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^{137}Cs – a potential environmental marker for assessing erosion-induced soil organic carbon loss in India

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The use of Cesium-137 (^{137}Cs) as a potential environmental marker was examined for estimating soil erosion induced carbon losses on slopping agricultural land. Depth-wise incremental soil samples were taken from uneroded reference sites and four levels of cultivated slopping lands representing different erosion phase in Doon valley region of India. Comparing the ^{137}Cs inventories for eroded sites with the reference inventory, the erosion rates were computed. The estimated erosion rates were then compared with the actual measured values of erosion at each erosion phase. Since soil erosion preferentially removes the finer soil particles, these results were used to assess erosion induced loss of OC. The result indicated that erosion in different phases relocate 137 kg C ha^{-1} in slightly eroded plots to 384 kg C ha^{-1} in severely eroded plots which in turn contributes to 27 to 77 kg C ha^{-1} the atmosphere as net source of C respectively.

Keywords: ^{137}Cs technology, soil erosion, soil erosion induced C-loss, soil conservation, slopping agricultural land.

SOIL erosion at slow rates is acceptable[1]. However, if it goes beyond the soil regeneration rate, then soil erosion becomes a destructive process[2–4]. Anthropogenic activities such as intensive cultivation and inappropriate soil management techniques have accelerated the process of soil erosion, therefore, worldwide it is now described as the principal form of degradation[1,4]. The demand for more agricultural productivity increased the pressure on land, leading to accelerated soil loss[5–7].

Hill and mountain landscapes are most susceptible to erosion. Globally, nearly 1.1 billion ha (b ha) of land area is affected by water-induced erosion, of which about 0.75 b ha is in a severe state[1]. Erosion process impacts the redistribution of soil material, including carbon colloids within a landscape[8–12].

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Globally, the amount of carbon displaced by erosion ranges between 4.0 and 6.0 Pg yr^{-1} (1 Pg = 10^{15} g). Therefore, this component must be included while measuring the C budget at regional or global scale[1]. As estimated globally, erosion redistributes about 75 Pg of soil and 1–5 Pg of soil organic carbon (SOC)[13,14] from the soil ecosystem per annum[15]. Approximately 20–30% of the eroded C is mineralized leading to 0.7–1.2 Pg C yr^{-1} released to the atmosphere[16].

Some studies have indicated that soil erosion promotes carbon sequestration within the biosphere[8,13]. However, very strong erosion events will displace large amounts of C from soil. The intensity and frequency of rainfall primarily affect the long-term erosion-associated C loss or depletion[17].

According to Ritchie and McCarty[11], carbon concentration in topsoil is strongly correlated with caesium-137 (^{137}Cs). Their finding implies that the inventories of ^{137}Cs can be employed to understand the movement of soil and associated carbon on a landform. This relationship is mainly due to favoured removal of both elements by the physical process of soil erosion[18]. Takenaka *et al.*[19] also observed similar correlation of ^{137}Cs with SOC concentration in Japanese forest lands.

^{137}Cs is regarded as a widespread environmental marker in soil redistribution studies because of its strong attraction to clay particles and relatively long half-life[20–23]. Many researchers have established the strong relationship between ^{137}Cs and clay content[24,25]; and that the proportion of ^{137}Cs increases with increase in clay concentration[26]. Application of ^{137}Cs technology is simple, and estimates can be made by one-time sampling. Therefore, ^{137}Cs technology has been proven as a reliable tool to accurately measure soil erosion[27] and erosion-induced carbon losses (EICL). However, this technology is not popular in India to assess soil loss and deposition on arable hill slopes and catchment areas. Some studies on ^{137}Cs are available in the country[28–32], but only a few reports are known on redistribution of carbon in cultivated area with constant changes typical of northwestern conditions of India.

