# $^{137}$Cs USE IN ESTIMATING SOIL EROSION: 30 YEARS OF RESEARCH

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## Abstract

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Significant amounts of fallout $^{137}$Cs from nuclear weapons tests were introduced to the landscape during the 1950s and 1960s. Once $^{137}$Cs reaches the soil surface it is strongly and quickly adsorbed by clay particles, and is essentially nonexchangeable in most environments. Thus, $^{137}$Cs becomes an effective tracer of the movement of soil particles across the landscape. Over the past 30 years, researchers have shown that $^{137}$Cs can be used to study soil movement. Early work used empirical relationships between soil loss and $^{137}$Cs loss to estimate erosion. This was followed by the development of proportional and theoretical models to relate $^{137}$Cs movement and soil redistribution. Most of the problems related to the $^{137}$Cs technique are the same as those encountered with other techniques (i.e., sampling, measurement). The $^{137}$Cs technique can make actual measurements of soil loss and redeposition in fields, fostering the formulation of better plans to conserve the quality of the landscape. This paper reviews the development of the $^{137}$Cs technique to show how it can be used to understand erosion and soil movement on the landscape.

## 1. INTRODUCTION

Soil erosion is a natural process caused by water and wind. The accelerative effects of man's activities on erosion and the off-site damage caused, are major concerns around the world. The size of the problem and concern over degradation of the landscape are well documented [1, 2 ,3]. Economic effects of soil erosion along with off-site, downstream damage from eroded soil particles have also been described [3, 4, 5].

Measurements of soil erosion on the landscape using classical erosion techniques are difficult, time consuming, and expensive [6]. Empirical and theoretical mathematical equations/models have been developed. The most widely used is the Universal Soil Loss Equation (USLE), which is an empirical-based equation developed with data collected from soil erosion plots on "typical" soils of the United States east of the Rocky Mountains [7]. The USLE has been used and misused in the United States and around the World [8]. However, it is still the most widely used, powerful and practical tool for estimating sheet and rill erosion on the landscape. A Revised Universal Soil Loss Equation (RUSLE) is currently being used in the United States with applications to a wider range of conditions and locations than the original USLE [9]. There are many other efforts to model soil erosion and its off-site effects [10] that have had varying degrees of success and applications in management and research. One such effort is the Water Erosion Prediction Project (WEPP), which is a process-based, simulation model of soil erosion [11].

Over the past 30 years, researchers have studied the potential of using natural and man-made radioisotopes to study the erosion and sediment-deposition cycle. Several radioisotopes have been used. The potential for using fallout $^{137}$Cs to provide independent measurements of actual soil erosion rates and patterns and sediment deposition is well documented [12, 13]. The purpose of this paper is to review the development of the $^{137}$Cs technique for studying erosion and redeposition, based on a bibliography [14] of 1500 papers that show extensive use of the technique globally.

## 2. BACKGROUND

Most classical methods for estimating soil erosion are based on measuring soil loss from plots or at the edge of a field. They do not give unbiased measurements of actual soil movement, and, more importantly, they do not address spatial patterns of erosion and redeposition within fields. Mathematical models have the same limitations. There is a need to be capable of making measurements at any location on the landscape, especially in areas where other erosion data are not available and where long-term experiments have not, nor cannot be, established. Classical erosion measurement techniques and mathematical models cannot meet these criteria. Tracer techniques have the potential to provide the necessary type of data. However, such techniques can be difficult if tracer must be added to the environment. A tracer is needed that is naturally distributed across the landscape, easily measured, and readily adsorbed to soil particles.

Fallout $^{137}$Cs from atmospheric nuclear weapons tests of the 1950s and 1960s is a unique tracer for the erosion and deposition cycle because no natural sources are in the environment. Yet, $^{137}$Cs is globally distributed across the earth's surface due to fallout deposition from such tests and releases from nuclear reactors [15, 16]. Before 1952, releases were localized around weapon test sites or reactors. With the coming of high-yield thermonuclear weapons testing in November 1952 [17], $^{137}$Cs was injected into the stratosphere and circulated globally [18]. Fallout rates decreased with distance from the northern temperate zone. Regional patterns and rates of fallout were linearly related to precipitation in latitudinal zones [18].

