crystal lattice may then "trap" the cesium ions by preventing further movement.

The retention of cesium by clay minerals is dependent upon pH; the adsorption is generally reported to be stronger at higher pH (Elprince, 1978; Nishita et al., 1956). However, Shuvalov (1980) concluded for soils of the subtropical zone of Georgia, that a change from strongly acid to alkaline reduced the amount of cesium sorbed. All the soils studied were nevertheless found to effectively adsorb ¹³⁷Cs. Squire and Middleton (1966) observed more downward movement in calcareous soils than in acid clay soils. Elprince (1978) suggested that hydroxy Al interlayers were the main source for the pH dependent charges making Cs⁺ adsorption pH dependent.

As a result of the strong retention of cesium in soils, most of it is found in the top few centimeters of the solum of undisturbed soils (Lomenic and Tamura, 1965; Rogowski and Tamura, 1965, 1970a; Walton, 1963). Miller and Teitemeier (1963) reported that 96.6

to 100% of applied cesium was in the top 3.4 cm (1.4 inches) after 7620 mm of leaching with water. The soils tested were of silt loam, loamy sand, clay loam and clay texture. Cline and Rickard (1972) showed that 70% of applied cesium remained in the upper 2.5 cm eight years after application.

A few investigators have observed deeper displacement of radiocesium. Mishra and Sadasivan (1972) reported significant amounts (up to 50%) of cesium below 15 cm depth in several Indian soils. However, they did conclude that "most of the deposited ^{137}Cs is confined to the top few inches of soils." Mishra and Sadasivan attributed the deep penetration of cesium to high rainfall and subsequent leaching. Baltakmens and Gregory (1977) found up to 26% of cesium between 15 and 30 cm depth in some New Zealand soils. Oldfield et al. (1979) reported that the downward movement of cesium in peat soils in Ireland and England prevented cesium from being used for dating peat materials.

There is a trend observed in the literature related to depth of cesium retention. Older publications report shallower depths of cesium penetration. Walton (1963) suggested permeability and drainage properties as factors influencing the variability of nuclide concentrations with depth. Miller and Reitemeier (1963) suggested that movement of cesium in the field might be affected by such factors as freezing and thawing, wetting and drying, and burrowing of earthworms and other small animals.

Repeated plowing of soils results in homogenization of the activity of cesium within the plowlayer (McHenry and Ritchie, 1977; Ritchie et al., 1975; Walton, 1963).

Ritchie and McHenry and coworkers studied numerous watersheds in the U.S.A., using radiocesium to observe soil transport and determine accumulation rates in sedimentation traps. They correlated cesium levels in soils and sediments with several factors. McHenry et al. (1973) surveyed numerous watersheds distributed throughout U.S.A. and found the occurrence of ^{137}Cs in sediments significantly correlated with amount of clay and organic matter which provide sites for adsorption and retention of cesium. Ritchie and

McHenry (1978) found soil nitrogen to be the most important factor to account for variability in ^{137}Cs concentrations for noncultivated watersheds. For cultivated watersheds, organic matter was most important. The R factor of the Universal Soil Loss Equation (rainfall intensity) and precipitation were also important variables. Ritchie and McHenry (1977) have also correlated cesium content with organic phosphorus, clay, seasonal distribution of precipitation and particle size.

Use of Cesium to Estimate Deposition and Erosion

Cesium has been used to determine sedimentation rates into lakes and ponds, using the fallout pattern with 1954 as the first year of fallout and a fallout peak in 1963 (DeLaune, 1978; Pennington et al., 1976; Ritchie et al., 1975; Robbins et al., 1978).

Quantitative estimates of erosion based on radiocesium have been developed experimentally, using both field plots and undisturbed field conditions. Rogowski and Tamura (1965; 1970a; 1970b) studied runoff and erosion from field plots after ^{137}Cs had been applied. They developed an equation that showed a relationship between nuclide loss and erosion.

Ritchie et al. (1974a) calculated a "budget" for the distribution of fallout ^{137}Cs . They used an undisturbed forest site to indicate the cumulative fallout over the watershed they studied. On this basis it was shown how land use (forest, grass, and grass-crop) affected the levels of cesium remaining in the soils. Lowest cesium levels were found at the sites with highest erosion potentials. In another paper Ritchie et al. (1974b) used the same data to show the relationship between soil loss and cesium activity. Loss of cesium from soils under each land use was calculated by subtracting cesium present from ^{137}Cs input into the watershed. The relationship of computed gross soil loss under different land use to computed ^{137}Cs loss was

$$Y = 1.6 X^{0.68}$$

where Y = computed ^{137}Cs loss (nCi m^{-2}) and X = computed gross soil erosion in $\text{Mg ha}^{-1} \text{ yr}^{-1}$, using the Universal Soil Loss Equation (USLE). This equation took other available data into consideration, e.g., Rogowski and Tamura's (1970b). In a review article on fallout ^{137}Cs , Ritchie and McHenry (1975) gave the equation

$$Y = 0.88 X^{1.18}$$

In a study conducted at the White Clay Lake Watershed in Wisconsin, McHenry and Ritchie (1977b) used radiocesium at undisturbed areas as a basis for computing soil loss. It was theorized that all of the ^{137}Cs in cultivated fields would be within the plow layer. The assumption was made that if the depth of ^{137}Cs occurrence was greater than the plow depth and the amount of ^{137}Cs in the profile was less than that assumed deposited, both erosion and deposition had occurred. The soil loss from a given profile was assumed proportional to the measured loss of ^{137}Cs and erosion could therefore be calculated.

McCallan et al. (1980) studied redistribution of ^{137}Cs in some soils of Australia. The soils of the area studied contained approximately 70% clay, mainly montmorillonite. Little soil conservation had been practiced within the area which has steep cultivated slopes and evidence of severe erosion. They calculated cesium activity on an area basis and used undisturbed hillsites as a reference. However, variation was found in the cesium concentrations per unit area over short horizontal distances. They attributed these differences to variation in the penetration of rain through overhanging tree canopies, the effect of stemflow and the reduction in total soil mass in some profiles by the presence of large stones. It was concluded that plowing, soil cracking, root penetration and decay, and leaching through larger cracks could affect the depth at which detectable ^{137}Cs is found. McCallan and coworkers showed that concentration of cesium was lower at eroded sites and higher at locations where deposition was encountered. Soil erosion was not quantified.

Brown and coworkers undertook a study in the Willamette Valley in Oregon to quantify erosion (Brown, 1980; Brown et al., 1981a; 1981b). Two approaches were used: a volumetric approach and a gravimetric approach.

In the volumetric approach, depth of the profile containing cesium was used to calculate the volume of sediment that had accumulated over the period of fallout. In cultivated fields, the thickness of the plow depth was subtracted from the total depth of sediment accumulation together with a few additional cm to account for downward displacement of ^{137}Cs by soil fauna. The difference was assumed to be caused by soil deposition, which was used to estimate erosion rates for the eroded parts of the watershed being studied. Average surface soil bulk density in depositional areas was used to convert the volume to gravimetric estimates of soil erosion and deposition.

In the gravimetric approach, Brown et al. (1981b) used differences in ^{137}Cs concentrations between depositional and upland sites to compute soil loss. The apparent depletion of ^{137}Cs in the uplands from estimated ^{137}Cs input was used together with the average ^{137}Cs activity per unit weight of surface soil in the uplands to obtain an estimate of soil loss.

The soil loss estimates tended to be higher by the gravimetric approach than by the volumetric ($6\text{--}27 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ versus $3\text{--}14 \text{ Mg ha}^{-1} \text{ yr}^{-1}$). It was concluded that the results obtained by the different methods were similar and provided good evidence that the rate of modern erosion at the study site has been within or possibly above the range of erosion rates normally thought of as tolerable.

DeJong et al. (1982) investigated the possibility of using ^{137}Cs to estimate soil erosion in Saskatchewan, Canada. Data on fallout were gathered from Canada and U.S.A., including Montana and North Dakota. Soil samples were collected at cultivated and uncultivated sites. Activity of radiocesium was calculated on an area basis using density and thickness of the sampled layers. Seasonal fallout patterns indicated that most of the cesium

was "precipitated" during April-October due to injection of air from the stratosphere into the troposphere in the spring and increased precipitation in spring. Blowing snow was estimated to account for up to 4% losses of ^{137}Cs on cultivated fields. Cesium removal in grain was estimated to be less than 1% of the total fallout. These researchers used the reduced levels of cesium activity to compute soil loss from a sample site. One tenth loss of cesium from an Ap horizon (10 cm thick) with bulk density of 1.15 Mg m^{-3} gave soil loss of 115 Mg ha^{-1} .

DeJong and coworkers (1983) estimated soil erosion and deposition for eight small basins in Saskatchewan. Three of the basins were uncultivated and five were cultivated. Radiocesium activity was compared to nearby uneroded control sites and the difference was converted to soil loss by the following equation

$$\text{Soil loss} = {}^{137}\text{Cs loss} \times d \times \text{BD}$$

where d is the thickness of the layer in which ^{137}Cs is present (cm) and BD is the bulk density (Mg m^{-3}). Snowblowing and crop removal was assumed to account for 5% loss of cesium. The ^{137}Cs loss in the equation above was calculated as

$$(0.95 {}^{137}\text{Cs-control} - {}^{137}\text{Cs-erosion site})/0.95 {}^{137}\text{Cs-control}$$

Concentrations of ^{137}Cs were reported in pCi cm^{-2} . Gains of soil by deposition were calculated from the ^{137}Cs distribution with depth. In the uncultivated basins, ^{137}Cs activity showed little or no difference related to landscape position. The cultivated basins were divided into upper, middle or lower slopes. The lower slopes showed increased ^{137}Cs levels and calculated soil deposition varied from 25 to 81 kg m^{-2} . Some middle slopes gained soils while others lost but the upper slopes lost 20 to 60 kg m^{-2} . Increased slope length did not result in increased soil loss.

CHAPTER 3

MATERIALS AND METHODS

Site Descriptions and Sampling

The research undertaken to meet the objectives given in the Introduction can be divided into four parts.

1. Samples were gathered at eleven reference sites to determine levels of radiocesium in Montana soils.
2. A small wind erosion study was conducted in Pondera County.
3. A watershed in Teton County was sampled to study soil losses and gains at a cultivated field and in a sedimentation pond at the outlet of the watershed.
4. Other sampling conducted was to study variation in cesium levels at cultivated and native sites, and efficiency of plowing in mixing cesium within the plowlayer.

Reference Sites

Samples for radiocesium analysis were acquired from eleven representative sites in the state to determine the amount and depth distribution of ^{137}Cs in Montana soils. Approximate site locations are shown in Figure 2. All of the sites were nearly level and were covered with vegetation. Brief descriptions of the sites are in Table 1. Mean annual precipitation for the locations were drawn from a map (USDA-SCS, 1977). The sites were sampled during the summer of 1982. Samples were generally taken in 10 cm increments. Maximum sampling depth varied from 20 cm to 40 cm. Sampling intervals differed for the sites at Bozeman, Belgrade, Whitehall, and Kings Hill as will be explained later.

