MEASURING OF SOIL EROSION AND DEPOSITION WITH RADIOACTIVE FALLOUT CESIUM-137: A REVIEW

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Abstract

Soil erosion and deposition is a natural process and many human activities have increased frequency and rates of soil erosion. The use of ^{137}Cs measurements for investigating soil erosion and sediment redistribution within the landscape is now well established. Radioactive fallout ^{137}Cs deposited across the landscape from atmospheric nuclear tests and stick hard with clay particle very strongly. By measuring spatial patterns or ^{137}Cs in vertical and horizontal planes across the landscape, rates or soil loss or deposition can be measured for different parts or a watershed. Radioactive fallout is broken down into three components: atmospheric fallout is spatially uniform; transfer to the soil is spatially uniform; and no redistribution occurs during the transfer process. It is important to understand how bomb-derived ^{137}Cs fallout interacted with particles at the soil surface. Furthermore, as it is the surface soil which is mobilized by most wind and water erosion processes, it is important to determine how the ^{137}Cs content at the surface has changed over time. The technique relies upon a number of assumptions that this review evaluates in order to establish how soil erosion and deposition can be measure from the use of ^{137}Cs a fallout radio nuclide.

Key wards: Soil erosion and deposition, ^{137}Cs, measurement

Introduction

Soil erosion and deposition of eroded soil in fields, floodplains, and water bodies are major environmental concerns around the world. Although soil erosion is a natural process, many human activities have increased rates of soil erosion. Soil erosion reduces soil productivity, scars the landscape, and causes downstream damage. Sediment accumulation in water bodies affects water quality, causes loss of storage capacity, affects biological activity, and reduces recreational potential.

The radioisotope ^{137}Cs has been extensively used to provide information about soil erosion. In their bibliography of publications on ^{137}Cs, Ritchie and Ritchie (2003) cite nearly 3000 papers never-the-less only around 10% of these papers deal directly with its use in measuring soil erosion, and there has been a fall-off in the publication rate since a peak in the late 1990s, the bibliography is testament to the widespread use, and acceptance, of the technique to provide information on rates of soil erosion over decadal timescales which few have questioned or challenged (Higgitt, 1995).

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The Radio isotope [137]Cesium displacement by runoff and mechanical process of erosion, was later confirmed and compared to the empiric modeling by other researchers, specifically relating to research results presented by Felah, 2010. The same applies to specifying the emitting sectors of sediments in order to evaluate the silting up of dams and for dating deposited sediments and check dams against fast sedimentation (Sogon, 1999; Zhang *et al.,* 2015). With regard to the [137]Cesium behavior with soil element, several studies were devoted to specifying the cation exchange capacity of clay element in soils such as illite, smectite and vermiculite which have higher affinity to [137]Cesium (Staunton and Roubaud, 1997, Yigzaw, 2009; and Mabit *et al*., 2013). The [137]Cesium fallout has been significantly more important in the northern hemisphere- precisely around latitude 45° north - than in the southern hemisphere due to the greatest flux of [137]Cesium since 1954 (Zapata, 2002; Zhang *et al*., 2015 and Ni *et al*., 2017).

The ^{137}Cs method underwent significant development and became a well-established method for soil erosion quantitative assessment in the 1990s and early 2000s (Walling and Quine, 1995; Zupanc and Mabit, 2010; IAEA, 2014).

It is widely used for erosion studies to provide key information on sheet and rill erosion rates and soil/sediment dynamics and redistribution. This work is supported by the international research community. The ^{137}Cs method was described several times in detail in several handbooks (Walling and Quine, 1993; Zapata, 2002; Mabit *et al*., 2014), the last two being based on the results of the mentioned CRPs

These radioactive isotopes are of paramount importance as their introduction into the soil coincides with the major changes in the rural landscape and natural vegetation cover over the last five decades in Tunisia steppe, which has been marked by the emergence of new agricultural structures increasingly, based on mechanization, mono-cropping and unsuitable tillage methods (Azaiez, 2016). The use of the polydisc tractor caused the radioactive elements to be dragged deep, thus allowing their leaching with the clay fraction (Zhang, 1999 & Zhang *et al*., 2015). However, emphasis must be laid on the circumstances where it is appropriate to apply the isotopic method that is not prescribed to be routinely used in such cases by rote (Zhang, 1999; and Fulajtar *et al*, 2017).