Environmental markers such as caesium-137, lead-210 and beryllium-7 are being increasingly used during the past 40 years to assess soil erosion and sediment budget. The ^{137}Cs technique has been widely accepted and used[1–3]. Caesium is placed in the alkali group of metals with similar chemical behaviour as potassium. It is expected that caesium will be a surrogate for potassium in chemical exchange and replacement in soil clays. Such chemical behaviour can result in the enrichment of caesium in uneroded soils leading to its irreversible adsorption. Therefore, removal of topsoil is the primary mechanism for ^{137}Cs migration.

Although a range of estimates exists on the extent of land degradation in India, varying from 53 to 188 million hectare (m ha), according to harmonized database 120.72 m ha is degraded with 68% area affected only by water erosion. Variations in estimates are due to different approaches and criteria used in defining type, degree, extent and severity of degraded land. Use of environmental tracers such as ^{137}Cs and ^{210}Pb overcomes most of the drawbacks associated in the widely used approaches and models. Conservation efficiency of different soil conservation measures can also be adjudged following the technique of environmental markers. ICAR-Indian Institute of Soil and Water Conservation, Dehradun, has on-going research programmes since 1960s, encompassing nature, extent and management options to control erosion under different agro-ecological regions, including socio-economic aspects in an integrated manner. However, the radionuclide technique, as an independent tool or as a complementary technique, has not yet been used to study erosion-induced loss of SOC.

Soil erosion involves breakdown of aggregates and separation of soil particles, followed by relocation and deposition of sediments. Each erosion process has a strong influence on the state and dynamics of SOC. Erosion being a selective process, it preferentially removes the low-density organic colloids. We have developed a methodology for quantitative assessment of erosion-induced loss of SOC and its impact on crop yield using environmental tracer (^{137}Cs) in the tropical sub-mountain Indian Himalaya.

The study was conducted in the Doon valley region of Northwestern Himalaya (30°21′0″N, 77°52′31″E; 527.0 m amsl). The climate in the area is subtropical in nature with the hottest average temperature of 37°C and the coldest mean temperature ranging between 4°C and 5°C. The average yearly rainfall is 1625 mm, taxonomically soil in the area is Entisols[33]. The study area has the following features: (a) a range of heavily cultivated croplands affected by different degrees of soil erosion; (b) availability of potential uneroded reference site in the Doon valley region of undisturbed Sal forest area (500 m away from the eroded plots) near the run-off plots taken as reference site (Figure 1).

A field study was conducted on slightly (0.5% slope), moderately (2.5% slope), severely (4.5% slope) and very severely (9.5% slope) eroded plots. Each run-off plot size was 350 m^2. These plots were developed 32 years ago, with continuous cultivation since then. Different slopes induce varying levels of erosion. Based on the cumulative soil loss that occurred during the past 32 years, these run-off plots on different slopes can be considered as different phases of erosion. Actual erosion rates from these plots are being monitored by collecting run-off samples and measuring sediment concentration from each plot. Samples from topsoil surface were collected from both reference and eroded sites for analysis of various physical and chemical properties. A composite sample of *t* 500 g soil was obtained at each location. Soil samples were processed by passing through a 2 mm sieve, and soil