Figure 2. Study sites for ^{137}Cs .

Table 1. Some Environmental Characteristics of the Reference Sites.

Site	County	Vegetation	Rain-fall mm	Elevation m	Dominating Soils in Area	First Sampling Interval			n [#]
						OM %	CEC @	Clay %	
Hubbart	Flathead	forest	430	1200	Eutroboralf	3.1	9.5	15	4
Lolo Pass	Missoula	forest	1520	2000	Cryothent	>6.7	17.8	13	4
Browning	Glacier	range	460	1300	Cryoboroll	>6.7	31.4	28	5
Kings Hill	Cascade	forest	760	2300	Cryoboralf				*
Whitehall	Jefferson	meadow	610	2200	Borosaprist	65			*
Bozeman	Gallatin	range	485	1500	Cryoboroll	2.48	23 [†]	20 [†]	*
Belgrade	Gallatin	range	410	1400	Argiboroll	3.4	19.3	28 [†]	5
Beartooth	Park	range	1270	2700	Cryothent	>6.7	9.6	15	8
Musselshell	Musselshell	range	310	1000	Torriorthent	2.8	14.5	23	8
Fallon	Fallon	range	360	900	Camborthid	2.5	14.4	28	8
Sidney	Richland	range	360	700	Argiboroll	4.8	20.5	26	5

* Cores not obtained with steel tube.

[#] Number of cores composited for each sample.[†] Estimated value.@ CEC as meq 100 g⁻¹.

Soil samples were obtained by driving a 5.08 cm (2 inch) diameter steel sampling tube to the desired depth. As the cores often became compacted within the tube, the length of the soil core itself was never used to determine sampling increments. In order to reduce contamination of samples, loose material on top of each core (excluding the first sampling

interval) was placed in a separate bag. The dry weight was obtained for the loose material and added to the weight of each sample, but it was not analyzed for cesium as it may have contained material from the surface layer with relatively high ^{137}Cs activity.

Each sample was a composite of 4 to 8 cores (n in Table 1). The cores were taken within a 5 m² plot. Samples were stored in plastic bags. Samples from Kings Hill were obtained by cutting a core from the ground and the sampling intervals were 0-7.5 cm, 7.5-15.0 cm, and 15-22.5 cm. The above method proved to be time consuming and inaccurate so the method described earlier was used for other locations except where further subdivisions were acquired from the Bozeman and Whitehall sites.

At the Bozeman site, the soils were cut from a wall of a pit with a knife. Samples from the Whitehall site were cut from a core of peat soil that had been excavated and moved to Bozeman for further research (Dan Spencer, 1983). Sampling intervals for the Bozeman and Whitehall sites are listed in Table 2.

Table 2. Sampling Intervals at the Bozeman and Whitehall Sites.

Bozeman	Whitehall
0-3 cm	0-3 cm
3-6 cm	3-6 cm
6-9 cm	6-10 cm
9-12 cm	10-20 cm
12-15 cm	20-30 cm
15-20 cm	30-40 cm
20-30 cm	
30-40 cm	

The total number of samples analyzed for cesium from reference sites was 38 (not counting samples from Belgrade, which will be accounted for later).

Wind Erosion Study

The location for a wind erosion study was selected in Pondera County, approximately 32 km (20 miles) east of Brady on the McLean farm. The area is characterized by a glaci-

ated, gently rolling landscape. The soils are fine-loamy Argiborolls. Winter wheat and other cereal grains are grown in alternate years in a crop/summer fallow rotation. Samples were obtained both from a field where erosion was known to have occurred and from a field where deposition of soil materials was expected. The relative position of the two fields is shown in Figure 3. An attempt was made within both fields to sample deep enough (26 and 28 cm) to include all of the profile containing ^{137}Cs . In addition, a few extra cores were secured from deeper intervals to prove that all of the cesium was included in the samples from shallower depths. More detailed maps of the fields are shown with the results in Chapter 4.

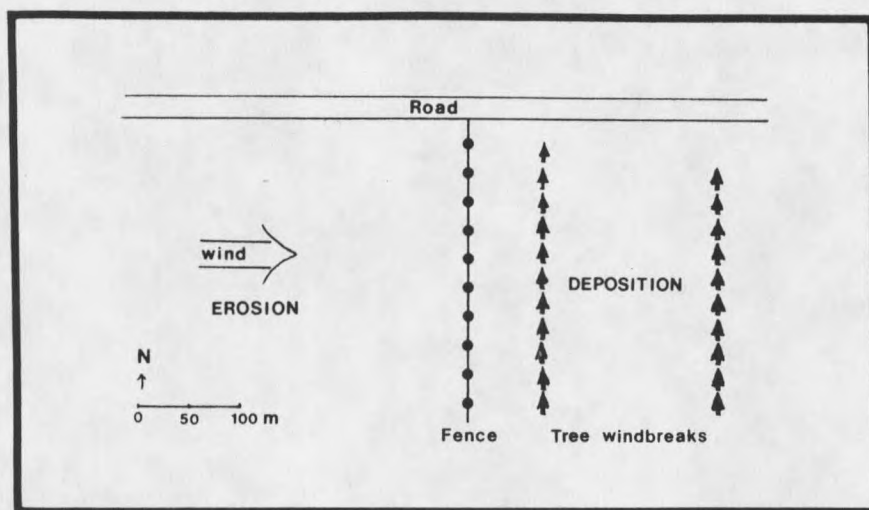


Figure 3. Wind erosion study site.

Soil samples were obtained by driving a steel tube into the soil as described earlier. Six samples were taken from the eroded field, the depth interval was 0-26 cm. Each sample was a composite of eight cores. Samples were taken from 120 m long transects. Transects were oriented parallel to the fence and windbreaks from topographic high to topographic low to obtain an average ^{137}Cs value across the landscape. The location of the transects is shown on Figures 6 and 7. Cores from 26-36 cm intervals were also sampled at two loca-

tions. In the field where soil had been deposited, the transects were 60 m long on nearly level topography. Each sample site was located 12 m from the fence or 12 m on either side of the windbreaks except for one sample, which was acquired midway between windbreaks.

Watershed Study

The watershed study was in Teton County, approximately 8 km (5 miles) NW of Power at the Lehnerz farm. The landscape in the area is characterized by gently rolling hills and the site has a slight southern aspect due to its location in the southern fringe of the Teton ridge. Slopes within the watershed range from zero to about 10%. The field drains into a pond at the southern end of the watershed. The soils are Borollic Vertic Camborthids.

The field can be divided into five topographic areas as shown on the map (Figure 4). The lowest part, which is nearly level, is termed the toeslope. Moving towards the higher parts of the field, the areas are named footslope, midslope, shoulder, and summit, which also is nearly level. A transect was laid out from the pond to the summit (dotted line from pond to A in Figure 4). Samples were taken along the transect at 50 m intervals. Short perpendicular transects were sampled at 100, 300, and 500 m. An additional sample was obtained from the 25 m interval.

Two preliminary samples were obtained in June 1982, one from the midslope and one from the toeslope. The sampling increments were 0-15 cm and 15-25 cm, each sample being a composite of 4 cores. The field was sampled again in September 1982. Two increments were used, 0-15 cm and 15-30 cm, and each sample was a composite of three cores. The samples were obtained with a steel tube in the same manner as described earlier. The 0-15 cm increment included approximately the plowlayer while the lower increment was sampled to include all of the ^{137}Cs that might occur within the profile. Twenty-one sites were sampled within the field.

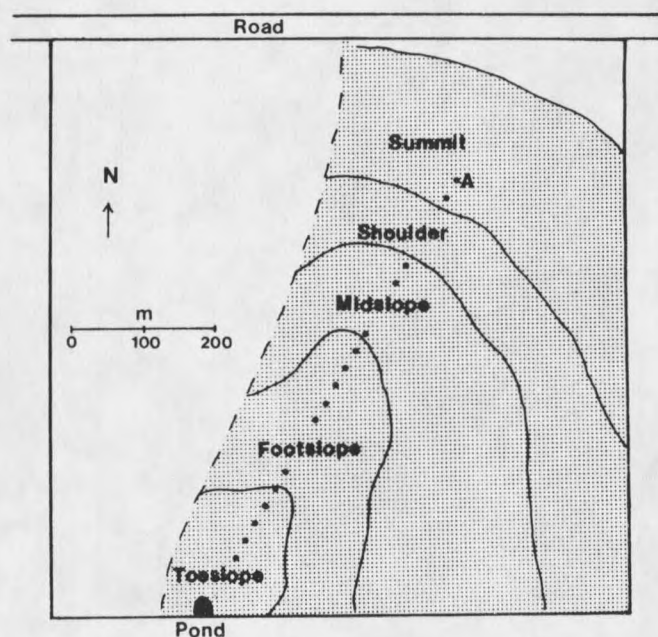


Figure 4. Watershed.

The pond at the bottom of the watershed was also sampled in September 1982. The pond was created with a dam before radioactive fallout began around 1954. The dam was partially breached in 1965, but still functions as an active sediment trap. The pond, transect layout, and sampling locations are shown on Figure 5. Sampling depths were partly based on results from preliminary sampling in June 1982. The preliminary samples showed that most of the cesium was within the first 12 cm at the edges of the pond while the ^{137}Cs profile was deeper than 20 cm nearer to the middle of the pond. Sampling depth varied from 20 to 75 cm according to locations within the pond and estimated depth of sediment. The pond was almost dry at the time of sampling in September 1982. A total of 63 samples were taken from the pond from 24 locations. Each sample was a composite of five cores with few exceptions (refer to Table 18 in Appendix for depth intervals and number of subsamples).

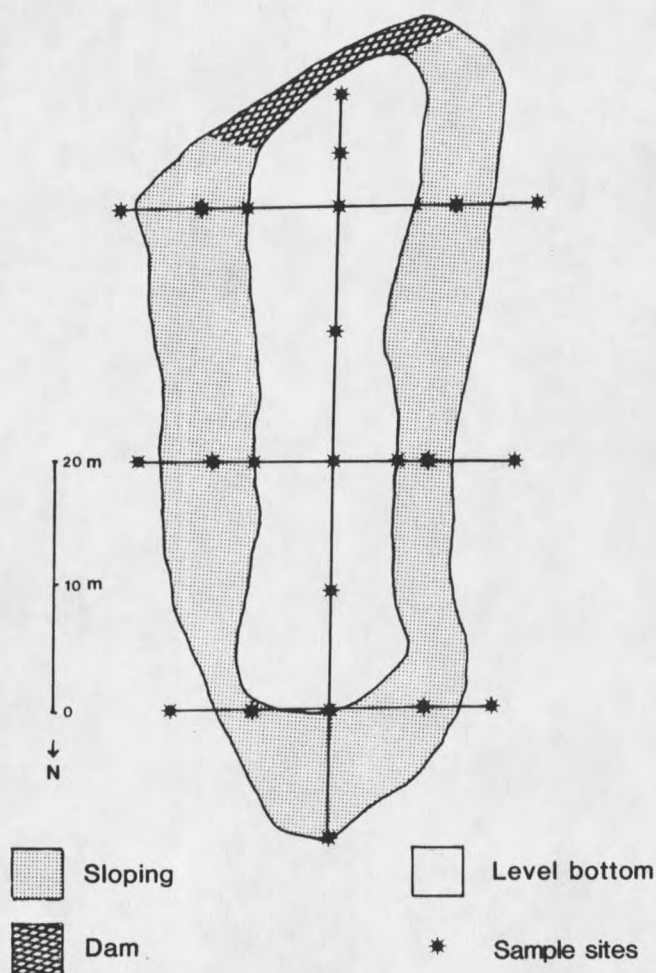


Figure 5. The pond at the outlet of the watershed.