The technique relies on a number of assumptions that have been outlined by Walling and Quine (1992), amongst others. These assumptions are that (1) the fallout is locally, spatially uniform, (2) the fallout is rapidly and irreversibly fixed onto soil particles; (3) the subsequent redistribution of fallout is due to the movement of soil particles; and (4) estimates of soil erosion can be derived from measurements of ^{137}Cs inventories. In addition to these assumptions, two other factors that affect the quality of the information that the use of ^{137}Cs can provide about soil erosion are (1) error margins of ^{137}Cs inventories, and (2) the accuracy of the understanding of soil-erosion processes. The first attempts to use ^{137}Cs measurements for estimation of soil erosion were carried out in the 1960-ties (Yamagata *et al*., 1963; Rogowski and Tamura, 1965) and since then ceasium-137 has been used to study soil erosion and deposition. Cesium is a fission product, it is a gamma emitter with energy

of 661.6 ke V and its half-life is 30.02 years. These properties make the ^{137}Cs isotope a valuable tracer of soil erosion in the medium term. In addition, the counting of the sample is very easy. For the last 35 years, the fallout of ^{137}Cs has been widely used as an environmental tracer to study soil erosion (Ritchie and McHenry, 1990; Zapata, 2003). The aim of this paper is to provide a comprehensive evaluation of the validity of the assumptions underpinning the technique; to assess the importance of the other factors; and, hence, to produce an appraisal of both what has been claimed and what can be learned about soil erosion from the use of ^{137}Cs. The purpose of this article is to review the development and application of a technique using radioactive fallout ^{137}Cs to measure rates and patterns of erosion and sedimentation.

Materials and methods

This is an exclusively a review paper that does not have specific methods of studies are followed. Secondary sources data and information were collected and used in this review paper. Different books, booklets, proceeding, journals, newsletters and consultancy report as well as internet browsing was being practiced. All necessary information was compiled and arranges accordingly for better understanding.

Discussions

Properties of radioactive ^{137}Cs make it unique as a tracer for studying erosion and sedimentation. Generally the temporal patterns of ^{137}Cs input are characterized by: (1) detectable ^{137}Cs began in 1954; (2) the first peak appeared in 1958/1959; (3) the second peak occurred at 1962-1964; (4) and the termination of ^{137}Cs input around mid-1980s. After Chernobyl incident in 1986 some additional areas has been contaminated with ^{137}Cs. This annual variation has been successfully used to determine sediment accumulation rates in a wide variety of depositional environments including reservoirs, lakes, wetlands, coast areas, and flood plains.

Atmospheric fallout of ^{137}Cs

Atmospheric ^{137}Cs radionuclide fallout to earth surface varies over time. It is generally accepted that fallout of ^{137}Cs enhances by rainfall as wet deposition is occurs more efficient. As it is generally known that wet deposition is more efficient than dry deposition (Smith, 1991) results that the ^{137}Cs fallout occurs mainly during rainfall (Clark and Smith, 1988). Sampling ^{137}Cs in soils all over the UK, the highest values were found where higher precipitation occurs (Cawse (1983) and Basher (2000) obtained a strong relationship between ^{137}Cs levels in soil and rainfall.

The local pattern of rainfall reflects the local spatial pattern of fallout in the specific area. In a unit of localities that receive their precipitation from frontal rain, for example, it would be more reasonable to assume a bias in rainfall amount towards the rain-bearing direction, rather than to assume a spatially uniform amount.

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Cesium-137 cycle on the landscape

Although dry deposition is important locally around nuclear test sites, on a global scale, ^{137}Cs deposition from the atmosphere to the landscape (Fig. 2) has been found to be strongly related to rainfall with total fallout varying linearly with rainfall within latitudinal zones.