Local variation of fallout $^{137}$Cs on the landscape can be significant. Studies have reinforced the need to make local measurements at undisturbed sites rather than by extrapolating from values determined at other locations [19, 20]. The rates of deposition of fallout $^{137}$Cs have decreased since the maxima of the early 1960s, and since the mid-1980s have often been below detection limits [15]. Releases from nuclear reactors are usually local in nature. However, the Chernobyl accident in April 1986 caused regional dispersal of measurable $^{137}$Cs [21] that affected the total global deposition budget [22]. Thus man's activities related to nuclear energy have distributed a unique radioactive element across the landscape surface in discernible patterns that can be used to trace natural events.

The chemistry of this unique tracer is well understood [18, 23]. Once $^{137}$Cs reaches the soil surface it is strongly and quickly adsorbed by clay particles, and is essentially nonexchangeable in most environments [24, 25, 26]. Thus, $^{137}$Cs becomes an effective tracer of the movement of surface soil. Distribution of $^{137}$Cs in soil profiles at undisturbed sites shows an exponential decrease with depth [27, 28, 29], whereas plowed soils show uniform distribution throughout the plowed layer [30, 31]. Less than 1% of the $^{137}$Cs is flushed in solution from a catchment immediately after deposition, and generally less than 0.1% moves in solution per year after the initial flush [32, 33]. Thus most movement of $^{137}$Cs across the landscape is due to the physical processes of erosion and sediment deposition.

Accurately measuring $^{137}$Cs in environmental samples is easy [34, 61]. In soil erosion studies, the challenge is to elucidate the changing patterns of distribution of $^{137}$Cs-tagged soil particles on the landscape. The redistribution of $^{137}$Cs between and within landscape elements provides information on soil erosion rates and patterns. Although biological and chemical processes move limited amounts of $^{137}$Cs in unique environments, water and wind are the dominant factors moving $^{137}$Cs-tagged soil particles between and within compartments of the landscape.

Thus, measurement of $^{137}$Cs redistribution on the landscape provides estimates of long-term soil loss. Estimates are location-specific and can be made with minimum disturbance to study sites, giving both spatial patterns and rates of erosion from a single visit.

## 3. EARLY RESEARCH

The first publication of the use of fallout radioactivity to estimate soil loss was in 1960 by Menzel [35], who measured the transport of fallout $^{90}$Sr in runoff from "standard" erosion plots. He concluded that $^{90}$Sr loss was greatest from those plots that had the most soil loss. Although this study did not include $^{137}$Cs, it showed that the movement of fallout radioactivity on the landscape was related to soil movement.

In 1963, Frere and Roberts [36] measured $^{90}$Sr across a small cultivated catchment in Ohio as a function of slope position and shape, and concluded that the pattern was due to the redistribution of soil particles by erosion processes. Graham [37] added $^{85}$Sr and $^{131}$I to standard erosion plots, and concluded that soil particles affected nuclide removal by runoff water. And Yamagata, Matsuda, and Kodaira [38] concluded that runoff was a factor in the removal of $^{137}$Cs and $^{90}$Sr from catchments.

In 1965, Rogowski and Tamura published the first of three reports [39, 40, 41] on the movement of $^{137}$Cs by runoff, erosion, and filtration from plots at the Oak Ridge National Laboratory in Tennessee, USA. They added $^{137}$Cs as a tracer and followed its movement by measuring runoff, soil loss and $^{137}$Cs loss at a flume at the end of erosion plots. The first publication [39] was based on the first 83 days of data collection. In follow-up publications in 1970, they discussed the environmental mobility of $^{137}$Cs [40] and erosional behavior of $^{137}$Cs [41]. They found a significant exponential relationship between soil and $^{137}$Cs losses, and concluded that erosion was a major factor in removing $^{137}$Cs. Although these studies were not based on fallout nuclear weapons tests, they showed that $^{137}$Cs and soil movements were related, and could be used as a tool for estimating soil redistribution on the landscape.