Other Sampling

To obtain an estimate of variation of ^{137}Cs activity, individual soil cores were sampled both from a plowed field in Bozeman (Montana State University, Arthur H. Post Field Research Laboratory) and from a preserved native range site close to Belgrade. The plowed field has been used for wheat trials. Six individual cores were taken from the plowlayer (0-15 cm). The samples from the native range site were taken from two depth intervals, 0-15 cm and 15-30 cm, five samples from each interval. The results from the Belgrade site are also included with the reference sites.

At the Northern Plains Research Center at Sidney, Montana, soil was removed from the top of a field to study the effect of erosion on productivity. This study is being conducted by the ARS/USDA personnel at the Research Center at Sidney. The Ap horizon before soil removal was 12.7 cm thick, and the plots were tilled several times to the same depth after the soil was removed. In order to correlate cesium activity with known soil loss, eight samples from this site were analyzed for ^{137}Cs . Samples were taken from the surface down to 7.5 cm depth; three cores were composited for each sample. The diameter of the steel tube was 7.62 cm. The soils are Typic Argiborolls. The sampling scheme is summarized in Table 3.

Table 3. Treatment of Soils at Sidney Prior to Sampling for ^{137}Cs Determination.

Amount of Soil Removed	Field in 1982
none	fallow
none	cropland
6 cm	fallow
6 cm	cropland
12 cm	fallow
12 cm	cropland
18 cm	fallow
18 cm	cropland

Analysis of Samples and Units Used to Report ^{137}Cs Activity

All samples were oven dried at 40-50 C and weighed. The soils were ground and sieved through a 2 mm screen. A representative proportion of each sample was placed into a petri dish of known weight, and the weight of the sample in the dish was determined. Each petri dish was carefully sealed with electrical tape and packaged for shipment.

The samples were analyzed for ^{137}Cs at the Oak Ridge National Laboratory with a Canberra lithium drifted germanium (Ge(Li)) gamma ray detector. The detector was coupled with a Nuclear Data 6620 multi-channel analyzer system. Data were reduced using

Nuclear Data software, modified by Cutshall and Larsen (1980). Counting time was 100 minutes. The method of analysis has been described in greater detail by Larsen and Cutshall (1981). The total number of samples analyzed was 188.

Results of analyses were reported as ^{137}Cs activity per gram of soil. The unit of radioactivity was pCi (picocurie). A curie is a measure of radioactivity in terms of rate of atomic disintegrations. One curie is 3.7×10^{10} disintegrations per second. A picocurie is 10^{-12} curies. Error due to counting is dependent on magnitude of cesium activity. Values with more than 50% counting error were considered insignificant. Samples with high counting deviation contained only a small portion of total ^{137}Cs activity for each site. Areal activity of ^{137}Cs was determined for each sampling site in pCi cm^{-2} . This was done by multiplying the dry weight of each sample (g) by cesium activity of the sample (pCi g^{-1}) to obtain total activity (pCi) for each sampling interval. The total activity divided by the area of the sampling tube times the number of cores (cm^2) results in areal activity for each sampling interval (pCi cm^{-2}). Adding up for all intervals results in areal activity for each sampling site (pCi cm^{-2}). It is assumed that sampling at all sampling sites included all ^{137}Cs found within each profile and no radiocesium is below the deepest sampling increment at each site (unless otherwise stated).

CHAPTER 4

RESULTS

Radiocesium in Montana SoilsReference Sites

Radiocesium, as found at various locations and depths in selected soils in Montana is presented in Table 4.

Table 4. ^{137}Cs in Montana Soils.

cm	Sidney A %	Fallon A %	Musselshell A %	Lolo Pass A %	Hubbart A %	Browning A %	Beartooth A %
0-10	0.87 100.	0.59 100.	0.92 80.7	5.41 85.2	1.04 93.7	1.29 42.7	2.23 95.2
10-20	ns	ns	0.19 19.3	0.40 8.5	0.09 6.3	0.37 22.8	0.11 4.8
20-30	ns	ns		0.17 6.3	ns	0.19 15.2	
30-40		ns				0.22 19.3	

cm	Bozeman A %	cm	Whitehall A %	cm	Kings Hill A %	cm	Belgrade A %
0-3	0.51 17.4	0-3	2.80 62.0	0-7.5	1.72 95.5	0-155	0.56 100.
3-6	0.87 29.6	3-6	0.70 24.8	7.5-15.0	0.05 4.5	15-30	ns
6-9	0.55 20.1	6-10	0.29 13.1	15.0-22.5	ns		
9-12	0.38 14.0	10-20	ns				
12-15	0.22 8.7	20-30	ns				
15-20	0.14 9.5	30-40	ns				
20-30	ns						
30-40	ns						

A = ^{137}Cs activity on a weight basis (pCi g^{-1}).

% = Portion (%) of ^{137}Cs activity (pCi) found within profile.

ns = nonsignificant counting.

The left column for each site reports ^{137}Cs activity in pCi g^{-1} . The right column shows % of total ^{137}Cs activity of each site.

The average activity per unit area (all increments added up) is given for each reference site in Table 5. The mean activity for all of the sites is 10.3 pCi cm^{-2} .

Table 5. Total ^{137}Cs Activity at Reference Locations.

Location	Activity pCi cm^{-2}
Sidney	7.2
Fallon	5.2
Musselshell	9.5
Lolo Pass	20.2
Hubbart	9.5
Browning	14.8
Beartooth	16.8
Kings Hill	10.3
Whitehall	3.6
Belgrade	7.1
Bozeman	8.9

Variation in Areal Activity

Individual cores (0-15 cm) were sampled from a plowed field (Post Field Research Laboratory) and preserved range site (Belgrade) to obtain estimates of local variability in cesium levels. Results are shown in Table 6, both as pCi g^{-1} and pCi cm^{-2} . None of the samples from 15-30 cm interval in Belgrade showed significant levels of ^{137}Cs .

Table 6. Sampling Variation in ^{137}Cs at Post Field Research Laboratory and at Belgrade Range Site.

	Post Field Res. Lab.		Range Site	
	pCi g^{-1}	pCi cm^{-2}	pCi g^{-1}	pCi cm^{-2}
	0.21	2.9	0.78	9.9
	0.28	4.4	0.30	3.6
	0.26	4.6	0.56	7.3
	0.22	3.4	0.56	6.7
	0.31	5.0	0.60	7.9
	0.29	3.9		
$\bar{x}$:	0.26	4.03	0.56	7.08
SD:	0.04	0.79	0.17	2.29

Erosion Studies

Experimental Plots at Sidney

Table 7 reveals the results of sampling the experimental plots at Sidney.

Table 7. ^{137}Cs in Experimental Plots in Sidney From Which Soil Had Previously Been Removed.

Soil Removed cm	Use in 1982	^{137}Cs Mean for Treatment	
		pCi g ⁻¹	
0	fallow	0.50	0.54
0	crop	0.58	
6	fallow	0.49	0.45
6	crop	0.42	
12	fallow	0.18	0.14
12	crop	0.10	
18	fallow	ns	
18	crop	ns	

ns = nonsignificant count.

Wind Erosion Study

Results from the field where erosion had occurred are shown in Figure 6. Each value represents eight subsamples obtained from a 120 m transect. The depth of sampling was 0-26 cm. The two samples acquired below the 26 cm depth did not show any significant ^{137}Cs activity. The scale of the figure is in meters. The prevalent winds are from west to east. The mean activity for the eroded field was 3.8 pCi cm⁻², with standard deviation of 0.87 pCi cm⁻².

Some of the soil lost from the field shown in Figure 6 was assumed to be deposited on an adjacent field to the east (right in Figure 6) where the blowing soil was stopped by tree windbreaks. Results of sampling the downwind field are shown in Figure 7.

The columns represent ^{137}Cs activity as pCi cm⁻² and the columns give approximate locations of each transect as related to the fence and windbreaks. The distance from the fence or tree windbreak to each transect is 12 m, except for one transect, Cs activity values

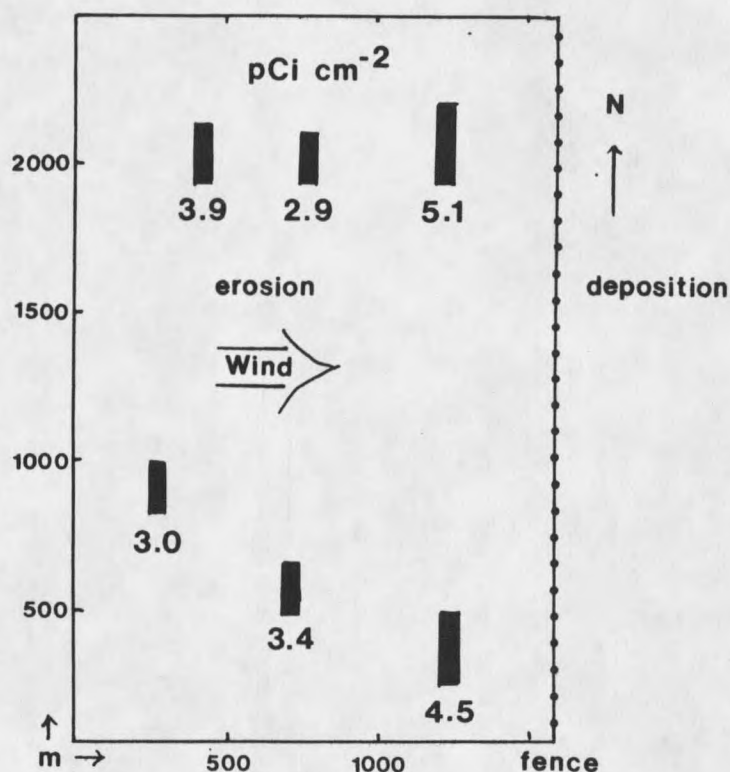


Figure 6. ^{137}Cs activity within wind eroded field.

can be divided into two groups, values obtained from the leeward sides of the fence and windbreaks and values obtained from the windward sides (refer to Figure 7). The mean for each group is given in Table 8 together with standard deviations. The difference between the means is significant at the 95% level (using students t-test).