Three primary components: vegetation, soil and water involve transport of ^{137}Cs in the landscape. Although biological and chemical processes can move limited amounts of ^{137}Cs between vegetation, soil, and water, physical factors are the dominant processes transferring ^{137}Cs in natural systems (Fig. 1) (Ritchie *et al.*, 1974). Because ^{137}Cs is uniformly distributed across the landscape and strongly adsorbed on soil particles, radioactive fallout ^{137}Cs can be used as a tracer for studying the physical processes of erosion and sedimentation. Therefore, erosion and deposition rates and patterns can be measure by spatial measurements of ^{137}Cs.
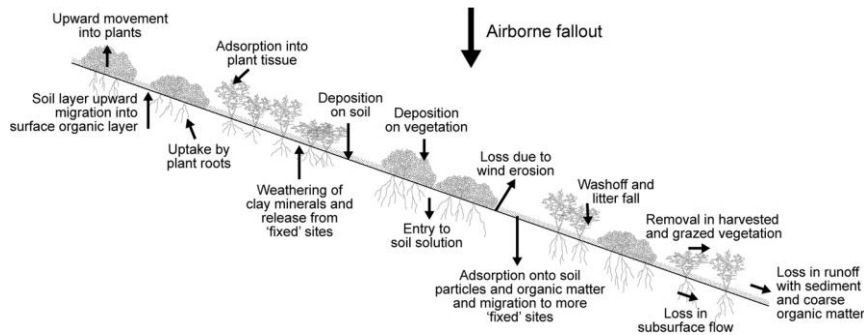

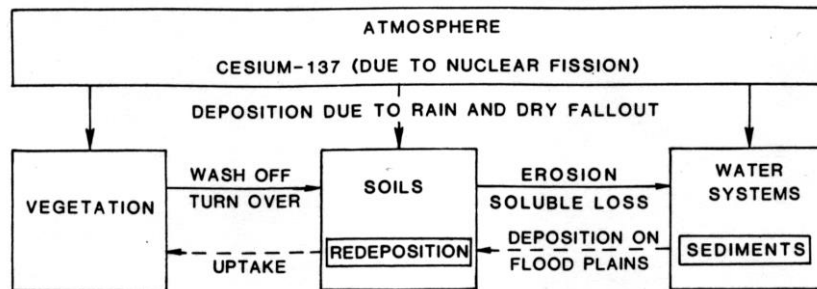**Fig. 1.** Pathways of ^{137}Cs movement through the soil–plant system.

Fig. 2. Diagram of the ^{137}Cs cycle on the landscape.

Behavior of ^{137}Cs in the soil

Atmospheric fallout of ^{137}Cs mainly falls first on the vegetation in a vegetated environment that subsequently transferred to the soil through both liter fall and wash off. Cesium-137 is strongly fixed by soil particles (clay and organic particles) minerals and become non-exchangeable although this monovalentcation with low hydration energy. Clay

selectivity is associated with its high charge density and frayed edges, once cations such as the K^+ and the Cs^+ penetrate the layers and cause them to collapse through electrostatic attraction force. This causes the cations to be trapped or fixed.

Cesium-137 adsorption studies revealed that most soils could retain ^{137}Cs when applied in low quantities, as it occurs in the fallout. Extraction was done repeatedly with many different chemical agents which results is strongly adsorbed and fixed by soils; however, their movement is restricted by lixiviation and other natural chemical processes.

Physical processes are the only way for redistribution of ^{137}Cs from the fields (Livens and Loveland, 1988; Livens and Rimmer, 1988). Depth distribution of ^{137}Cs in the profile mainly depends on uncultivated soil after the fallout. In non-cultivated soils ^{137}Cs concentration decreases exponentially with the depth, whereas in cultivated soils, it shows a uniform distribution until the depth of the plough layer.

