A Method for Measuring Soil Erosion and Deposition with Beta Particle Attenuation[1]

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Highlight

A method utilizing beta particle attenuation was developed for measuring soil erosion and deposition in a shortgrass plains ecosystem. This method used a sealed strontium-90 source located below ground level. Soil erosion and deposition was observed by fluctuations in detected count rates using a portable Geiger Mueller counting system. Initial results indicate that quantitative measurement of soil depth fluctuations in amounts considerably less than one millimeter and over a period of a few weeks are possible. Data are presented from application of this method in six soil series under heavy, moderate, and light summer grazing treatments.

The impact of management practices upon soil fluctuations is often suggested, but seldom measured. Dowel pins inserted into the ground have been used to measure soil movement in a plowed seed bed (Hyder and Bement, 1970), and "erosion stakes" were employed in a chaparral community to examine soil behavior following a fire (Sampson, 1944). The use of such stakes may create an artificial barrier and thus bias soil movement data. Furthermore, soil depth changes on the order of one millimeter or less would be difficult to measure with accuracy.

Woolridge (1965) has successfully used the radioactive isotope, iron-59, to measure soil particle movement. Broad coverage of the use of radioactive tracers in erosion research is given in an article by McHenry (1968) in which it is stated that measurement of total volume of eroding soil is difficult to evaluate, and that as a result, erosion data obtained with tracers is often more qualitative than quantitative.

In order to measure soil depth fluctuations quantitatively in a relatively undisturbed shortgrass plains ecosystem, a method involving strontium-90 beta particle attenuation was developed and applied on the U.S. International Biological Program Grassland Biome Site at the Central Plains Experimental Range near Nunn, Colorado (Pawnee Site).

Methods and Materials

The basic principle of this method involves measurement of beta particles which penetrate the soil above a buried radioactive source. As soil or litter, measured in milligrams per square centimeter, is deposited over the source, a decreased count rate is measured using a portable Geiger-Mueller (GM) survey instrument. Removal of material results in an increased count rate.

Beta particles travel tortuous paths through matter as a result of multiple interactions with electrons in which energy is lost. The range of a beta particle of a given energy depends upon the number of electrons which it encounters in passing through absorbing materials. The effectiveness of a material in absorbing beta particles depends upon the number of electrons per unit mass of material: the ratio of the atomic number (Z) to the atomic mass (A). In general, the ratio of Z to A is nearly the same for all elements except hydrogen. The ratio, in general, decreases slightly as A increases. Range of beta particles in a material is generally expressed in grams or milligrams per square centimeter, (density multiplied by thickness). When range is expressed in this manner, beta particle absorbance is moderately independent of absorbing material. Further discussion of beta particle attenuation is given in Lapp and Andrews (1964).

Strontium-90 was selected as the radioactive source for this study because it decays to yttrium-90 which emits a 2.27 MeV beta particle. A particle of this energy enables detection of reasonable differences in soil fluctuations. For example, a 45% change in count rate corresponds approximately to a 1 mm change in soil depth for a ^{90}Sr-^{90}Y source. The 30 year half life of strontium-90 allows continuation of investigation over a considerable period of time without need to replace the source. When working with any radioactive material such as strontium-90 one must recognize that a potential health hazard exists and precautionary measures need to be taken. State and federal regulations concerning use of radioactive materials should be consulted prior to any investigation utilizing such materials.

An absorption curve was obtained in the laboratory for a typical strontium-90 source using machined aluminum absorbers (Fig. 1). Similar data were obtained using soil and litter as absorber media (Fig. 2). Similar absorption characteristics for these materials were expected because, as has already been pointed out, beta particle attenuation is proportional to the atomic number divided by the atomic weight which is nearly constant for all elements. Also, when absorber thickness is expressed in milligrams per square centimeter, attenuation is nearly

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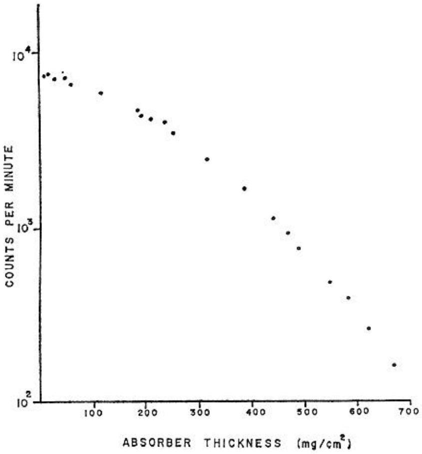