Watershed Study

The watershed was divided into five sections as explained in the Materials and Methods chapter. The activity for each class is given in Table 9 with means and standard deviations.

The toeslope had the highest activity for ^{137}Cs (7.3 pCi cm $^{-2}$) whereas the lowest mean activity was at the midslope (3.8 pCi cm $^{-2}$). The footslope, shoulder and summit reflected medium levels of ^{137}Cs . A series of t-tests were made to compare the means for topographic positions within the field. A table revealing significant differences between

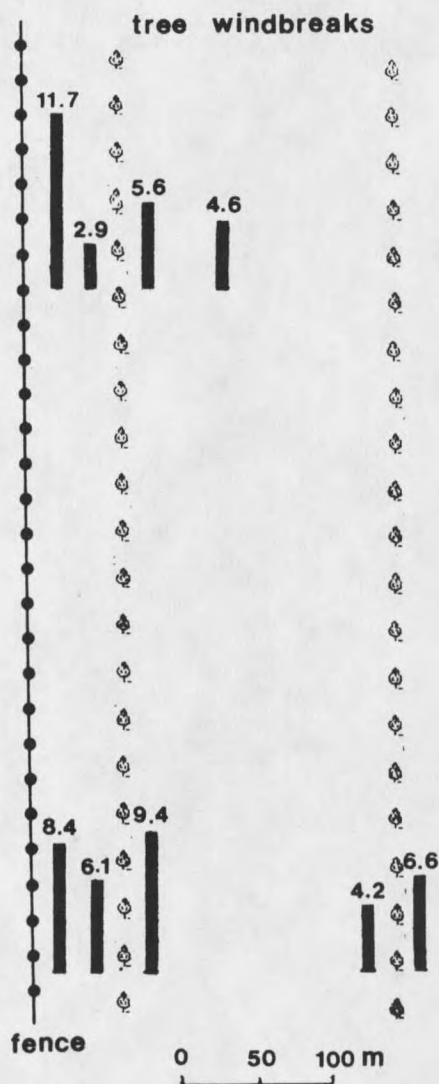


Figure 7. ^{137}Cs activity within the field of deposition (pCi cm $^{-1}$).

sections is given below. Since the sample variances differed greatly, a t-test for independent samples with unequal variances was used (Snedecor and Cochran, 1980; pp. 96-98). Other differences were not significant perhaps because of high variation at the shoulder and summit.

In order to show a possible soil deposition resulting in the presence of ^{137}Cs below the plowlayer, cesium activity from the 15-30 cm interval is listed in Table 11. Most ^{137}Cs

Table 8. ^{137}Cs at Windward Sites and Leeward Sites Within the Same Field (pCi cm^{-2}).

	Leeward Sides	Windward Sides
	11.7	2.9
	8.4	6.1
	5.6	4.6
	9.4	4.2
	6.6	
mean	8.3	4.4
SD	2.4	1.3

Table 9. Areal ^{137}Cs Activity as a Function of Location Within the Watershed (pCi cm^{-2}).

	Toeslope	Footslope	Midslope	Shoulder	Summit
	7.1	5.6	3.1	2.9	5.0
	7.1	4.9	3.4	2.4	6.8
	9.5	5.0	3.7	6.9	2.4
	5.1	5.9	5.2	7.8	7.5
	6.3	5.6	4.0	5.6	
	8.6				
mean	7.3	5.4	3.8	5.1	5.4
SD	1.6	0.4	0.9	2.4	2.3

Table 10. Significant Differences in ^{137}Cs Levels Within the Watershed.

Comparison	Significance
toeslope vs footslope	95%
toeslope vs midslope	99%
footslope vs midslope	98%

Table 11. ^{137}Cs Activity in the 15-30 cm Soil Depth as a Function of Location (pCi cm^{-2}).

	Toeslope	Footslope	Midslope	Shoulder	Summit
mean	2.2	1.3	0.8	1.2	1.1
SD	0.7	0.6	0.7	1.1	1.0

within the 15-30 cm interval is found at the toeslope, while the least is found at the mid-slope which is analogous to the results given in Table 9.

The pond was divided into four areas based on radiocesium input as shown in Figure 8. The areal cesium activity together with the area of each category are also given.

Area	Activity pCi cm ⁻²	Size m ²
A	21.6	58
B	13.0	923
C	7.5	627
D	14.7	253

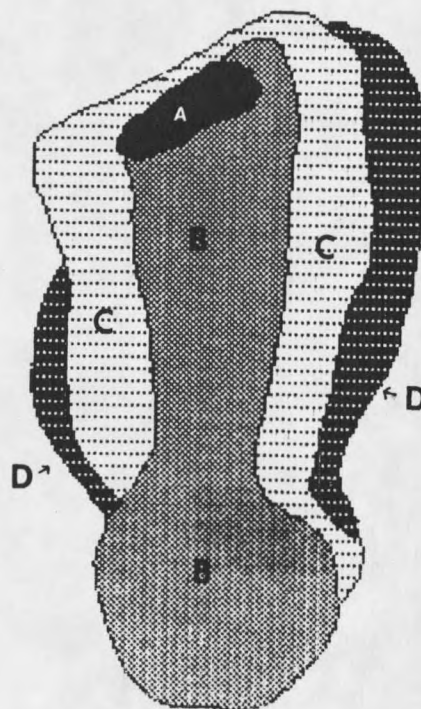


Figure 8. ¹³⁷Cs activity in pond sediments.

Area A represents the relatively small deepest part of the pond, closest to the dam. This part had the highest concentration of cesium. Area B represents the bottom of the pond excluding area A, together with the transition from the pond to the field. The slopes of the pond have lower values of radiocesium (area C), but the edges have considerable (14.7 pCi cm⁻²) ¹³⁷Cs activity.

CHAPTER 5

DISCUSSION

Radiocesium in Montana SoilsAreal Variation

Radiocesium levels from worldwide fallout have been related to several factors such as latitude, hemisphere and rainfall (Whicker and Schultz, 1982). Fallout levels within the same area can be expected to have strong relationship with annual precipitation (Mishra and Sadasivan, 1972). In the present study regression analysis of the relationship between precipitation and cesium activity at all the sites resulted in R^2 of 0.54 with confidence level of 85%. Cesium activity was not significantly correlated with elevation. Two of the sites, Browning and Whitehall, show considerable variation from expected activity. When these two sites are omitted from the regression analysis, R^2 becomes 0.91 (confidence level 99.9%). Omitting these same sites resulted in $R^2 = 0.53$ with elevation.

Radioactive fallout has been monitored in Helena (Montana) and Williston (North Dakota, close to the Montana state line). These data were summarized for ^{137}Cs by DeJong et al. (1982). The cesium input was 6.1 pCi cm^{-2} at Williston and 6.5 pCi cm^{-2} at Helena during 1959 to 1976. Assuming the same rate of ^{137}Cs fallout since 1966, the addition from 1977 through 1981 can be estimated from the fallout during the ten previous years. This results in a total activity of 6.6 pCi cm^{-2} at Williston and 6.9 pCi cm^{-2} at Helena. Using these data with the ^{137}Cs activity at the reference sites (the Whitehall and Browning sites are excluded) and precipitation data results in $R^2 = 0.92$ between cesium activity and annual rainfall.

The correlation between precipitation and cesium levels indicates that ^{137}Cs activity can be predicted on the basis of annual rainfall. Cesium fallout and precipitation is plotted in Figure 9. The regression line omits the Whitehall and Browning data ($R^2 = 0.92$) and the equation is

$$^{137}\text{Cs activity} = 3.566 + 0.01055 \times \text{precipitation}$$

where cesium activity is reported in pCi cm^{-2} and mean annual precipitation is in mm.

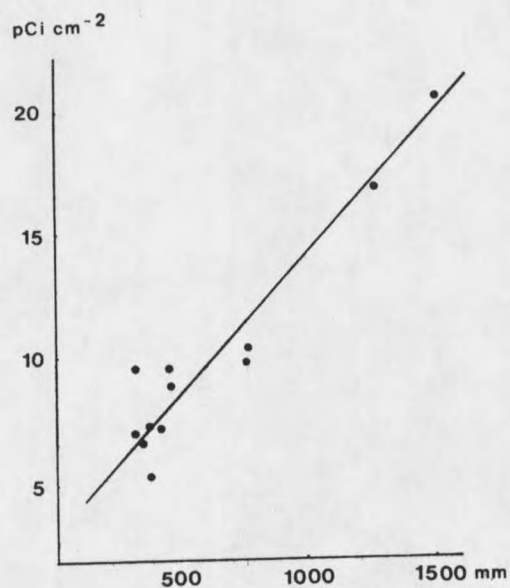


Figure 9. ^{137}Cs activity versus precipitation.

As can be seen in the graph above, most data points are clustered between 5 and 10 pCi cm^{-2} . Further sampling would establish a more dependable relationship. This equation should be considered a first approximation for Montana.

To show the difference between measured cesium activity and predicted activity using the equation, both values and the variation from the predicted value are given in Table 12. The precipitation values are drawn from a map that shows average annual precipitation (USDA-SCS, 1977). The values are not precise and local variations in precipitation can affect the ^{137}Cs fallout considerably.

Table 12. Measured and Predicted Areal Activity of Cesium.

Location	Measured Activity	Predicted Activity	Difference
Sidney	7.2	7.4	2.7
Fallon	5.2	7.4	29.7
Musselshell	9.5	6.8	39.7
Lolo Pass	20.2	19.6	3.1
Hubbart	9.5	8.1	17.3
Beartooth	16.8	17.0	1.2
Kings Hill	10.3	11.6	11.2
Belgrade	7.1	7.9	10.1
Bozeman	8.9	8.7	2.3
Helena	6.9	6.8	1.5
Williston	6.6	7.0	5.7
(Browning	14.8	8.4	76.2)
(Whitehall	3.6	11.6	70.0)

The explanation for low measured value at the Whitehall site is probably due to runoff. The soils are organic (Borosapristis) and are waterlogged for extended periods of the year. Some of the rainwater could be carried away with runoff before the ^{137}Cs equilibrates with soil particles.

The most likely explanation for high activity in the Browning samples is animal disturbance. Evidence of pocket gophers was extensive at the site. Although an attempt was made to avoid such disturbances, some of the cores from subsurface intervals may have contained displaced surface soil resulting in relatively high activity. This possibility is supported by the presence of ^{137}Cs in the lower sampling intervals which was by far the highest at the Browning site as will be discussed later.

The samples from Fallon had lower ^{137}Cs activity than expected. Some soil could have been lost because of erosion from this extensive but lightly grazed range area. Disturbances by animals cannot be ruled out as a possible explanation. Relatively high ^{137}Cs activity at the Musselshell and Hubbart sites could be attributed to additions caused by wind erosion in cultivated areas nearby.

