RECENT ADVANCES IN RADIOTRACER TECHNIQUES FOR SOIL EROSION AND SEDIMENTATION STUDIES

Abstract

Globally, soil degradation driven by erosion is a severe hazard to food production and ecosystem services. Approximately 95 million hectares of land are affected by soil erosion in India. Therefore, it is the need for an hour to assess the extent and rates of soil erosion. This chapter explains how fallout radionuclides (FRNs), such as ^{137}Cs, ^{7}Be, ^{210}Pb excess, etc., are useful for studying soil erosion rate. This method can provide retrospective data on erosion/deposition rates and spatial patterns of soil redistribution over short-term (a few days), medium-term (decades), and long-term (centuries) periods. These radioactive inventory data were converted into quantitative estimates of erosion and deposition rates using a variety of theoretical models. Different models, including basic proportional models (PM) and mass balance models (MBM), are extensively employed and require the inclusion of all the crucial factors influencing how these FRNs are distributed in the soil profile. Mass balance model- 3 (MBM-3) is regarded as one of the best models because it also accounts for soil redistribution caused by tillage erosion. In general, the spatial patterns of soil redistribution provided by ^{137}Cs and soil- morphological techniques are comparable. However, the USLE-based model provides accurate estimates of sediment mobilization from slopes but does not adequately represent the spatial pattern of soil redistribution because it does not account for within-slope redeposition. For further validation of the use of the radiotracer technique in different landscapes and land uses, a large number of databases are required.

Keywords: fallout radionuclides (FRNs), simple proportional model (PM), mass balance models (MBMs), USLE

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I. INTRODUCTION

Natural or geological soil erosion is a constructive process with multiple ecological functions, including the formation of alluvial and aeolian (loess) soils, weathering of aluminosilicates and sequestration of atmospheric carbon dioxide, formation and evolution of the landscape with distinct soil types concerning landscape position, biogeochemical recycling, etc. When soil erosion exceeds the rate of geological erosion resulting in severe negative consequences on ecosystem functions and services and unfavorable transformation/division of the terrain, it is called accelerated soil erosion. Globally, soil erosion has reached a level that jeopardizes the food security of a growing global population. It already poses a danger to food production and environmental services. Globally, **1.1 billion hectares** of land are affected by soil erosion, of which **0.75 billion hectares** are in a severe state.

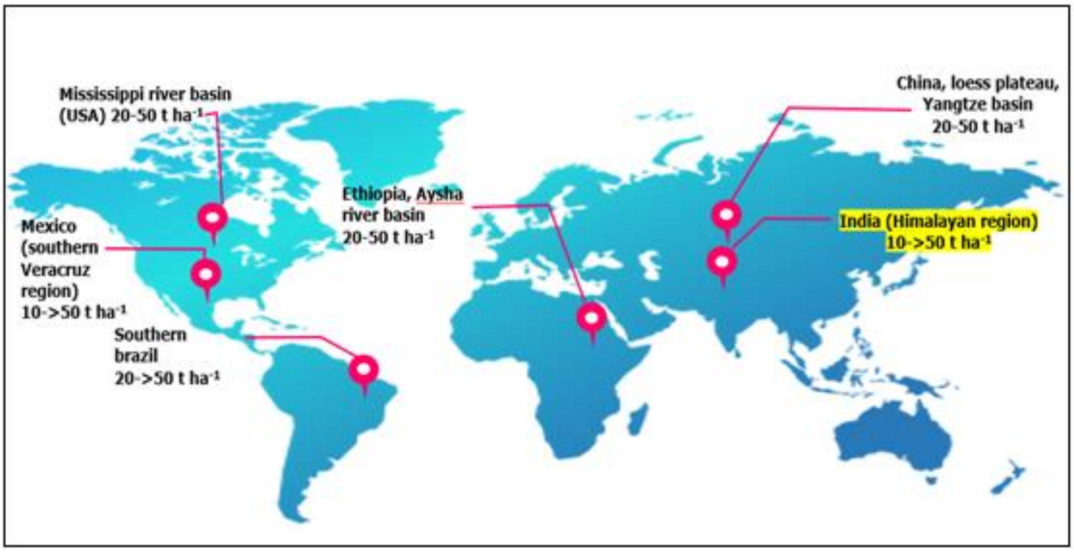


Figure 1: Global Soil Loss Hotspots through Revised Universal Soil Loss Equation (RUSLE) Modelling