FIG. 1. Absorption of beta particles from a ^{90}Sr-^{90}Y source using aluminum absorbers.

independent of absorbing media. Primary elements comprising soil are aluminum and silicon with atomic numbers of 13 and 14, respectively. Utilizing the data presented by Lyons et al. (1952), for relative elemental constituents of soil, and applying Mayneord's formula for effective Z (Johns, 1964 p. 206), an approximation of 12 was obtained for the effective Z of soil. Using an average bulk density value of 1.21 (Galbraith, 1969) for Pawnee Site soils, 80 mg/cm² corresponds approximately to 1 mm of soil depth.

Application of polynomial regression techniques to the data for Fig. 1, resulted in the following regres-

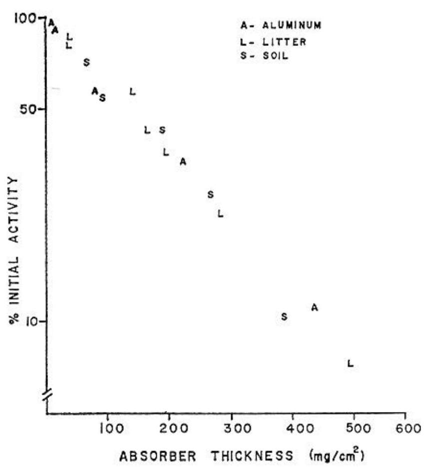

FIG. 2. Absorption of ^{90}Sr-^{90}Y beta particles by aluminum, litter, and soil.

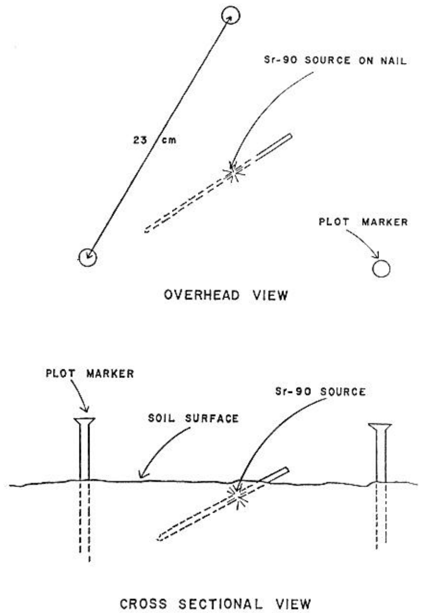

FIG. 3. Schematic representation of permanent field plots for measurement of soil movement.

sion equation with an r^2 of 0.9983, $N = 20$:

$$Y = -24946.26 + 32918.87X - 15574X^2 + 3226.01X^3 - 249.32X^4$$

Where:

X = log of net counts per minute obtained from field data

Y = thickness of absorbing media in mg/cm²; (cm × mg/cm³)

This equation was used to relate count rate data from the field to the quantity of soil above each source. Obviously, the equation should not be construed as a mathematical explanation for beta particle absorption processes or soil erosion relationships.

Field application of the beta particle method is illustrated in Figure 3. A 0.5 microcurie aliquot of strontium-90 in a small drop of 0.125 N hydrochloric acid solution was placed in a notch filed in a 15 cm ring-shank nail. The acid solution reacted with the nail at the point of application and helped to fix the isotope in the notch. The isotope was dried under a heat lamp and was then sealed in place with clear Krylon (commercial name, Krylon, Inc.) and spray enamel. It was verified experimentally that this process sealed the source

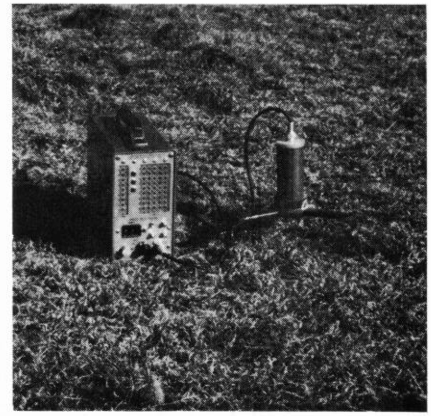

FIG. 4. Counting system in operation on the shortgrass plains.

sufficiently to prevent any leaching of the isotope into surrounding soil. The head of the source nail was removed to eliminate any artificial wind barrier it might have caused.