It is interesting that in 1965 Wischmeier and Smith [7] first published the USLE (Universal Soil Loss Equation) in USDA Agriculture Handbook No. 262 on predicting rainfall-erosion losses for cropland east of the Rocky Mountains. The USLE, an empirical equation based on measured soil loss from standard erosion plots on "typical soils" east of the Rocky Mountains in the United States, received wide acceptance in the United States and around the world. The equation is used and misused [8] for areas where the empirical relationship developed for United States soils is probably not applicable. The early work of Rogowski and Tamura on using the $^{137}$Cs to measure soil loss, however, has yet to be implemented as a tool for soil conservationists to study soil redistribution.

In another study at Oak Ridge, Dahlman and Auerbach [42] added $^{137}$Cs to a grass plot (fescue meadow) and used its redistribution to estimate erosion. They also found an exponential relationship between soil and $^{137}$Cs losses. These early studies with high levels of added $^{137}$Cs raised the question of whether measurement of the much lower fallout levels could be used to estimate soil redistribution patterns across the landscape.

In 1968, Ritchie and McHenry began a series of studies to determine if fallout levels of $^{137}$Cs could be used as a tracer of sediment movement and deposition across natural and agricultural landscapes, supported jointly by the United States Department of Agriculture and the U.S. Atomic Energy Agency (now Department of Energy). In 1970 [43, 44], they concluded that differences in distribution of fallout $^{137}$Cs between vegetation types on a catchment in Mississippi were due to soil loss from the landscape. In 1972 [45, 46, 47], they designed an experiment to determine the relationship between losses of soil and of fallout $^{137}$Cs in a catchment. Soil loss was estimated using the USLE and fallout $^{137}$Cs loss was calculated as a percent compared with a non-eroded reference site. They found an exponential relationship between soil and $^{137}$Cs loss, and, along with data from two other catchments [47, 48], concluded that most of the $^{137}$Cs loss from the catchments was from the eroded areas.

In 1975, Ritchie and McHenry [49] combined their data with those from the earlier studies of Rogowski and Tamura [39, 40, 41], Menzel [35], Frere and Roberts [36], and Graham [37], and found a significant exponential relationship between soil loss and radionuclide loss. This was encouraging since the data used to develop this empirical relationship came from a variety of soil and erosion conditions, used different radionuclides, and varied from fallout levels to high levels added as tracers. Their basic conclusion was that $^{137}$Cs would be a useful tool for measuring soil loss from the landscape.

While most of the early research in the 1970s was in the United States, in 1977 McCallan and Rose [50] used $^{137}$Cs and $^{210}$Pb to estimate erosion in a basin in Australia. The same year, Wise [51] published a review paper in England on the use $^{137}$Cs and $^{210}$Pb to measure denudation rates.

Simultaneously, McHenry and Ritchie [52] found that $^{137}$Cs distribution in an agricultural field could also be used to show that most of the soil particles were being redeposited within the field rather than being lost from it. This opened a new area of interest in erosion, using the distribution of $^{137}$Cs to determine spatial patterns of erosion within a field and areas of net loss and of net gain (deposition) within a landscape element.

In the 1980s, four major centers of research on the use of $^{137}$Cs to study erosion were active. McHenry and Ritchie [12] continued their activities in the United States. In Australia, Campbell [53], Elliott [54], Loughran [55], and others used the low levels of $^{137}$Cs in the southern hemisphere to measure erosion and sediment deposition. A group lead by de Jong [56] and his students [57, 58] used $^{137}$Cs extensively to study erosion on the Canadian prairie. In England, Walling [59, 60, 61] developed a center at Exeter University for using $^{137}$Cs to quantify changes in landscape geomorphology. These centers are still active in their research efforts and continue to provide new methods to use $^{137}$Cs to quantify soil redistribution across the landscape.

## 4. EQUATIONS/MODELS

Empirical equations have been developed to explain the relationship between $^{137}$Cs and soil loss. The studies vary from simultaneous measurement of losses of soil and of $^{137}$Cs (radionuclide) from erosion plots, to correlation between soil loss from the plots and the reduction of $^{137}$Cs in these plots, to correlation between estimates of soil loss from fields and the reduction of $^{137}$Cs in the soils of these fields. Although important in showing a relationship between soil and $^{137}$Cs loss, these studies have many limitations. The general form of these equations is $Y = aX^B$. Such empirical equations are affected by climate, soils, time since fallout, time period of development, and other landscape and environmental factors. Similar concerns for the application and misuse of the empirical-based USLE have been expressed [8]. Empirical equations are applicable only to the data domain used in their development. Using this approach to estimate soil erosion will require the development of an empirical equation (calibration curve) for each site or at best, for each region. Empirical equations are dependent on the time since fallout and time of fallout. While they may help explain and better define the role of different factors that affect the relationship between soil loss and radionuclide loss, the many limitations to their application reduce their usefulness for estimating soil loss on a large scale.