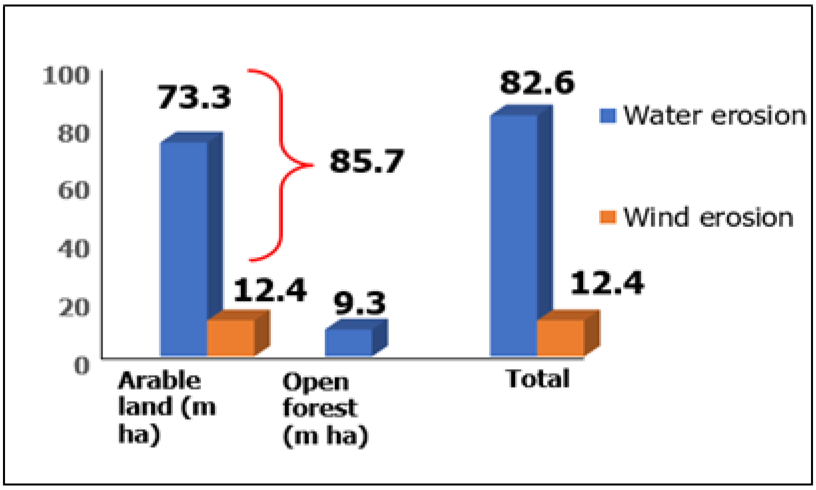


Figure 2: Area (mha) Affected by Soil Erosion in India

In India, around 82.6 million hectares (m ha) of land area in India are prone to water erosion. Wind erosion affects approximately 12,4 million hectares of land. Approximately 61% of the net sown area and 45% of the gross cultivated area is damaged by one of the two types of erosion (NRAA, 2008) (Fig.2). Several on-site and off-site effects of soil erosion are represented in Fig.3 (Lal, 2014)

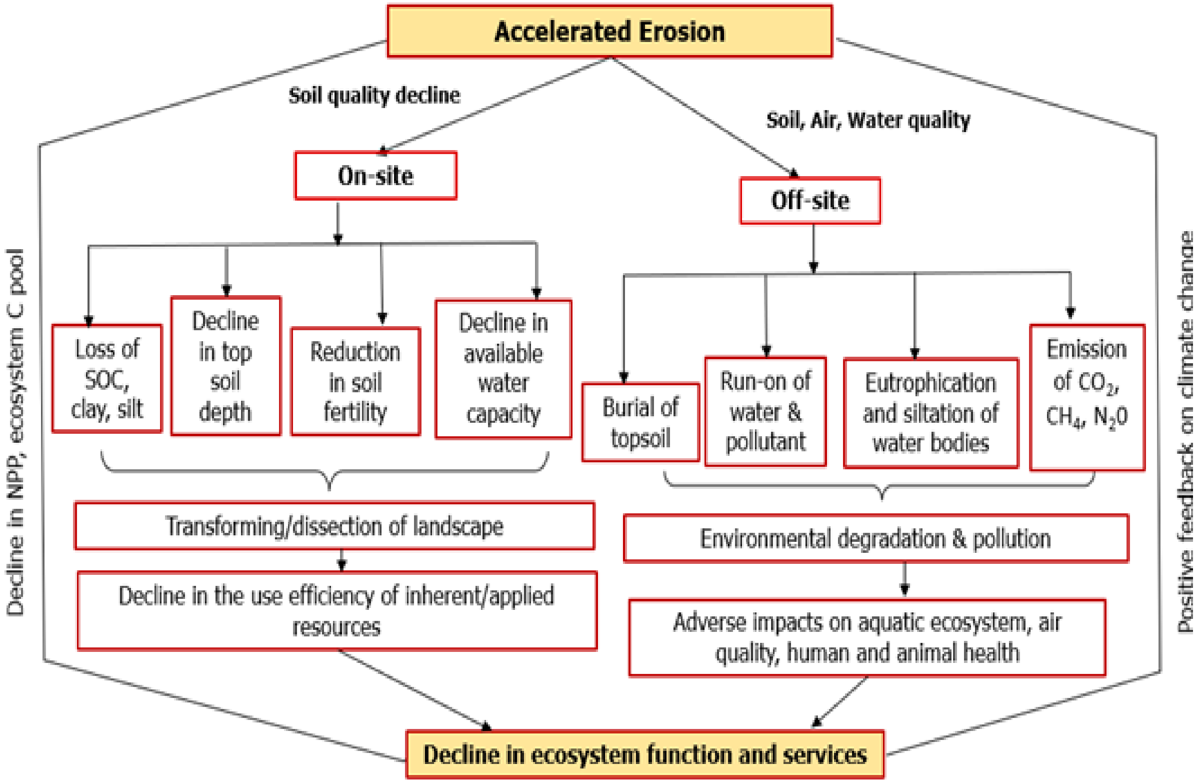


Figure 3: Adverse effect of accelerated soil erosion on ecosystem functions and services