Analysis of five individual cores from the Belgrade site showed considerable variation (standard deviation of 2.3). Half of the variation was due to one sample, which lowered the mean from 7.9, which is also the predicted value in Table 12, to 7.1 pCi cm⁻². That sample may have been affected by animal activity. The Belgrade samples show that considerable local variation can be expected at undisturbed native sampling sites. A composite of five samples at the Belgrade site would not have overcome the differences between individual cores caused by local variation.

Depth Variation

All the detected ¹³⁷Cs was found within the first sampling interval at three sites: Sidney, Fallon, and Belgrade. More than 90% of the radiocesium was confined to the first sampling interval at seven sites. At two sites, Browning and Bozeman, less than 80% of ¹³⁷Cs activity was confined to the first 10 cm. Cesium distribution within the profiles is shown on Figure 10.

Burrowing animals at the Browning site probably cause the deep incorporation of cesium. This was the only site where ¹³⁷Cs occurred below the 30 cm depth. The presence of radiocesium so deep within the profile supports the likelihood of physical disturbance at the site.

Although the total activity at the Bozeman site was within 2.3% of the predicted value, only 67.1% of the ¹³⁷Cs was confined to the top 9 cm. Animal disturbances are a possible explanation, but some of this deviation may be caused by students, who come to the site for an introductory soils class twice a year. Uncontaminated subsoil material from the bottom of a soil pit may have been deposited on the surface of the soil.

The soil at Lolo Pass had 85.2% of the ¹³⁷Cs activity confined to the first interval (0-10 cm) but showed some cesium activity down to the 20-30 cm increment. This site has the highest precipitation of all the reference sites and highest areal ¹³⁷Cs activity. A pos-

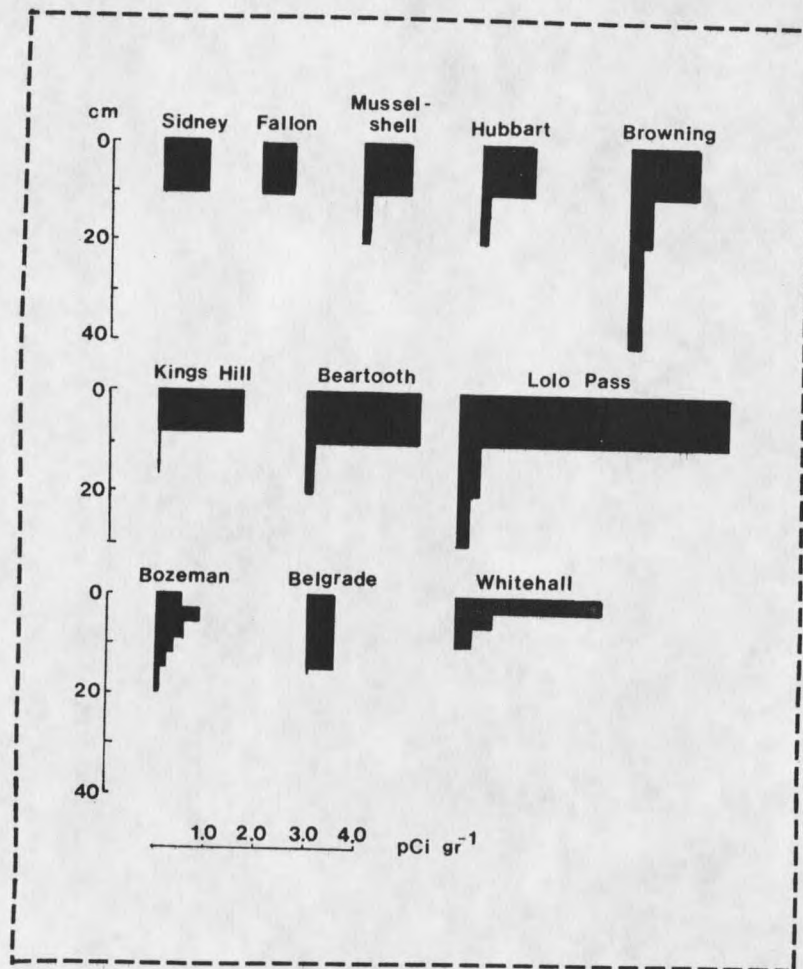


Figure 10. Cesium distribution in soil profiles.

sible explanation for the downward movement is leaching. Mishra and Sadasivan (1972) reported more downward displacement of cesium at stations in India receiving the most precipitation. Animal disturbance is also possible. High activity within the 10-20 cm interval at the Musselshell site is likely caused by animal disturbance. There are several processes in addition to those already mentioned that could affect the depth of ^{137}Cs penetration, such as freezing and thawing, wetting and drying, and soil clay activity causing cracking and mixing of surface soils into the cracks. Nevertheless, most of the presented data concur with the findings of numerous other researchers, that ^{137}Cs is mostly confined to the top

of the soil profile and mechanical movement of soil particles is mainly responsible for displacement of ^{137}Cs vertically and laterally.

Erosion Studies

Experimental Plots at Sidney

An estimate of soil loss from the plots can be made by using the ratio of ^{137}Cs activity where soil has not been excavated, versus ^{137}Cs activity in the soil removal plots. All of the cesium is assumed to be within the 12.7 cm thick plowlayer as has been postulated for cultivated fields (Ritchie et al., 1975). This assumption is supported by the results from the Post Field Research Lab., where six individual cores showed the mean of 0.26 pCi g^{-1} with standard deviation of 0.04 pCi g^{-1} . The relatively low variation suggests thorough homogenization of ^{137}Cs within the cultivated layer. The ratio between cesium activity in control plots and activity in excavated plots can be used to estimate soil loss. An example is the calculation for the 6 cm soil removal plot, which had a cesium activity of 0.45 pCi g^{-1} . The reference value at the control plots was 0.54 pCi g^{-1} ; and $0.45/0.54 \times 12.7 = 10.6$ cm. Subtracting 10.6 from 12.7 results in a calculated soil loss of 2.1 cm. Soil removed is compared with calculated figures in Table 13. The cesium activity where 6 cm of soil had been removed was considerably higher than expected and the estimate of soil loss is low. Less difference occurred in the 12 cm soil removal plots. Cesium was not detected in the plot where 18 cm soil had been removed. Based on cesium, it can only be concluded that at least the plowlayer (> 12.7 cm) has been removed. A possible explanation for the large difference at the plot where 6 cm of soil had been removed is insufficient mixing of subsoil into the new plowlayer after soil was removed. The sampling depth was 7.6 cm on all plots and the upper part of the tillage layer (12.7 cm) could have contained relatively higher concentrations of ^{137}Cs than the lower part. The plots had been tilled two to five times after soil removal. This indicates that considerable plowing has to take place before thor-

ough mixing of ^{137}Cs is attained. However, the degree of mixing depends on the plowing equipment. Some types of equipment invert the plow layer, whereas other types stir the plowlayer without bringing up much subsoil. The equipment used for the plots at Sidney did mix rather than invert soil.

Table 13. Soil Removed Compared With Estimated Values.

Soil Removed (cm)	^{137}Cs Based Estimate (cm)
0	0
6	2.1
12	9.4
18	> 12.7

Methods of Calculating Erosion and Deposition

Estimates of soil erosion and deposition using ^{137}Cs levels are made by comparing current ^{137}Cs activity with estimated ^{137}Cs input. The calculations are based on several assumptions some of which have been discussed by Brown et al. (1986b) and DeJong et al. (1983).

1. ^{137}Cs levels have been stable since 1964. Since 1964, the fallout of cesium has been about equal to ^{137}Cs loss because of decay, resulting in relatively stable levels (Figure 11).
2. ^{137}Cs has been mixed uniformly into the plowlayer and is tightly adsorbed by soil particles. These assumptions were discussed in the Literature Review chapter and in the preceding section.
3. Most of the cesium was incorporated into the plowlayer without severe losses prior to 1964. Most of the worldwide fallout entered the surface from 1962 through 1964 (Figure 11). The initial concentration of ^{137}Cs at the surface is therefore high until cesium is mixed into the plowlayer with repeated plowing. Subsequently, the amount of ^{137}Cs mixed into the plowlayer is greatly reduced

if erosion was active between 1962 and 1964 (DeJong et al., 1983). A loss of ^{137}Cs due to erosion prior to 1964 is at least partly compensated by input from wind erosion in the surrounding area. Such wind deposits might explain the high cesium activity at some of the reference sites in this study.

4. The rate of erosion has been rather even on a yearly basis.

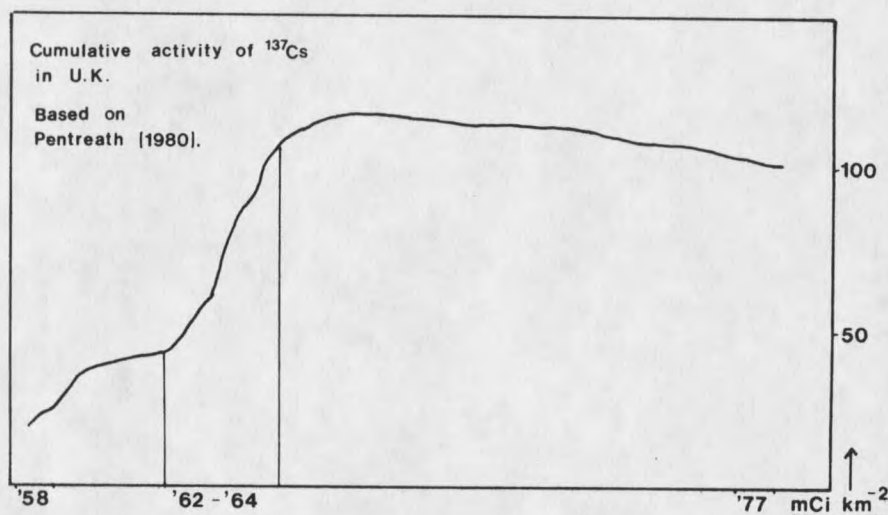


Figure 11. Cumulative activity of ^{137}Cs .

Erosion causes dilution of ^{137}Cs activity within the plowlayer, because subsoil materials low in ^{137}Cs are incorporated into the new plowlayer with plowing after erosional events. If plowing depth is constant and soil is lost from the top, subsoil with little or no cesium will be mixed into the plowlayer with the next plowing. The first erosion events will cause relatively more dilution than later events when the soils have already been diluted. Assuming constant rate of erosion, the rate of change in the ^{137}Cs concentration in the soils per year is dC/dt where C is the ^{137}Cs activity and t is time in years and

$$dC/dt = bC$$

where b is a proportionality factor. Integration of this equation gives

$$\ln C = bt + \ln C_0$$

where C_0 is the concentration at $t = 0$ or the activity of ^{137}Cs before erosion has occurred. A similar equation to describe rate of change in eroded material was derived by Avnimelech and McHenry (1984). Conversion of the equation gives

$$C/C_0 = e^{bt}$$

where b has a negative value, C is the current ^{137}Cs activity, C_0 is the initial activity before erosion occurs, and t is time in years. If the assumptions given earlier hold, the equation describes the reduction in cesium levels after the peak in 1964 (Figure 11) has been reached. The equation should be considered to be an approximation.