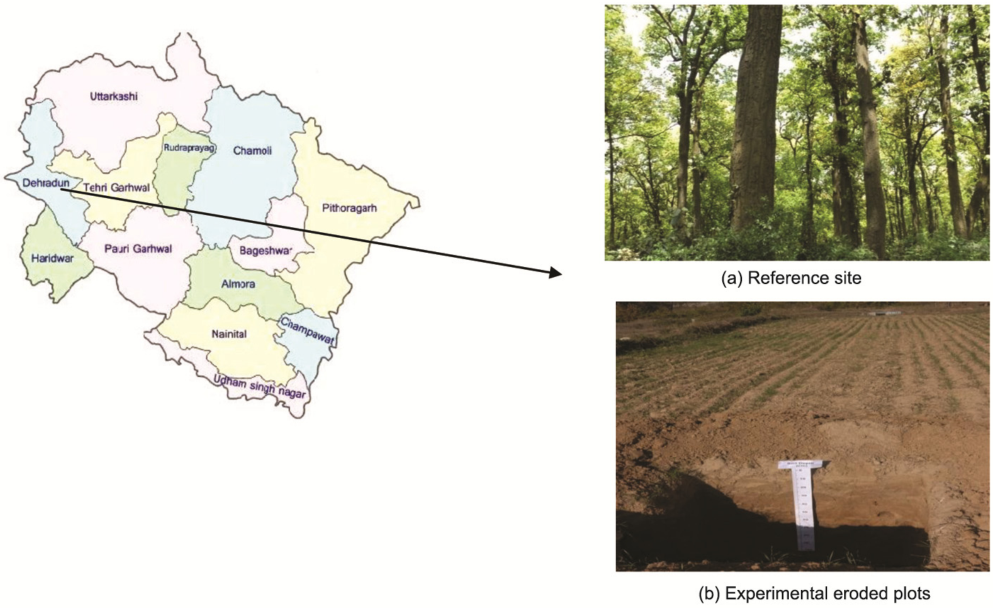

Figure 1. View of the study site.

reaction was determined in a 1 : 2.5 soil : water suspension[34]; SOC was determined by the wet digestion method[35]. Soil bulk density was determined using the method proposed by Blake and Hartge[36].

Soil samples were collected up to 40 cm × 5 cm depth increments from 16 sampling sites (eight from reference sites and eight from eroded sites) to study the vertical distribution patterns of ^{137}Cs and SOC. Depth distribution profiles were sampled using the scraper-plate technique as described by Campbell *et al.*[37]. Processed soil samples were placed in airtight containers and sealed for ^{137}Cs analyses. A total of 128 soil samples were analysed for measuring ^{137}Cs concentration (Bq kg^{-1}).

The measurements of ^{137}Cs in the samples were made using ultra-low gamma spectrometry employing 661 keV gamma line of ^{137}Cs (Canberra Industries Inc. Meriden, model-BE5030, USA). Both the reference materials and samples were placed in containers of uniform geometry so that the detection configuration remained the same. The samples were run for a sufficient period of time (60,000 sec).

The quantification of ^{137}Cs for each profile of the eroded plots was made by comparing the average inventories with that of reference inventory. ^{137}Cs activity was measured in Bq kg^{-1}. Depending upon the requirement, ^{137}Cs concentration was converted to Bq m^{-2} by multiplying it with bulk density of the soil from which the sample was taken. Equation (1) was used for quantification of ^{137}Cs. Soil loss rates were computed by comparing the activity of ^{137}Cs in the run-off plot with the reference site.

These estimated erosion rates were then compared with the actual measured values of erosion from suspended sediment load at flumes during each erosion phase.

$$\mathrm{Cs}_{\mathrm{Red}} = \frac{(\mathrm{C}_{\mathrm{sp}} - \mathrm{Cs}_{\mathrm{ref}})}{\mathrm{Cs}_{\mathrm{ref}}} \times 100, \quad (1)$$

where $\mathrm{Cs}_{\mathrm{Red}}$ is the percentage of redistribution – a negative value represents soil loss while a positive value represent deposition. $\mathrm{Cs}_{\mathrm{ref}}$ is the average inventory at the reference site (Bq m^{-2}). Sample sites with lesser ^{137}Cs than the reference sites are assumed to be eroding, and vice versa. Soil redistribution was calculated depending upon the change in ^{137}Cs concentration in the sampling sites[38–40].

The conversion of $\mathrm{Cs}_{\mathrm{Red}}$ (%) values into rates of soil erosion E (Mg ha^{-1} yr^{-1}) was done using the model presented by Walling and He[39] as given in eq. (2)

$$E = \frac{(\mathrm{Cs}_{\mathrm{Red}} \rho D)}{TP100} \times 10, \quad (2)$$

where ρ is the soil bulk density (kg m^{-3}), D the plowing depth (m), T the time since peak fallout (yrs) and P is the particle size correction factor (taken as unity in the present study).