Therefore, systematic assessment of erosion-induced land deterioration using the right methods is the need of the hour. Radiotracer techniques including environmental radionuclides or fallout radionuclides (FRNs) are employed to measure soil redistribution rates (Zapata, 2002).

II. SOIL EROSION ASSESSMENT: CONVENTIONAL VERSUS RADIOTRACER TECHNIQUE

Different tools and techniques for assessing water erosion using geographic information system (GIS), digital elevation model (DEM), empirical models for sediment transport, Ramser's rational formula, runoff measurements *viz.* standing wave fumes, rainfall simulator, etc., have been presented in Fig. 4.

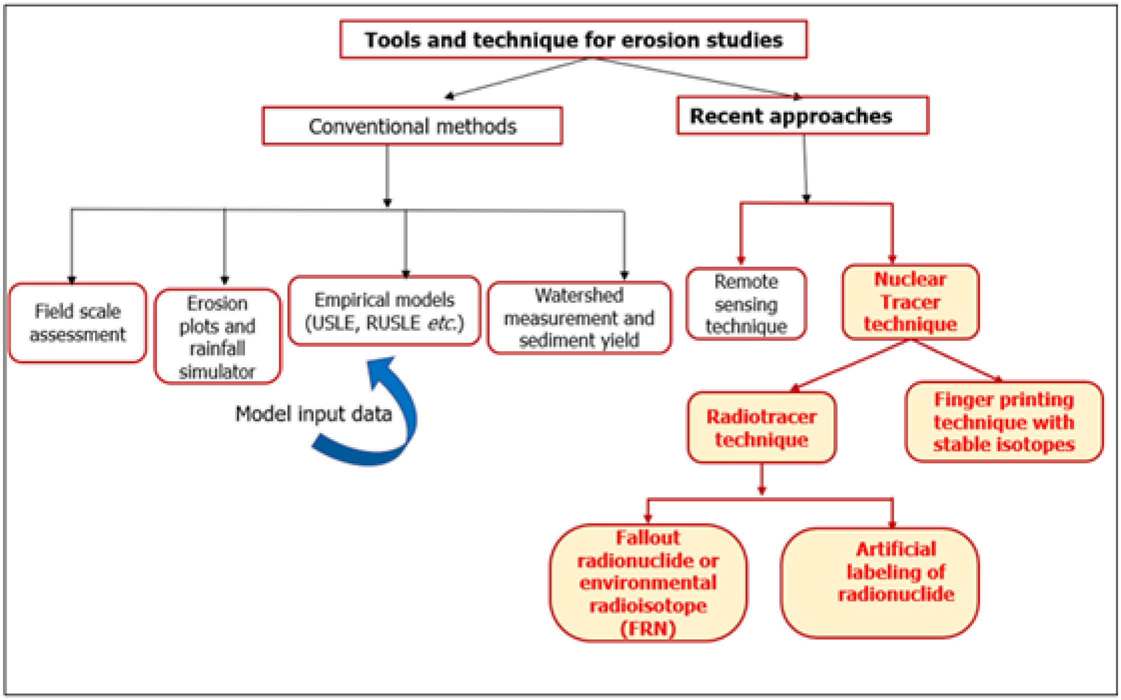


Figure 4: Progressive Development of Techniques for Erosion Studies

Nuclear approaches, such as fallout radionuclides (FRNs) and artificially labelled radionuclides, can supplement traditional erosion measurement and modelling. Table 1 lists the major limitations of traditional approaches and the unique benefits of radiotracer techniques.