The equation represents a curve that becomes a straight line if plotted on semilogarithmic graph paper. The initial input (beginning of curve in 1964) and current reading (1982) allow the determination of the slope of the line and calculation of b . For this example t is 18 years, C is the current areal activity (pCi cm^{-2}) while C_0 is the areal input of cesium. If b is known, C can be calculated for any selected value of t . The difference between C and C_0 at $t = 1$ serves as an estimate of reduction in cesium activity for the first year if no dilution takes place. Multiplying this difference by 18 gives reduction in cesium activity caused by erosion if no dilution because of plowing occurs. An example of the calculations described above is presented in Appendix B.

Erosion can then be calculated by the equation

$$\text{Soil loss (cm)} = (dC/C_0) \times d \text{ (cm)}.$$

The d in the equation is the depth of the plowlayer, dC is reduction in cesium activity if dilution is considered (pCi cm^{-2}) and C_0 is the initial activity before erosion occurs or estimated areal input (pCi cm^{-2}). A 20 year period between 1962 and 1982 was chosen to assess erosion rates. The period from 1954 to 1962 was ignored, but during that time ^{137}Cs levels were low and cesium activity after 1964 was therefore little affected by erosion during this period. Calculations for the experimental plots at Sidney were made by a different method as described earlier.

Calculating soil deposition can either be based on the increase in total ^{137}Cs activity from estimated input, or from measured activity below the plowlayer. The depth of the plowlayer is dependent upon whether the steel tube is inserted on high or low positions of the plowed surface and is subject to local variation of the plow depth. In short, it is difficult to sample the plowlayer precisely. However, sampling of the plowlayer is subjected to less error in cesium activity than sampling below the plowlayer. The increase in total areal ^{137}Cs activity was chosen to calculate soil deposition. Accumulation of ^{137}Cs from snowdrifts in deposition areas was not considered. Such deposition would increase the ^{137}Cs input. Snow accumulation is not believed to affect results from the watershed, but may affect results from the wind erosion study. The increase in areal ^{137}Cs activity caused by soil deposition was used to estimate amount of soil gain. The method can be described by this equation

$$\text{Deposition (cm)} = (dC/CI) \times d \text{ (cm)}$$

where dC is the increase in ^{137}Cs activity (pCi cm^{-2}), d is the depth of the present plowlayer and CI is the reference value. Estimated input (Co) was used as CI to calculate minimum deposition (dilution of materials deposited not considered). The current activity within the present plowlayer is lower than initial activity because of dilution of cesium activity in the deposited materials. The current activity within the present plowlayer was used to calculate maximum deposition.

Undisturbed native sites, adjacent to the field being studied have been used to estimate reference ^{137}Cs activity (DeJong et al., 1983; McCallan et al., 1980). Undisturbed locations in intensively farmed areas are subjected to soil deposition from surrounding cultivated fields because of wind erosion. Individual cores from the preserved range site at Belgrade showed high variation indicating difficulties in gaining dependable results for such sites unless they are sampled very intensively. Since radiocesium levels are closely related

to precipitation, annual precipitation data were used to estimate ^{137}Cs fallout at the wind erosion study site and at the watershed in Teton County.

If there are no additional nuclear explosions that contaminate the atmosphere, ^{137}Cs levels in the soil will eventually decrease due to radioactive decay. Soil erosion measurements by this method will become more difficult because of reduced levels, mixing of cesium with material from subsurface horizons and complications caused by erosion and deposition.

Wind Erosion Study

The mean annual precipitation for the site is approximately 290 mm, based on climatological data from Brady (U.S. Dept. of Commerce, 1965) and annual precipitation map (USDA-SCS, 1977). The method presented earlier in this chapter was used to calculate ^{137}Cs fallout activity of 6.6 pCi cm^{-2} . The value was reduced by 5% to account for cesium removal by crop and snowdrift as described by DeJong et al. (1983) so the reference value is 6.3 pCi cm^{-2} .

The mean ^{137}Cs activity of the eroded field was 3.8 pCi cm^{-2} with a standard deviation of 0.87 pCi cm^{-2} . The deviation suggests non-uniform redistribution and losses of cesium by erosion. The method described earlier to calculate erosion resulted in an estimated 7.4 cm loss or $740 \text{ m}^3 \text{ ha}^{-1}$.

The average bulk density of the soil samples was 0.94 Mg m^{-3} , based on the volume of the sampling tube and dry weight of the samples. Soil loss of $740 \text{ m}^3 \text{ ha}^{-1}$ equals 697 Mg ha^{-1} . Averaging this value over 20 years results in an erosion rate of $34.8 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. These calculations are not based on extensive sampling but give an indication of soil loss that the field has experienced due to erosion by wind and water since fallout from nuclear testing started.

Applying the same method (not accounting for dilution) to the field where soil had been deposited results in 4.8 cm average soil gain at the leeward sides of the fence and tree windbreaks, while an average 4.5 cm ($450 \text{ m}^3 \text{ ha}^{-1}$) of soil had been lost from the windward sides. The accumulation at the windward sides ranged from 0.7 cm to 12.9 cm or 70 to $1290 \text{ m}^3 \text{ ha}^{-1}$. The soil deposition does not account for all the soil lost from the eroded field. This indicates that wind erosion removed some soil from the field in spite of the tree windbreaks. A soil loss of 8 cm occurred at one windward side transect where severe water erosion was the likely explanation. The results suggest that wind erosion and subsequent deposition can be quantified using radiocesium.

Watershed Study

An undisturbed range site was not found near the watershed being studied. Radiocesium input was estimated on the basis of precipitation. The mean annual precipitation was about 320 mm according to annual precipitation figures for Power, Montana (U.S. Dept. of Commerce, 1965). The site is located on the southern fringe of the Teton Ridge. The calculated ^{137}Cs activity is 6.9 pCi cm^{-2} and subtracting 5% due to crop and snow removal leaves 6.6 pCi cm^{-2} as reference activity.

Erosion at the field was estimated quantitatively by considering dilution in ^{137}Cs activity with repeated erosion as described earlier. The plowlayer remained close to 15 cm deep throughout the period being considered. At some of the sites, which had low areal ^{137}Cs activity (erosion sites), cesium was found below the present plowlayer. This was because of local variations in plow depth where the plowlayer was locally deeper than 15 cm and some soil having high ^{137}Cs activity was included with the 15-30 cm sample. Deposition at the toeslope was calculated based on increase in areal activity of ^{137}Cs . Estimated ^{137}Cs input (6.6 pCi cm^{-2}) was used to calculate minimum deposition whereas current activity within the plowlayer (5.1 pCi cm^{-2}) was used to compute maximum

deposition. The average of calculated maximum and minimum deposition was used as an estimate of soil deposition at the toeslope. The results are tabulated in Table 14. The mid-slope lost about 8.2 cm of soil since approximately 1964, while the toeslope gained 1.8 cm. The footslope and summit have lost 3.0 cm and the shoulder 3.8 cm. Soil loss or gain in $\text{m}^3 \text{ ha}^{-1}$ is given in the next column of Table 14. Multiplying the size of each part of the watershed by soil loss or gain per hectare gives the amount of soil lost or gained at each area during approximately a 20 year period. A relatively small fraction of the soils lost from the upper areas of the watershed are deposited at the toeslope or remain deposited there. Most of the losses were apparently due to wind erosion that carried soil out of the field. Table 15 lists soil deposition in the pond calculated the same way as for the toeslope (6.6 pCi cm^{-2} as a reference). The calculations of soil deposition within the pond did not account for dilution of ^{137}Cs levels within the watershed. This factor would have increased the estimate of soil deposition. Sorting of soil particles that results in deposition of fine materials in the pond with high ^{137}Cs activity was also not considered. This factor would have decreased the estimate of soil deposition in the pond. Apparently only a very small amount of soil lost from the watershed was deposited into the pond. The reason is either that the pond did not trap sediment effectively after it was breached (in 1965) or relatively little soil was carried with water into the pond. Wind erosion may be responsible for most of the soil loss within the watershed. It is also possible that soils that are lost from the upper part of the watershed because of water erosion were deposited at the toeslopes, but active wind erosion at the toeslope resulted in less soil accumulation there than expected.

Grouping the cesium activity values according to steepness of slopes did not show clear trends as can be seen in Table 16. The steepest slopes were mostly close to the top of the field while the 4-6% slopes were mostly confined to the midslopes. Length of slopes or position within the field was more important to erosion than steepness alone. If wind

erosion causes more soil loss than water erosion in the field, steepness of slope would have less influence on erosion and ^{137}Cs activity.

Table 14. Soil Erosion and Deposition Within the Watershed.

Topographic Position	Area ha	cm	Soil Loss/Gain $\text{m}^3 \text{ha}^{-1}$	Total m^3
Toeslope	2.8	+1.8	+180	+504
Footslope	5.9	-3.0	-300	-1770
Midslope	11.8	-8.2	-820	-9676
Shoulder	8.3	-3.8	-380	-3154
Summit	10.5	-3.0	-300	-3150

Table 15. Soil Deposition in the Pond.

Area	Size m^2	cm	Deposition m^3
A	58	33.4	19.1
B	923	13.9	128.3
C	627	1.5	9.4
D	253	17.7	44.8
total deposition:			201.6 m^3

Table 16. Percent Slope Versus Mean Cesium Activity.

Slope (%)	Mean ^{137}Cs Activity (pCi cm^{-2})
0-1.5	6.2
2-3	6.0
4-6	4.2
7-10	5.8

The average bulk density of the field, based on dry weight of samples and volume of the sampling tube, is 1.1 Mg m^{-3} . Using this bulk density and averaging the erosion and deposition over 20 years, the rate of erosion in $\text{Mg ha}^{-1} \text{yr}^{-1}$ can be determined. The results are presented in Table 17.

Table 17. Erosion Rates at the Watershed.

	Erosion in $\text{Mg ha}^{-1} \text{ yr}^{-1}$	
	By ^{137}Cs	SCS Method
Summit	16.5	
Shoulder	20.9	27.6
Midslope	45.1	38.7
Footslope	16.5	16.4
Toeslope	+9.9	

Soil loss from the field was predicted with the methods used by the SCS in Montana. Both water erosion (USDA-SCS, 1978; Wischmeier and Smith, 1978) and wind erosion (USDA-SCS, 1981; Woodruff and Siddoway, 1965) were estimated. The field was divided into three areas for this purpose. The first area represented mostly the shoulder area, the next corresponded with the midslope position, and the last represented mostly the foot-slope. Table 17 lists calculated erosion and deposition using ^{137}Cs and erosion predicted by SCS. The erosion estimates obtained by using ^{137}Cs show only slight differences from the predictions by the SCS. Wind erosion was dominant for all areas by the SCS erosion estimate.