Adsorption of ^{137}Cs by the soil particle

Adsorption of ^{137}Cs varied over time and types of soil particle. The fixation of ^{137}Cs by clay minerals in soils is a rather slow process which obviously extends over many years (Bunzl *et al*. 1995). The affinity for ^{137}Cs in clay minerals varies, and that whereas illite appears to have a very large preference for ^{137}Cs over other available cations, montmorillonite and vermiculite show only a small preference (Eberl, 1980). Although, the availability of exchange sites within any soil is such that, given dosage rates from fallout, this will not be a limiting factor in its adsorption, the presence of different clay minerals in soils will affect subsequent loss of ^{137}Cs from the soil due to its bioavailability (Francis and Brinkley, 1976).

Cesium-137 to study erosion

The relationship between soil erosion and movement of fallout radionuclide's studies began in early 1960s. Principles of the use of ^{137}Cs for the assessment of soil redistribution have been described in several studies (Mabit *et al*. 2008). The total ^{137}Cs was greater than input from fallout and/or the depth distribution of ^{137}Cs in soil profiles was greater than that measured in a non-eroded site or deeper than the plow layer at deposition sites in the watershed. A baseline input of ^{137}Cs must be determined to use fallout ^{137}Cs to measure erosion. This baseline input to the environment is due to fallout from the atmospheric nuclear testing rather than natural sources and across the landscape its initial distribution is normally uniform or can be related to measurable environmental gradients. Direct measurement of actual ^{137}Cs in a watershed is easy and local input of ^{137}Cs to a landscape unit can be estimated by measuring ^{137}Cs in soil profiles where neither erosion nor soil deposition has occurred (Ritchie and Ritchie 2008).

References site

Reference sit is the main consideration to measure and identify for measuring soil erosion and sedimentation by using ^{137}Cs technique. It is the most important to find out the references site for sampling. The references site is the unit local area where soil are not cultivated or disturbed after radionuclide fallout. The selection of reference sites is the key for successful execution of a ^{137}Cs based erosion study. It is used to establish the ^{137}Cs inventory in the study region against which the changes in inventory, both in disturbed sites and in depositional environments, can be assessed.

Basic of ^{137}Cs technique

The key feature of ^{137}Cs behavior in the soil, on which the method is founded, is the strong bonding of ^{137}Cs to the soil particle and its chemical stability in soil environments. The basis of the ^{137}Cs technique can be summarized as follow:

1). Caesium-137 was deposited as fallout primarily during the late 1950s and the 1960s and in most environments was rapidly and strongly absorbed by soil particles at the ground surfaces.

2). Subsequent redistribution of the radio-cesium reflects the movement of soil particles since the ^{137}Cs remains absorbed and moves in associated with the soil particles.

3). If it is assumed that the initial distribution of the ^{137}Cs fallout input was uniform, the deviations in the measured distribution of ^{137}Cs from the local fallout inventory represent the net impact of soil redistribution during the period since ^{137}Cs deposition. In the same area higher inventory of cesium indicates deposition and lower inventory indicates erosion of soil particles.

4) If a relationship between ^{137}Cs loss and gain and soil loss and gain can be established, it will be possible to estimate rates of soil erosion and aggradations from ^{137}Cs measurement.

Measuring and sampling methodology

The following items should be observed before using ^{137}Cs technique:

a) The level of the ^{137}Cs inventory, the history of soil use, the topographical information of the area and the meteorological data during ^{137}Cs deposition period;

b) The topographical recognition of the area in order to define the sampling strategy and identifying the potential erosion locations;

c) In each area, a grade or multiple transect may be used, with uniform distances between the sampling points and the selection of reference points that are adequate to determine the local ^{137}Cs input should also be considered;

c) A sampling point in layers must be included for each soil use in order to provide information on ^{137}Cs vertical distribution; and

d) The choice of the geometry to be used such as detector (efficiency and resolution in energy), sample size, calibration procedures, counting time, etc.