SOC of the run-off plots was determined by the Walkley and Black[35] method and carbon erosion was calculated using the formula

$$\text{C-erosion (kg ha}^{-1}\text{ yr}^{-1}) = \frac{\text{Erosion} \times \text{SOC} \times \text{CAR} \times 1000}{100}, \quad (3)$$

where CAR is the carbon amplification ratio, defined as the ratio of SOC content in the sediment and SOC in the

Table 1. Analysis of variance in reference and slightly eroded sites

Erosion phases with descriptive statistics	^{137}Cs in eroded site (Bq m^{-2})	^{137}Cs in reference site (Bq m^{-2})	^{137}Cs loss (%)	Erosion (Mg ha^{-1} yr^{-1})	SOC (%)	CAR	C-erosion (kg ha^{-1} yr^{-1})
Northwestern region							
Slightly eroded phase							
(Min–Max) average	(728–933)	(944–1170)	(20.16–23.85)	(7.28–8.61)	(0.55–0.62)	2.96	(125–149)
	846.05	1081.87	21.88	7.90	0.59		136.68
Sum	4230.24	5409.33	109.39	39.50	3.52	2.96	683.40
Variance	7054.02	8004.104	2.66	0.35	0.004	0	103.92
Moderately eroded phase							
(Min–Max) average	(650–810)	(944–1170)	(28.91–36.82)	(10.76–13.70)	(0.52–0.58)	2.85	(167–213)
	729.78	1081.87	32.51		0.55		188.77
Sum	3648.92	5409.33	162.54	60.50	2.74	2.85	943.83
Variance	4114.52	8004.10	8.66	1.20	0.002	0	292.07
Severely eroded phase							
(Min–Max) average	(460–607)	(944–1170)	(48–53.02)	(18–20.47)	(0.47–0.52)	2.76	(252–278)
	542.39	1081.87	49.89	19.26	0.49		261.96
Sum	2711.95	5409.33	249.43	96.31	2.47	2.76	1309.78
Variance	2852.70	8004.10	4.76	0.71	0.004	0	131.15
Very severely eroded phase							
(Min–Max) average	(181–220)	(944–1170)	(76–82)	(29–31)	(0.42–0.52)	2.54	(361–389)
	198.71	1081.87	81.48	31.46	0.46		383.84
Sum	993.57	5409.33	407.42	157.31	2.28	2.54	1919.18
Variance	241.41	8004.10	7.30	1.09	0.001	0	161.88

original soil. Since ^{137}Cs is irreversibly fixed by clays, any subsequent movement of this radionuclide across the slopy landscape is due to physical movement of particles such as erosion[38–41]. Owens and Walling[42] suggested that a good presumption to the amplification ratio is based on a comparison of soil particles of the eroded material with those of the topsoil[43].

All the statistical tests were performed using SPSS 16.0 software. Analysis of variance (ANOVA) was used to compare the data and to test the significance of differences between erosion phases. The means were compared using ANOVA tests. Simple correlation analysis was carried out to test the relationship between ^{137}Cs and SOC concentration ($P < 0.05$). A relationship was established between ^{137}Cs concentration and erosion for all the run-off plots, and soil erosion rates were also measured via direct method collecting run-off samples from all run-off causing events. Similarly, an empirical model, viz. universal soil loss equation (USLE) was employed to estimate erosion rates in these plots.

The highest ^{137}Cs concentrations were found in reference sites, since ^{137}Cs is strongly attached to clay minerals and organic matter fraction[38,44]. The ^{137}Cs data revealed that there were different redistribution patterns in different phases of erosion. In the study areas, the ^{137}Cs concentration was in the range 198.71 ± 15.54 Bq m^{-2} in very severely eroded phase to maximum 1081.87 ± 89.97 Bq m^{-2} in the reference site (Table 1). Among the eroded plots, concentration of ^{137}Cs was the highest (846.05 Bq kg^{-1}) in slightly eroded plot. The lowest concentration was recorded in very severely eroded plots (198.71 ± 15.54 Bq kg^{-1}). The loss of ^{137}Cs was significantly higher in very severely eroded plots. ^{137}Cs inventories decreased linearly with slope, indicating an increasing trend of erosion and SOC loss (Figure 2).