CHAPTER 6

CONCLUSIONS

Radiocesium as measured at various undisturbed sites in Montana ranged from 5.2 pCi cm⁻² to 20 pCi cm⁻². Areal ¹³⁷Cs activity was closely related to precipitation ($R^2 = 0.92$). However, two sites that showed considerable within-site variation were not included in the regression. This relationship can be used to predict ¹³⁷Cs levels in Montana.

At undisturbed sites, cesium was mostly confined to the first sampling interval (upper 10 cm) and showed limited movement within the profile. At other sites radiocesium within soil profiles was susceptible to physical disturbances such as erosion, deposition, faunal activity, and tillage.

Cesium was uniformly distributed within the plowlayer of thoroughly tilled fields. Mixing of ¹³⁷Cs is partly dependent upon type of tillage equipment used. Considerable variation in ¹³⁷Cs activity occurred between individual cores at range sites disturbed by animals such as pocket gophers.

Methods of using ¹³⁷Cs levels to calculate erosion and deposition are presented. At a wind erosion study site soil deposition of 70 to 1290 m³ ha⁻¹ was calculated for the leeward sides of a fence and tree windbreaks; 450 m³ ha⁻¹ were lost from the windward sides of the same field. An average of 740 m³ ha⁻¹ or 34.8 Mg ha⁻¹ yr⁻¹ was lost from an adjacent wind eroded field. The results indicate that deposition caused by wind erosion can be quantified and efficiency of windbreaks determined using ¹³⁷Cs.

The amount of soil lost from the upper areas of a watershed ranged from 300 to 820 m³ ha⁻¹ in about 20 years. The soil gain at the toeslope was 180 m³ ha⁻¹. A pond at the bottom of the watershed accounted only for 202 m³ deposition. A relatively small fraction

of the soil eroded from the upper areas was deposited again within the same watershed. Wind erosion is probably responsible for most of the soil loss. Length of slopes or position within the field were more related to erosion than was steepness alone. The ^{137}Cs estimates of erosion rates ranged from $16.5 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ at the summit and footslope of the watershed to $45.1 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ at the midslope. Predictions by conventional methods that included both a wind erosion equation and the Universal Soil Loss Equation (USLE) gave results similar to those based upon ^{137}Cs activity. The radiocesium method provides a different way of calculating soil erosion that can be compared with other methods. With further research and improved calculations, it may be possible to rely on ^{137}Cs for erosion measurements with less reliance on assumptions used in conventional methods for erosion estimates.

Soil erosion measurements by ^{137}Cs methods will become more difficult in the future because of reduced cesium radioactivity levels, mixing of cesium with material from subsurface horizons and complications caused by erosion and deposition.

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APPENDICES

APPENDIX A

APPENDIX A

Table 18. Cesium Activity in Soil Samples and At Each Site.

I.D. ¹	Depth cm	n	D.W. g	¹³⁷ Cs		B.D. Mg m ⁻³	¹³⁷ Cs		Total ¹³⁷ Cs at Site
				pCi g ⁻¹	Area cm ²		pCi	pCi cm ⁻²	
Browning	0-10	5	496.8	1.286	101.3	0.49	638.9	6.3	14.8
	10-20	5	929.3	0.367	101.3	0.92	341.1	3.4	
	20-30	5	1170.9	0.194	101.3	1.16	227.2	2.2	
	30-40	5	1325.4	0.218	101.3	1.31	288.9	2.9	
Beartooth	0-10	8	1166.2	2.230	162.1	0.72	2600.6	16.0	16.8
	10-20	3	446.7	0.106	60.8	0.73	47.4	0.8	
Lolo Pass	0-10	4	258.4	5.410	81.1	0.32	1397.9	17.2	20.2
	10-20	4	351.1	0.395	81.1	0.43	138.9	1.7	
	20-30	4	619.1	0.167	81.1	0.76	103.6	1.3	
Hubbart	0-10	4	695.3	1.039	81.1	0.86	722.4	8.9	9.5
	10-20	4	562.1	0.087	81.1	0.69	49.1	0.6	
	20-30	4	645.7	ns ⁴	81.1	0.80	0	0	
Sidney	0-10	5	833.1	0.870	101.3	0.82	725.1	7.2	7.2
	10-20	5	930.1	ns	101.3	0.92	0	0	
	20-30	5	1040.9	ns	101.3	1.03	0	0	
Fallon	0-10	8	1454.3	0.576	162.1	0.90	838.4	5.2	5.2
	10-20	8	1385.3	ns	162.1	0.85	0	0	
	20-30	8	1416.7	ns	162.1	0.87	0	0	
	30-40	8	1483.1	ns	162.1	0.91	0	0	
Musselshell	0-10	8	1350.0	0.922	162.1	0.83	1244.2	7.7	8.5
	10-20	8	1550.0	0.190	162.1	0.96	297.8	1.8	
Whitehall	0-3	* ²		2.80				2.3	3.6
	3-6	*		0.70				0.8	
	6-10	*		0.29				0.5	
	10-20	*		ns				0	
	20-30	*		ns				0	
	30-40	*		ns				0	
Bozeman	0-3	*	511.0	0.51	140.3	1.0	262.3	1.5	8.9
	3-6	*	548.0	0.87	182.7	1.0	479.4	2.6	
	6-9	*	504.5	0.55	152.9	1.1	280.1	1.8	
	9-12	*	452.4	0.38	137.1	1.1	170.0	1.3	
	12-15	*	412.0	0.22	116.9	1.2	90.7	0.8	
	15-20	*	987.9	0.14	164.6	1.2	138.0	0.9	
	20-30	*	797.4	ns	61.3	1.3	0	0	
	30-40	*	772.3	ns	55.1	1.4	0	0	

Table 18 (continued).

I.D.	Depth cm	n	D.W. g	¹³⁷ Cs	Area cm ²	B.D. Mg m ⁻³	¹³⁷ Cs	¹³⁷ Cs	Total ¹³⁷ Cs at Site
				pCi g ⁻¹			pCi	pCi cm ⁻²	
Kings Hill	0-75	*	970.5	1.72	170	0.76	1643.7	9.8	10.3
	7.5-15.0	*	1884.5	0.05	200	1.26	94.2	0.5	
	15.0-22.5	*	1952.8	ns	200	1.20	0	0	
Belgrade ⁵	0-15	1	259.1	0.776	20.3	0.85	200.9	9.9	Average 7.08
	0-15	1	239.9	0.300	20.3	0.79	72.0	3.6	
	0-15	1	264.1	0.558	20.3	0.87	147.5	7.3	
	0-15	1	242.9	0.558	20.3	0.80	135.5	6.7	
	0-15	1	265.7	0.599	20.3	0.87	159.1	7.9	
Post Ag. Farm	0-15	1	281.6	0.211	20.3	0.93	59.4	2.9	
	0-15	1	318.9	0.280	20.3	1.05	89.2	4.4	
	0-15	1	361.8	0.257	20.3	1.19	93.0	4.6	
	0-15	1	309.1	0.222	20.3	1.02	68.7	3.4	
	0-15	1	322.5	0.315	20.3	1.06	101.6	5.0	
	0-15	1	278.1	0.287	20.3	0.91	79.9	3.9	
Prepond 1	0-6	7	926.5	0.84	141.9	1.09	778.3	5.5	9.0
	6-12	7	852.1	0.48	141.9	1.00	409.0	2.9	
	12-20	7	1286.5	0.07	141.9	1.13	90.1	0.6	
Prepond 2	0-6	7	598.9	0.72	141.9	0.70	431.2	3.0	11.3
	6-12	7	785.1	0.65	141.9	0.92	510.3	3.6	
	12-20	7	1264.9	0.53	141.9	1.11	670.4	4.7	
Prefield - 1 (midslope)	0-15	4	1360.8	0.17	81.1	1.12	231.3	2.9	4.0
	15-25	4	1082.9	0.08	81.1	1.34	86.6	1.1	
Prefield - 2 (toeslope)	0-15	4	959.3	0.59	81.1	0.79	566.0	7.0	8.6
	15-25	4	992.6	0.13	81.1	1.22	129.0	1.6	
Wind er. ^{3,5}	0-26	8	3741.0	0.17	162.1	0.89	636.0	3.9	3.9
	0-26	8	4421.3	0.11	162.1	1.05	486.3	3.0	3.0
	0-26	8	3919.8	0.14	162.1	0.93	548.8	3.4	3.4
	0-26	8	3825.9	0.19	162.1	0.91	726.9	4.5	4.5
	0-26	8	3851.2	0.12	162.1	0.97	820.1	5.1	5.1
	0-26	8	4100.6	0.20	162.1	0.97	820.1	5.1	5.1
Wind acc. ^{3,5}	0-28	5	3390.5	0.25	101.3	1.19	847.6	8.4	8.4
	0-28	5	3893.0	0.16	101.3	1.37	622.9	6.1	6.1
	0-28	5	3828.2	0.25	101.3	1.35	957.0	9.4	9.4
	0-28	5	4215.5	0.10	101.3	1.49	421.5	4.2	4.2
	0-28	5	3920.3	0.17	101.3	1.38	666.5	6.6	6.6
	0-28	5	3387.0	0.35	101.3	1.19	1185.4	11.7	11.7
	0-28	5	3656.3	0.08	101.3	1.29	292.5	2.9	2.9
	0-28	5	3760.2	0.15	101.3	1.33	564.0	5.6	5.6
	0-28	5	3896.0	0.12	101.3	1.37	467.5	4.6	4.6

Table 18 (continued).