In the field, the radioactively tagged nail was inserted into the soil at a 35 degree angle such that the notch bearing the isotope was a few millimeters below the surface and centered in a triangle formed by the plot markers (Fig. 3). Source depth was established by inserting the nail until the observed count rate was in the mid-portion of the calibration curve (Fig. 1). Placement of the source in this manner allowed quantitative measurement of both removal and deposition of soil and litter up to 300 mg/cm². When soil or litter accumulated, or was removed to the extent that the count rate exceeded the limits of the regression equation (1000 to 7000 cpm), the source was reset to well-within the bounds of the equation. The source nail protrudes above ground 5 to 8 mm presenting only a slight wind barrier as compared to microterrain and vegetational variations.

When reading plots, any standing vegetation between the source and the detector window was clipped, but all litter was left in place. This procedure was followed to remove any absorbance of beta particles by materials not directly subject to agents of erosion. Initial fluctuations in count rates observed shortly after establishing plots or resetting

Table 1. Typical counting and soil movement data from field transects.

Plot No.	March 20, 1971 CPM*	March 20, 1971 mg/cm²	June 11, 1971 CPM	June 11, 1971 mg/cm²	Change mg/cm²
166	2221	430.6	2469	416.4	– 14.2
167	2190	432.5	1302	506.9	+ 74.4
168	2269	427.8	1767	462.3	+ 34.5
169	1912	451.3	1593	477.2	+ 25.9
170	2092	438.8	1900	452.1	+ 13.3
171	1859	455.2	2403	420.0	– 35.2
172	3103	386.0	1538	482.3	+ 96.3
173	1964	447.5	2049	441.7	– 5.8
174	1558	480.4	1515	484.6	+ 4.2
175	1364	500.1	960	553.4	+ 53.3
176	3380	374.7	1310	506.1	+131.4
177	4489	335.3	7325	251.2	–120.1
178	2450	417.4	2180	433.2	+ 15.8
179	2288	426.6	2371	421.8	– 4.8
180	2329	424.2	1297	507.6	+ 83.4

* CPM stands for corrected counts per minute.

source nails were believed to have been caused by minor disturbance of the soil by the investigator. Therefore, we allowed a period of about two weeks for the plots to come to a state of "homeostasis" with their environment before actual data collection was begun.

Three 26 cm ring-shank bridge spikes driven approximately 21 cm into the ground were used as reference markers for each plot. The 5 cm portions of the spikes protruding above the soil surface served as legs for a portable tripod that contained the GM probe used in counting (Fig. 4). Markers were placed so as to leave an open area in the direction of prevailing northwesterly winds. Source nails were placed normal to the prevailing winds. This procedure reduced any wind shadow effect that might be caused by the markers and source nails.

Counting was done with a Ludlum Model 44–7 end-window GM probe attached to a portable Ludlum Model 20-A scaler. The probe, encased in an open-ended tube on a tripod, was placed over the radioactive source with arms resting on the plot markers (Fig. 4). The source-to-probe-window distance was approximately 5 cm and was constant for repeated measurements. Three-minute counts were taken at each plot, and every two hours a standard strontium-90 source and background were counted to assure reproducibility and reliability of the counting system. Gross counts from field data were converted to net counts per minute with correction for natural background radiation, physical decay, and counter efficiency. Corrected counts were applied in the regression equation to obtain milligrams per square centimeter of soil over the point source at the time of counting. Soil depth fluctuations were determined from the differences between successive readings. Table 1 illustrates typical plot data.

To field test the beta particle attenuation method and obtain soil movement data, 265 plots were established at the Pawnee Site during the fall season of 1970 in light, moderate, and heavy summer-grazed pastures. Plots were located in specific soil types along predetermined transects 200 to 800 meters in length, established for their similarity in slope, aspect, and adjacent soil series. Other transects were located on the basis of special interest such as varied soil series, opposite facing slopes, and topographic sinks. Individual plots were established on transects by pacing a distance equal to the transect length divided by the number of plots for that transect. Characteristics of the soils examined are given in Table 2. The specific location of each plot was determined without bias, except that patches of plains pricklypear (*Opuntia polyacantha*) were purposely avoided. Plant community structure and soil associations for this area have been previously reported (Hyder et al., 1966).