The ^{137}Cs inventory recorded for depth increment profile revealed that soil erosion of around 7.90 Mg ha^{-1} yr^{-1} occurred at slightly eroded phase and 31.46 Mg ha^{-1} yr^{-1} in very severely eroded phase. While the estimated erosion rate was 12.10 Mg ha^{-1} yr^{-1} in moderately and 19.26 Mg ha^{-1} yr^{-1} in severely eroded phase in the Northwest Himalayan region (Table 1). The ^{137}Cs inventory-based assessment for measuring the magnitude of soil erosion is managed and unmanaged ecosystems has been successfully demonstrated by Khodadadi *et al.*[45] on steep hill slopes in the semi-arid regions of Iran. Recently, relative contribution of soil erosion by water has been measured using the same method in Chinese Loess plateau by Zhang *et al.*[46]. Except in slightly eroded phase, the erosion rates in all other phases are 1.2–3.1 times higher than the permissible limit prescribed by Mandal *et al.*[2] for these soils. Therefore, suitable conservation measures and best management practices, especially in moderate to steep slopy lands in the region could bring soil erosion below permissible limit. The appropriate conservation measures which will help control excessive erosion within permissible limit for these cultivated lands are suggested by Sharda and Mandal[47].

SOC was highest in the top layers and decreased slowly through the sub-soil layers. The mean values of SOC concentration varied from 0.46% in severely eroded phase to 0.59% in slightly eroded phase. Strong relationship was found between ^{137}Cs and SOC content of the soil. Selective displacement of clay particles and SOC[48]

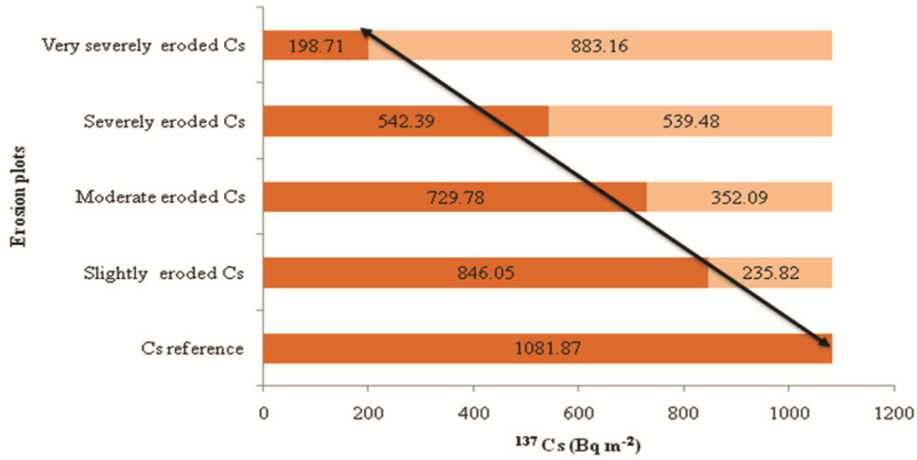

Figure 2. ^{137}Cs inventory in reference and eroded sites.

Table 2. Accuracy percentage calculated for erosion rate using Cs-137 over traditional methods

Experimental plot	Soil erosion measurement	Erosion rate (Mg ha^{-1} yr^{-1})	Accuracy (%)
Slightly eroded phase	Actual measurement	7.6	–
	Cs-137 method average	7.90	103
Moderately eroded phase	Actual measurement	11.6	–
	Cs-137 method average	12.10	104
Severely eroded phase	Actual measurement	19.44	–
	Cs-137 method average	19.26	99
Very severely eroded phase	Actual measurement	33.60	–
	Cs-137 method average	31.46	93

during the erosion process affects the redistribution of SOC in any landscape[1]. Redistribution of soil material and SOC in eroded cultivated land has been reported by Zhang *et al.*[49].