I.D.	Depth cm	n	D.W. g	¹³⁷ Cs	Area cm ²	B.D. Mg m ⁻³	¹³⁷ Cs	¹³⁷ Cs	Total ¹³⁷ Cs at Site
				pCi g ⁻¹			pCi	pCi cm ⁻²	
Toeslope ⁶	0-15	3	875.9	0.263	60.8	0.96	230.4	3.8	7.1
30	15-30	3	980.8	0.206	60.8	1.08	201.8	3.3	
Toeslope	0-15	3	1082.2	0.263	60.8	1.19	284.9	4.7	7.1
31	15-30	3	1154.1	0.126	60.8	1.27	145.0	2.4	
Toeslope	0-15	3	1060.6	0.389	60.8	1.16	412.3	6.8	9.5
32	15-30	2	957.1	0.116	40.5	1.57	111.3	2.7	
Toeslope	0-15	3	906.0	0.193	60.8	0.99	175.1	2.9	5.1
33	15-30	3	1273.0	0.104	60.8	1.40	132.8	2.2	
Toeslope	0-15	3	980.5	0.322	60.8	1.06	312.8	5.1	6.3
34	15-30	3	1135.9	0.63	60.8	1.25	72.0	1.2	
Footslope	0-15	3	841.1	0.281	60.8	0.92	236.1	3.9	4.9
37	15-30	3	1263.1	0.049	60.8	1.38	61.5	1.0	
Footslope	0-15	3	955.2	0.235	60.8	1.05	224.1	3.7	5.0
38	15-30	3	1087.6	0.075	60.8	1.19	81.5	1.2	
Footslope	0-15	3	1030.8	0.348	60.8	1.13	358.4	5.9	5.9
39	15-30	3	1247.0	ns	60.8	1.37	0	0	
Midslope	0-15	3	942.5	0.197	60.8	1.03	186.1	3.1	3.1
40	15-30	3	1166.0	ns	60.8	1.28	0	0	
Midslope	0-15	3	1009.8	0.228	60.8	1.11	229.8	3.8	5.2
41	15-30	3	1199.3	0.070	60.8	1.31	83.6	1.4	
Midslope	0-15	3	939.7	0.135	60.8	1.03	126.7	2.1	3.4
42	15-30	3	1170.2	0.070	60.8	1.28	81.7	1.3	
Footslope	0-15	3	762.9	0.270	60.8	0.84	205.8	3.4	5.6
43	15-30	3	1042.7	0.129	60.8	1.14	134.0	2.2	
Midslope	0-15	3	949.6	0.197	60.8	1.04	187.4	3.1	3.1
44	15-30	3	1169.0	ns	60.8	1.28	0	0	
Footslope	0-15	3	1008.4	0.294	60.8	1.11	269.5	4.9	5.6
45	15-30	3	1012.8	0.043	60.8	1.11	43.9	0.7	
Shoulder	0-15	3	1012.4	0.142	60.8	1.11	144.2	2.4	2.4
46	15-30	3	1181.9	ns	60.8	1.30	0	0	
Shoulder	0-15	3	886.6	0.345	60.8	0.97	306.0	5.0	6.9
47	15-30	3	1089.8	0.105	60.8	1.19	114.5	1.9	
Shoulder	0-15	3	875.8	0.368	60.8	0.96	322.4	5.3	7.8
48	15-30	3	1047.3	0.145	60.8	1.15	151.3	2.5	
Shoulder	0-15	3	891.1	0.280	60.8	.98	249.7	4.1	5.6
49	15-30	3	1233.0	0.074	60.8	1.35	91.0	1.5	
Shoulder	0-15	3	1018.9	0.175	60.8	1.12	178.3	2.9	2.9
50	15-30	3	960.9	ns	60.8	1.05	0	0	

Table 18 (continued).

I.D.	Depth cm	n	D.W. g	¹³⁷ Cs	Area cm ²	B.D. Mg m ⁻³	¹³⁷ Cs	¹³⁷ Cs	Total ¹³⁷ Cs at Site
				pCi g ⁻¹			pCi	pCi cm ⁻²	
Summit 51	0-15	3	824.2	0.235	60.8	0.90	193.7	3.2	5.0
	15-30	3	1165.6	0.095	60.8	1.28	111.3	1.8	
Summit 52	0-15	3	1082.2	0.384	60.8	1.19	416.0	6.8	6.8
	15-30	3	1162.0	ns	60.8	1.27	48.3	0	
Summit 53	0-15	3	904.0	0.119	60.8	0.99	107.5	1.8	2.4
	15-30	3	1058.4	0.035	60.8	1.16	37.0	0.6	
Summit 54	0-15	3	956.9	0.345	60.8	1.05	330.3	5.4	7.5
	15-30	3	959.7	0.135	60.8	1.05	129.8	2.1	
Pond 1	0-15	5	1090.6	0.409	101.3	0.72	446.1	4.4	5.3
	15-30	4	1077.1	0.071	81.1	0.89	76.2	0.9	
	30-45	4	1404.4	ns	81.1	1.15	0	0	
Pond 2	0-25	3	1064.0	1.258	60.8	0.70	1338.5	22.0	24.6
	25-50	3	1906.2	0.083	60.8	1.25	158.0	2.6	
	50-75	3	1889.0	ns	60.8	1.24	0	0	
Pond 3	0-25	3	1038.7	0.582	60.8	0.68	604.2	9.9	11.7
	25-50	3	1975.5	0.055	60.8	1.30	108.7	1.8	
	50-75	3	2082.0	ns	60.8	1.37	0	0	
Pond 4	0-15	5	1047.7	1.098	101.3	0.69	1150.4	11.4	18.7
	15-30	5	1484.3	0.355	101.3	0.98	526.3	5.2	
	30-45	5	1640.2	0.133	101.3	1.08	217.5	2.1	
Pond 5	0-15	5	1248.4	0.682	101.3	0.82	850.8	8.4	10.7
	15-30	5	1580.8	0.080	101.3	1.04	125.8	1.2	
	30-45	5	2050.7	0.055	101.3	1.35	113.6	1.1	
Pond 6	0-15	5	1093.5	0.985	101.3	0.72	1077.4	10.6	14.3
	15-30	5	1338.5	0.282	101.3	0.88	377.2	3.7	
	30-45	5	1931.3	ns	101.3	1.27	0	0	
Pond 7	0-15	5	1084.2	0.754	101.3	0.71	817.7	8.1	17.6
	15-30	5	1262.7	0.731	101.3	0.83	923.0	9.1	
	30-45	5	1511.3	ns	101.3	0.99	0	0	
Pond 8	0-15	5	1326.9	0.571	101.3	0.87	757.1	7.5	8.7
	15-30	5	1324.4	ns	101.3	0.87	0	0	
	30-45	5	1586.0	0.050	101.3	1.04	78.7	0.8	
Pond 9	0-15	5	1247.9	1.047	101.3	0.82	1306.6	12.9	14.0
	15-30	5	1617.7	0.072	101.3	1.06	116.3	1.1	
	30-45	5	1861.9	ns	101.3	1.22	0	0	
Pond 10	0-10	5	849.1	0.841	101.3	0.84	714.1	7.0	8.1
	10-20	5	978.6	0.115	101.3	0.97	112.3	1.1	
	20-30	5	1009.6	ns	101.3	1.00	0	0	
Pond 11	0-10	5	994.4	0.891	101.3	0.98	885.7	8.7	14.6
	10-20	5	1121.7	0.537	101.3	1.11	602.4	5.9	

Table 18 (continued).

I.D.	Depth cm	n	D.W. g	¹³⁷ Cs		B.D. Mg m ⁻³	¹³⁷ Cs		Total ¹³⁷ Cs at Site
				pCi g ⁻¹	Area cm ²		pCi	pCi cm ⁻²	
Pond 12	0-10	5	662.8	1.158	101.3	0.65	767.5	7.6	8.9
	10-20	5	960.9	0.060	101.3	0.95	57.3	0.6	
	20-30	5	1161.0	0.063	101.3	1.15	72.7	0.7	
Pond 13	0-10	5	985.0	0.629	101.3	0.97	619.4	6.1	8.1
	10-20	4	696.6	0.237	81.1	0.86	164.9	2.0	
Pond 14	0-10	5	842.3	0.786	101.3	0.83	661.8	6.5	8.6
	10-20	3	450.1	0.134	60.8	0.74	60.3	1.0	
	20-30	3	657.0	0.100	60.8	1.08	65.8	1.1	
Pond 15	0-15	5	1450.5	0.627	101.3	0.95	910.2	9.0	16.3
	15-30	4	1412.6	0.419	81.1	1.16	591.7	7.3	
Pond 16	0-10	5	856.9	0.638	101.3	0.85	546.6	5.4	5.4
	10-20	5	955.7	0.051	101.3	0.94	48.7	0.5	
	20-30	5	1184.8	ns	101.3	1.17	0	0	
Pond 17	0-15	5	1377.6	0.698	101.3	0.91	961.4	9.5	13.3
	15-30	5	1733.1	0.219	101.3	1.14	380.4	3.8	
Pond 18	0-15	5	1279.6	0.715	101.3	0.84	914.5	9.0	17.2
	15-30	5	1574.8	0.527	101.3	1.04	830.4	8.2	
	30-45	5	1417.0	ns	101.3	0.93	0	0	
Pond 19	0-10	5	867.0	0.779	101.3	0.86	675.0	6.7	14.0
	10-20	5	985.5	0.290	101.3	0.97	286.2	2.8	
	20-30	5	1609.3	0.345	101.3	1.59	554.7	5.5	
Pond 20	0-15	5	1344.1	0.663	101.3	0.88	890.7	8.8	13.1
	15-30	5	1568.0	0.277	101.3	1.03	434.8	4.3	
Pond 21	0-15	5	1487.2	0.480	101.3	0.98	714.5	7.0	7.0
	15-30	5	1997.1	ns	101.3	1.31	0	0	
Pond 22	0-15	5	1391.5	0.677	101.3	0.92	942.6	9.3	11.2
	15-30	5	1594.1	0.123	101.3	1.05	196.1	1.9	
Pond 23	0-15	5	1291.5	0.568	101.3	0.85	734.1	7.2	10.2
	15-30	5	1651.9	0.186	101.3	1.09	307.4	3.0	
Pond 24	0-15	5	1469.1	0.569	101.3	0.97	836.2	8.3	14.8
	15-30	5	1769.0	0.374	101.3	1.16	661.6	6.5	

¹ I.D. — Identification of sample.² * — Cores not obtained with sampling tube.³ Wind er. — Samples from wind eroded field. (Wind erosion study).³ Wind acc. — Samples from field where soil was deposited. (Wind erosion study).⁴ ns — Unsignificant values (counting error > 50%) or cesium was not detected in sample.⁵ Unsignificant values at the wind erosion study site and Belgrade (15-30 cm) are excluded from this table.⁶ Names refer to position within the watershed studied.

APPENDIX B

APPENDIX B

Example of Soil Loss Calculations, Considering Dilution

The equation used to describe the reduction in cesium due to erosion is

$$C/Co = e^{bt}$$

where b is a negative constant for each site, C is the current ^{137}Cs activity, Co is the initial activity before erosion occurs, and t is time in years. Obtaining the natural logarithms gives

$$\ln C/Co = bt$$

As an example, calculation for an arbitrary site with current activity of 3.8 pCi cm^{-2} will be shown. The values used for obtaining b are

$$t = 18 \text{ years (the period from 1964 to 1982).}$$

$$Co = 6.6 \text{ pCi cm}^{-2} \text{ (calculated cesium input).}$$

$$C = 3.8 \text{ pCi cm}^{-2} \text{ (current cesium activity at the site)}$$

Solving the equation for b gives

$$b = -0.03067$$

If the rate of erosion is constant, reduction in ^{137}Cs activity the first year can serve as an estimate of erosion rate per year. Solving for C at $t = 1$ results in

$$C = 6.4 \text{ pCi cm}^{-2}$$

and the reduction is

$$Co - C \text{ or } 6.6 - 6.4 = 0.2 \text{ pCi cm}^{-2}$$

Soil loss per year can now be calculated

$$dC/Co \times 15 = \text{Soil loss (in cm yr}^{-1}\text{)}$$

where 15 is the depth of the plowlayer.

$$0.2/6.6 \times 15 = 0.455 \text{ cm yr}^{-1}$$

Over the 18 years period from 1964 to 1982 the soil loss is

$$18 \times 0.455 \approx 8.2 \text{ cm}$$

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