Table 2. Characteristics of soils examined.*

Soil series	Parent material	% Gravel	% Sand	% Silt	% Clay
Ascalon	Granitic fluvial outwash	2.4	64.2	19.2	16.6
Vona	Coarse outwash, Pierre sandstone	—	74.0	12.8	13.2
Shingle	Shale and siltstone from Pierre sedimentary material	—	53.1	21.3	25.5
Renohill	Shale and siltstone from Pierre sedimentary material	2.4	68.6	16.4	15.0
Undifferentiated alluvial		—	52.1	22.1	25.8

* Data from Franklin (1969).

Results and Discussion

Data gathered from field plots over a 10 month period are summarized in Tables 3 and 4. Pasture, season, and total means are listed to indicate preliminary trend. To make valid comparisons among these averages each soil series mean should be weighted according to its relative contribution to the total soil surface area within each pasture. Continued investigation to define soil movement and the factors influencing the movement will be the subject of future research and reports.

The large standard error for the means in Tables 3 and 4, and the data in Table 1, illustrate the large variation found along transects. Such variation appears real and not due to poor precision of measurements. The standard deviation (σ) due to counting for the difference between two successive counts was calculated by the following relationship:

$$\sigma = \sqrt{\frac{R_{s+b}}{t_{s+b}} + \frac{R_b}{t_b} + \frac{R^*_{s+b}}{t_{s+b}} + \frac{R^*_b}{t_b}}$$

Where:

R_{s+b} = initial count rate of the sample plus background (counts/min)

R_b = initial count rate of the background (counts/min)

R^*_{s+b} = final count rate of the sample plus background (counts/min)

R^*_b = final count rate of the background (counts/min)

t = duration of a particular count (min)

This relationship is similar to that presented in Lapp and Andrews (1964) as it sums the counting variances associated with each of the four separate measurements needed to determine a change in sample count rate. By dividing the counting variation (σ) by the net difference between the successive count rates, an estimate of counting error of 12% with a standard error of 4% was obtained. This error can easily be reduced by increasing the counting time. This may be justified where differences between readings are small. Evaluation of other sources of error in the field is being conducted at the present time, but initial results indicate these errors to be relatively small. It becomes obvious when examining data and field plots that a high degree of micro-environmental variation between plots greatly influences soil movement data. Variability in soil erosion has been previously recognized and eleven factors influencing it have been presented (Woodruff and Siddoway, 1965).

Net soil loss for all pastures during the winter period is indicated by the data in Table 3. Examination of climatic data for the Pawnee Site indicates that during the winter a greater frequency of high velocity, gusty winds occur, and that precipitation is low (less than 0.12 cm/week). Such winds coupled with dry soil surface conditions and minimal vegetative cover produce high rates of erosion. As pointed out by Chepil et al. (1962) wind erosion of soil is directly proportional to the cube of the wind velocity and in-

Table 3. Summary of soil movement data for four soil series and three summer grazing treatments.

Grazing treatment and soil	Fall (Sept.–Nov.)			Winter (Nov.–Mar.)			Spring (Mar.–June)			Pasture mean Δ M
	Δ M	$S\bar{x}$	N	Δ M	$S\bar{x}$	N	Δ M	$S\bar{x}$	N	
Heavily grazed										
Ascalon	+144	109	13	−104	46	13	+ 80	75	10	
Vona	+118	85	15	−189	30	13	+ 70	58	11	
Shingle-Renohill	+ 3	114	14	− 99	43	10	− 33	110	7	
Undifferentiated	−190	185	14	− 89	37	9	− 59	80	8	
Seasonal mean	+ 18			−123			+ 14			−30
Moderately grazed*										
Ascalon				− 88	45	14	+254	104	13	
Vona				−130	42	14	+ 96	109	10	
Shingle-Renohill				−121	34	15	+ 38	79	13	
Undifferentiated				− 8	19	15	+ 85	57	15	
Seasonal mean				− 87			+118			+16
Lightly grazed										
Ascalon	+ 88	108	15	−192	38	14	+284	89	12	
Vona	+143	86	13	− 79	80	13	+ 6	114	9	
Shingle-Renohill	+152	75	15	−144	45	14	+ 57	93	14	
Undifferentiated	+221	59	14	−144	35	10	+ 42	69	8	
Seasonal mean	+151			−140			+ 97			+36
Combined pastures										
Ascalon										+58
Vona										+ 4
Shingle-Renohill										−18
Undifferentiated										−18
Total										+ 7

Δ M = mean soil movement in g/m²/month.
* = Winter data for this pasture extends from September through March.