Measurement of ^{137}Cs radio nuclides

Measurement of ^{137}Cs inventory from soil sample using bulk and core sampling method, bulk samples collected within the top 10 cm depth of different landform points along the hill slope. Core samples collected within the top 30 cm depth from different landforms such as top, middle and lower slope. In order to estimate the erosion and deposition within the catchments, bulk and core sampling will be also taken from the undisturbed soils from a reference site. For laboratory analysis, all samples will dry at room temperature, sieving (2 mm mesh sieve) and weighing. The radioactivity of ^{137}Cs in the soil samples can be measured by high-purity germanium (HPGe) gamma spectrometry detector, counting the gamma emission for 7200 seconds and estimating the photo peak at 662 keV. The ^{137}Cs activity will be expressing on a mass basic. The areal inventory (Bq m^{-2}) will be obtaining from the product of specific activity (Bq kg^{-1}), the bulk density (kg m^{-3}) and depth (cm). In order to calculate the total amount of ^{137}Cs per unit area, the ^{137}Cs concentrations (Bq kg^{-1}) are converted into area activity (Bq m^{-2}) by using the equation of Sutherland (1990):

^{137}Cs inventory $= \sum C_i \times BD_i \times DI_i \times 1000$

^{137}Cs inventory = total area inventory (Bq m^{-2}),

i = sampling depth,

n = maximum number of sample depth with detectable ^{137}Cs,

Ci = activity concentration per unit mass (Bq kg^{-1}) for depth i,

BDi = dry bulk density (Mg m^{-3}) for depth i,

Di = depth increment (m) for sample i,

By measuring the amount of ^{137}Cs in the soil, sediment redistribution patterns can be determined and soil erosion/deposition rates for specific fields, can be calculated by Mass Balance Model 2.

Advantage and constraints

The ^{137}Cs technique has some advantages over conventional techniques of measuring sediment accumulation rates.

1). The approach provides retrospective information. Past erosion rates can be estimated from samples collected at the present time. Erosion and deposition rate can be measured altogether thus quantify net erosion and sedimentation export.
2). The assessment of soil redistribution provided by ^{137}Cs integrates all processes involving soil particle movements (water, wind and tillage erosion).
3). The technique permits quantification of soil loss and deposition associated with sheet erosion, which is difficult to assess using classical approaches at the field scale.
4). Although ^{137}Cs is commonly used retrospective, by comparing the inventories measured at a study site with the local reference inventory, it can also be used for ongoing monitoring of soil redistribution by comparing the inventories measured at specific points within the study site between successive sampling campaigns separated by a period of several years.
5). Sampling is relatively simple and cost-effective and can be completed in a relatively short time, depending on the sampling density and the size of the area investigated.

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Constrains

1). In the southern hemisphere ^{137}Cs inventories are low and gamma analysis will require greater count times to obtain an acceptable precision for the measurements.
2). The Chernobyl accident provided additional fallout inputs that shout be taken into account otherwise the ^{137}Cs measurement will primarily reflects erosion before 1986 thus measurement and will not be perfect.
3). The technique is primarily suited to estimating medium-term (i.e. 50 years) average erosion rates and cannot readily provide the information needed to document changes in erosion rates linked to short-term changes in land use and managements practice.
4). It is very important to determined reference inventory accurately. In mountain regions where rainfall is high variability, stony soil, areas where snow represents a substantial proportion of the annual precipitation and arid and semiarid areas with poor vegetation cover reference samples determination is problem.

Conclusion

Cesium-137 is among the most common heavy fission products and this high fission yield results in an abundance of ^{137}Cs in spent nuclear fuel, as well as in regions contaminated by fission byproducts after nuclear accidents (OECD Nuclear Energy Agency, 2002). Research beginning in the late 1960s has shown that ^{137}Cs deposited across the landscape by fallout from nuclear test is a unique and useful tool for studying erosion and sedimentation. Cesium-137 has also been used to determine the sediment accumulation rates in a wide variety of depositional environments for sediment deposited since 1954. The reference value of 137Cs inventory is very important to measure where areas contaminated by "Chernobyl caesium" the application of this method may be difficult as well as the calculation of value of soil erosion and deposition strongly depends on the model used. It is our pleasure to note that, Bangladesh Institute of Nuclear Agriculture (BINA) start doing research with ^{137}Cs and a high-purity germanium (HPGe) gamma spectrometry detector for measuring soil erosion and deposition in the laboratory.

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