Table 1: The Main Advantages of the use of the Nuclear Tracer Technique vs. Conventional Erosion and Sedimentation Techniques

Major limitations of Conventional Methods	Advantages of radiotracer techniques
Modeling: • Precise information (such as Digital Elevation Model (DEM), climate, soil, and land-use data) is necessary • Complexity • Non-user-friendliness • A realistic model should be verified with actual data gathered using other traditional methods.	**Fallout radionuclide Technique** • Single sampling within a short time • Site disturbances are minimum • Retrospective measurement of erosion and deposition rate • Short, medium, and long-term soil-redistribution rate • Time and resource efficiency • All types of erosion • Avoids long-term monitoring program
Rainfall simulator with erosion plots: • At least 10 to 15 years of measurement are required to take climate variability into account • The small measuring scale prevents	**Artificial labeling of radionuclide** • Time and location independency

consideration of all erosion forms. • Climatological reliance **Watershed measurement** • Since only net erosion can be monitored, information regarding soil redistribution within the watershed is not available. • To integrate climatic variability, measurements must span at least 10 to 15 years. • Climatological reliance • Measures net production of sediment, not erosion rates.	**Fingerprinting Technique** • Suitable for sediment source identification, and tracing of sediment movement across the landscape at various temporal and spatial scales

Technique: 1

III. INVESTIGATING SOIL EROSION RATE IN AGRICULTURAL FIELDS WITH RADIOTRACER TECHNIQUE USING FALLOUTRADIONUCLIDES (FRN)

Three environmental radionuclides *viz.* cesium-137, lead-137, beryllium-7 (^{137}Cs, ^{210}Pb, and ^{7}Be) have been popularly used to assess soil erosion (Mabit et al. 2018) and the origin of FRN is depicted in Fig. 5.

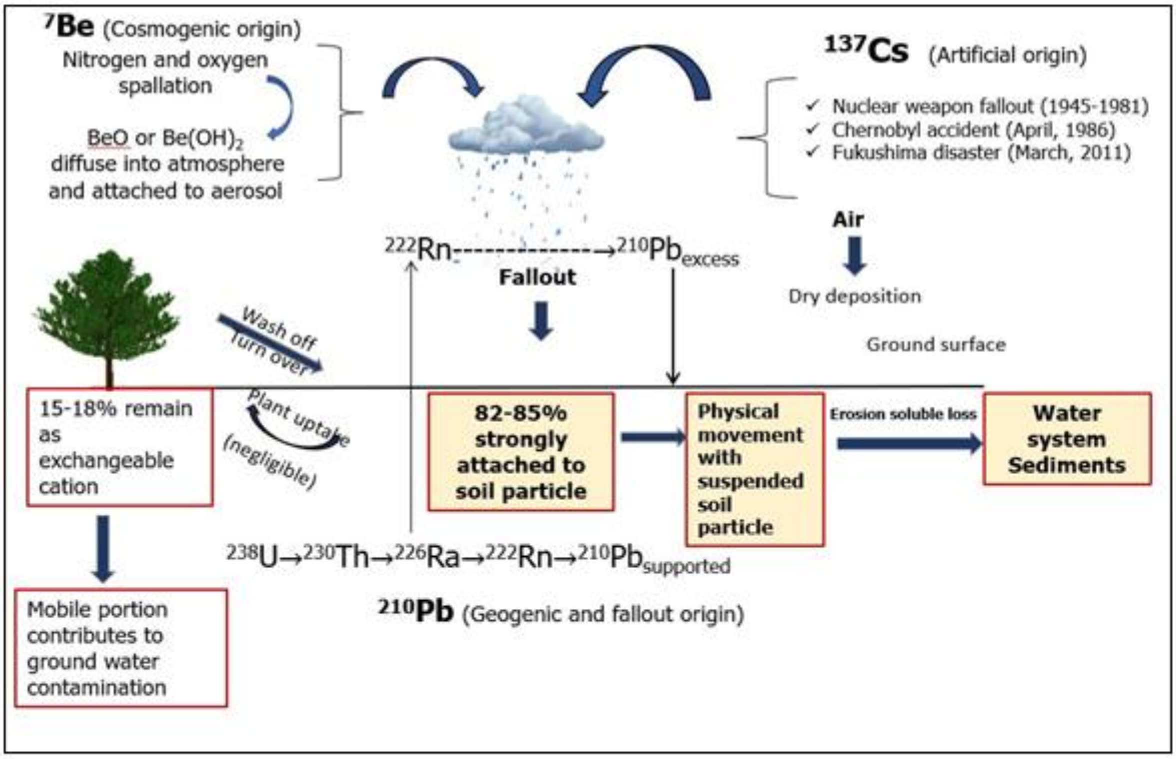
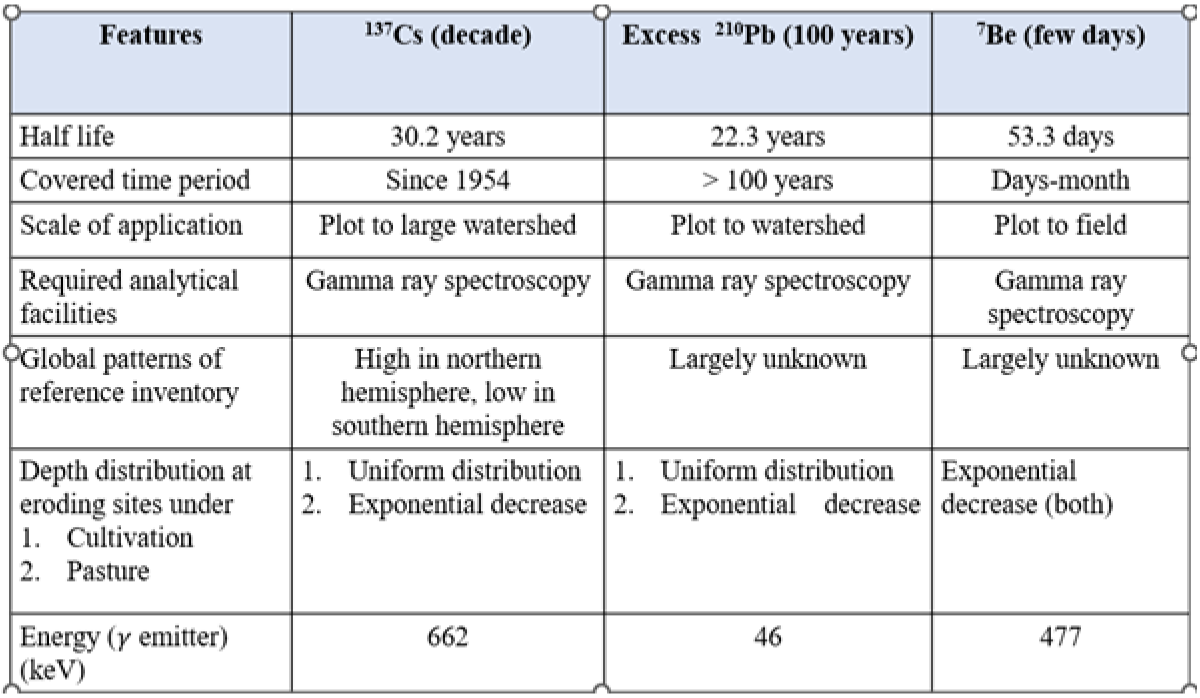