A second approach for using $^{137}$Cs to study erosion is to assume that the loss of $^{137}$Cs at a site is proportional to the loss of soil. The simplest form of this approach is to equate soil loss to $^{137}$Cs loss ($Y = X$), where Y is soil loss in weight per area per time and X is $^{137}$Cs loss in percent or weight. However, the X term is usually modified by depth distribution of $^{137}$Cs, density of soil, decay corrections, and other coefficients and modifiers [62]. Kachanoski [63, 64] provided an empirical verification of this approach by measuring $^{137}$Cs concentrations in erosion plots at two different times and comparing the results of measured soil loss with measured $^{137}$Cs loss. A major assumption with this model is that $^{137}$Cs is instantaneously uniformly distributed in the soil profile. Since $^{137}$Cs is deposited on the surface and strongly adsorbed, it requires mechanical mixing (plowing) to achieve uniform distribution. Thus, during times of fallout, these conditions are seldom met leading to excess removal of $^{137}$Cs with surface erosion, causing overestimation of soil loss. Since fallout and erosion are both related to rainfall, there are concerns about erosion rates during times of heavy fallout. During these times, greater erosion rates would remove proportionately more $^{137}$Cs from the surface layer of soil, leading to overestimation of long-term erosion rates. This problem is magnified if erosion rates are higher during maximum fallout, removing a disproportionate amount of the fallout. Usually the proportional method overestimates erosion rates for periods of heavy fallout. The proportional method will probably reflect actual erosion rates for a cultivated area that was undisturbed during the fallout period.

Another approach is theoretical models/mass accounting. Walling and Quine [61] have defined the theoretical models as "the aggregate effect of all redistribution processes operating over the period since the initiation of atmospheric fallout to establish site-specific calibration relationships." Getting all the data needed to run a "process" based model may be a concern in some regions. By determining the factors that influence $^{137}$Cs movement, a $^{137}$Cs balance for a catchment can be developed and the spatial pattern and loss of $^{137}$Cs from the catchment or field can be calculated. Such studies thus allow an understanding of erosion and deposition patterns of soil particles, and have been used [60, 65, 66] to study erosion and deposition patterns on the landscape. These techniques give qualitative and quantitative information on erosion patterns. As with the other techniques, the balance approach requires a determination of the baseline level of $^{137}$Cs for the study area. Several studies have cautioned against using fallout measurements to estimate total $^{137}$Cs loads in soils of a watershed. Measurements of actual $^{137}$Cs should be made at a noneroding site in the catchment. By comparing $^{137}$Cs measurement at a study site with the baseline level, one can determine whether erosion (less $^{137}$Cs present than at the baseline site) or deposition (more $^{137}$Cs present than at the baseline site) has occurred.

While there are limitations to the use of fallout $^{137}$Cs to estimate erosion, they are no greater than those associated with other techniques. Campbell et al. [67] suggest that the errors of the $^{137}$Cs technique may be less than current techniques used by soil scientists and geomorphologists to study erosion. If we understand the limitations and design studies to reduce the effects of these limitations, then measuring the concentration of $^{137}$Cs across the landscape can provide accurate and valuable information on erosion.

## 5. CONCLUSIONS

Thirty years of research have shown that the distribution of fallout $^{137}$Cs on the landscape can be used to measure soil loss. Measurements of spatial patterns of $^{137}$Cs can provide unique insights into soil movement and redeposition within a landscape element that other methods cannot provide. The $^{137}$Cs method is often the only way to get actual measurements of soil loss and redeposition. As such, research should continue the development of the technique to better understand the changing landscape. Applications should also be encouraged in areas of the world where resources are limited for developing long-term erosion monitoring programs.

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