CAR values ranged from 2.96 in slightly eroded phase to 2.69 in very severely eroded phase. Further, suspended sediments were enriched in clay fraction as well (not reported here). These differences of clay content and SOC concentration were probably due to the preferential removal of finer particles[1], causing enrichment of sediments with SOC compared to the original soil[50].

In the present study, EICL was calculated from erosion rate, SOC concentration and CAR that varied from 136.68 to 383.84 kg ha^{-1} yr^{-1} for different erosion phases (Table 2), leading to 27.33–76.76 kg C ha^{-1} yr^{-1} as net C-source to the atmosphere. The results confirm the role of soil erosion as a C source. CAR of sediment loads in the Northwestern Himalaya region vary from 2.69 to 2.96 depending on erosion phases. The eroded SOC is defined as the product of erosion multiplied by SOC content of sediments[51]. In many cases, CAR is the primary source of uncertainty in assessing the direct loss of SOC associated with erosion. In the present study, the CAR values were well considered while calculating EICL.

The results show that ^{137}Cs is more suitable for calculating soil redistribution over traditional methods, as about 93–99% accuracy was observed for severely to very severely eroded phases. Although 3–4% overestimation was observed in slightly and moderately eroded phases, again the accuracy level varied from 96% to 97% (Table 2). Thus, ^{137}Cs technology is a better method for soil erosion studies in the severely intensive croplands. It gives more accurate results for all types of erosion studies, including erosion due to water, wind and gravity, unlike the other traditional practices. Mandal and Dadhwal[52] computed the soil erosion rates for these plots using USLE, which showed that the estimated figures were 1.20–3.18 times more than the actual measured values. By comparing the results using ^{137}Cs inventory method with those of USLE, it has been clearly established that ^{137}Cs-based estimates provided reliable information of net soil loss rates for the Doon valley region of Indian Himalaya while USLE overestimated soil erosion rates. The ^{137}Cs method is more rapid and less expensive for assessing historic, comparative and long-term soil and SOC erosion. Although gamma-ray counting is a little expensive, there is saving in labour cost[53]. Moreover, the accuracy has an effective basis for validating the use of ^{137}Cs measurements to estimate soil and carbon erosion rates on cultivated and uncultivated soils.

The ^{137}Cs method has proved to be a valuable tool for studying erosion intensity and erosion–carbon relationship in different erosion phases in sloping cultivated lands of Northwestern Himalaya, India. The erosion rates estimated using the ^{137}Cs technique are in good agreement with the results obtained using conventional techniques. The results also exhibit that ^{137}Cs could be used as a potential marker for quantifying SOC redistribution.

The ^{137}Cs technology showed better accuracy compared to the traditional adopted methods. Therefore, it can be concluded that by selecting appropriate reference sites and various erosion phases in the Doon valley region of Northwestern Himalaya, or similar topographic regions, the ^{137}Cs technique can be used to determine the erosion intensities in different states of land degradation. Empirical ^{137}Cs conversion models provided reliable estimates of net soil loss rates for the Doon valley region while USLE overestimated soil erosion rates. The ^{137}Cs method has the potential to be an important tool for studying erosion intensity and erosion–carbon relationship. For further validation on the use of ^{137}Cs, a large number of databases is needed in different landscapes and land uses.

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Comparative implementation of the benchmark Dejong 5 function using flower pollination algorithm and the African buffalo optimization

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This communication presents experimental research findings on the application of the flower pollination algorithm (FPA) and the African buffalo optimization (ABO) to implement the complex and fairly popular benchmark Dejong 5 function. The study aims to unravel the untapped potential of FPA and the ABO in providing good solutions to optimization problems. In addition, it explores the Dejong 5 function with the hope of attracting the attention of the research community to evaluate the capacity of the two comparative algorithms as well as the Dejong 5 function. We conclude from this study that in implementing FPA and ABO for solving the benchmark Dejong 5 problem, a population of 10 search agents and using 1000 iterations can produce effective and efficient outcomes.

Keywords: Benchmark, comparative implementation, iteration, optimization algorithms, search agents, test functions.

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