Table 4. Summary of soil movement data for slopes, sinks, shingle, and renohill soils.

Grazing treatment and location	Fall (Sept.–Nov.)			Winter (Nov.–Mar.)			Spring (Mar.–June)		
	Δ M	S$\bar{x}$	N	Δ M	S$\bar{x}$	N	Δ M	S$\bar{x}$	N
Heavily grazed									
Ascalon Northeast Slope	+12	21	5	−86	37	4	+104	45	4
Ascalon Southwest Slope	+65	34	4	−31	33	4	+105	75	3
Sinks	+28	15	8	−70	34	6	+ 75	47	5
Lynn Lake	−91	52	6	—	—	—	—	—	—
Moderately grazed*									
Renohill				−38	23	15	+ 40	27	12
Shingle				−23	33	12	+ 43	18	10
Shingle Southeast Slope				−44	49	7	+ 76	25	5
Shingle Northwest Slope				+ 6	44	5	+ 9	17	5

Δ M = mean soil movement in g/m²/month.
* Winter data for this pasture extends from September through March.

versely proportional to the square of the effective soil water content.

Franklin (1969) speculated that the Shingle-Renohill soils occupying the steeper slopes at the Pawnee Site were relatively unstable. This speculation is supported by the net loss shown in our data for this soil series. The loss of material from the undifferentiated alluvial soil is primarily from the transect in the heavily grazed pasture. This transect is located in an area near cattle watering and handling facilities and a large amount of physical disturbance as well as extreme grazing occurs there.

To examine opposing slopes, two transects were established, one each, on the Shingle soil series in the moderately grazed pasture and on the Ascalon soil series in the heavily grazed pasture. Resulting data (Table 4) indicate that the southwest facing Ascalon slope accumulates more soil in the fall and loses less in the winter than does the northeast slope. Little difference exists between data from these slopes during the spring. The opposing Shingle slopes illustrate the same general pattern of greater total accumulation on the southerly exposure. However, the accumulation on the northwest Shingle soil slope during winter contrasts with observations from the Ascalon investigation. Prevailing winter winds from the northwest possibly account for these observations. Prevailing southwest summer winds may reverse winter erosional patterns. The possibility also exists that neither slope will exhibit any significant difference in soil erosional behavior and that only the tops of the knolls will continually lose soil. This possibility has been pointed out by Chepil et al. (1964).

The sinks examined in this study were covered with a dense mat of buffalo grass (*Buchloe dactyloides*) and were accumulating soil (except in winter), while a dry lake (Lynn Lake), characterized by erosion pavement in its basin, appears to be eroding. However, observations on the lake are tenuous because no data were collected during the winter or spring when freezing and thawing of the high clay soil caused surface cracks and exposed many of the source nails.

Minor problems have arisen in in field application of the beta particle attenuation method for measuring soil fluctuations. Disturbance of plots by man, livestock, and antelope has been observed, but for the duration of this study, less than two percent of the plots were altered. Frost heaving of nails has been suggested as a potential problem, but field observation has revealed no such phenomenon. One plot, established with the source exposed to evaluate alterations in count rate from factors other than erosion and deposition of material, yielded consistent count rates throughout the study period.

Soils high in clay have been observed to crack open with freezing and thawing, often exposing nails. These soils generally have a high water holding capacity and are thus more susceptible to frost action. This problem has occurred with much less frequency in soils with a lower clay content. Low soil water content in the winter greatly reduced problems arising from freezing.

Moisture in the surface soil presented a problem in collection of field data. Laboratory studies indicated that when gravimetric soil water was greater than two percent, count data were altered. At each counting period, soil samples were taken and water content was determined. Attempts were made to correct for soil water content, but due to non-uniform distribution of moisture throughout the transect, this was not feasible. Counting was therefore restricted to periods when water content of the surface soil was less than two percent.

Conclusions

Initial investigations indicate that sensitive, quantitative measurement of soil movement in a shortgrass plains ecosystem over short periods of time may be made utilizing the beta particle attenuation method. However, the attenuation method is sensitive to soil water content, restricting data collection to periods when surface soil water content is less than two percent. Frost heaving of nails is recognized as a potential problem, but thus far it has not been observed.

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