Figure 5: Origin of Fallout Radionuclides (Zupanc *et al.* 2010)

It is challenging to quantify soil loss and deposition related to sheet erosion using other traditional methods, however, FRN procedures combine all processes involving soil particle movements. Individual point sampling enables spatially distributed data on soil redistribution rates and patterns. Table 2 lists some of this FRN's key characteristics.

Table 2: Comparison of the Key Features of Fallout Radionuclides



Features	^{137}Cs (decade)	Excess ^{210}Pb (100 years)	^{7}Be (few days)
Half life	30.2 years	22.3 years	53.3 days
Covered time period	Since 1954	> 100 years	Days-month
Scale of application	Plot to large watershed	Plot to watershed	Plot to field
Required analytical facilities	Gamma ray spectroscopy	Gamma ray spectroscopy	Gamma ray spectroscopy
Global patterns of reference inventory	High in northern hemisphere, low in southern hemisphere	Largely unknown	Largely unknown
Depth distribution at eroding sites under 1. Cultivation 2. Pasture	1. Uniform distribution 2. Exponential decrease	1. Uniform distribution 2. Exponential decrease	Exponential decrease (both)
Energy (γ emitter) (keV)	662	46	477

IV. FALLOUT RADIONUCLIDE TECHNIQUE: IMPORTANT PARAMETERS

1. **Activity Concentration:** Radioactivity per unit of volume or mass *e.g.* Bq L^{-1}; Bq kg^{-1}
2. **Inventory**: Radioactivity per unit area (Bq m^{-2}) or areal activity.
3. **Inventory= CM/S**
4. Where C is activity concentration (Bq kg^{-1}), m is the dry mass of collected soil core and S is the cross-sectional area of the sampling tube
5. **Cumulative mass depth (ζ)** or **areal mass** (kg m^{-2}):
6. z
7. $\zeta = \int \rho (z') dz'$
8. 0
9. Where ρ is soil density, z is actual soil depth
10. **Relaxation mass depth ($h0$):** The soil mass depth (kg m−2) at which the concentration of RNs reduces to 1/e of the concentration at the ground surface

V. RECENT ADVANCES IN THEORETICAL MODELS ASSOCIATED WITH THE FALLOUT RADIONUCLIDE TECHNIQUE

Quantitative estimates can only be produced if there is a reliable technique to translate the measured inventory at a specific sample location into an estimate of erosion or deposition there. Various approaches are used to convert FRN inventory measurements to erosion and deposition rates (Walling and He, 1993). These techniques include theoretical models, accounting procedures, and empirical relationships. The models varied from simple proportional models to comprehensive mass balance models and models that identified the primary mechanisms driving FRN distribution in the soil profile. Here, the emphasis has been on excess ^{210}Pbex, ^{137}Cs, and ^{7}Be (Mabit et al. 2018). (Blake et al.1999). Most of the following ^{137}Cs technique's presumptions are shared by these other radionuclides as well:

1. Rainfall is the main source of wet deposition.
2. Strong affinity for soil constituents, especially fine particles
3. For cultivated sites, a homogenized distribution within the plough layer and an exponential drop in mass concentration and inventory with depth down an undisturbed soil profile.
4. Inventories on undisturbed (uneroded) sites were distributed in a remarkably regular manner.

Table 3: Various Conversion Models Applicable to Specific Land-use

	Cultivated	**Pasture**
^{137}Cs	• Proportional model • Simplified mass balance model • Mass balance model 2 • Mass balance model with tillage	• Profile shape model • Diffusion and migration model
^{210}Pb	• Mass balance model 2 • Mass balance model with tillage	• Diffusion and migrationmodel
^{7}Be	• Profile Shape model	• Profile shape model

Table: 4 Parameters Required for Individual Models

Model	**Parameters required**
Proportional model and Simplified mass balance model	Tillage depth, bulk density, year of tillage commencement
Mass balance model	Tillage depth, year of tillage commencement proportional factor, relaxation depth, annual fallout flux
Mass balance model with tillage	Tillage depth, tillage constant, proportional factor, relaxation depth, slope length, and slope gradient for each section of the transact, annual fallout flux
Profile shape model	Profile shape factor

Use of ^{137}Cs as a tracer for assessment of soil erosion and sedimentation studies: Using ^{137}Cs and the USLE approach, Sac et al. (2015) conducted an experiment in western Turkey to compare the annual erosion rate. For uncultivated soil, the proportional model was employed, and for two cultivated soils, the simplified mass balance model (SMBM) and the proportional model (PM) were both used. In general, for high soil erosion rates, like in the Kaysalan case, the differences between the two models become more significant (Table 5). The erosion rates calculated using the PM are consistently less than those anticipated using the SMBM. Because SMBM considers the impact of surfaced ^{137}Cs loss due to erosion in contrast to PM.

Table: 5 Estimation of Average Annual Erosion Rates using ^{137}Cs Technique and USLE Model

Site No.	**Sampling sites**	**USLE (t ha^{-1}year^{-1})**	**^{137}Cs technique (t ha^{-1} year^{-1})**		
			PDM	**PM**	**SMBM**
1	Peynirli (uncultivated)	16	15		
2	Yatagan (uncultivated)	29	36		
3	Kirtas (uncultivated)	28	27		
4	Umez (cultivated)	46		47	70
5	Kayisalan (cultivated)	74		65	116

Furthermore, it was reported that soil losses estimated by the two ^{137}Cs and USLE approaches had a good agreement (R=0.97) (Fig.6). Since the ^{137}Cs technique includes wind erosion while the USLE technique does not, this suggests that the soil loss by wind is not very effective in all of the regions investigated. The large tillage contribution to soil loss has been highlighted by the high erosion rates seen in the cultivated areas using both techniques, but water erosion appears to be the primary contributor among a multitude of others. The SMBM technique would therefore be more appropriate for investigations of water-affected erosion in cultivated settings.

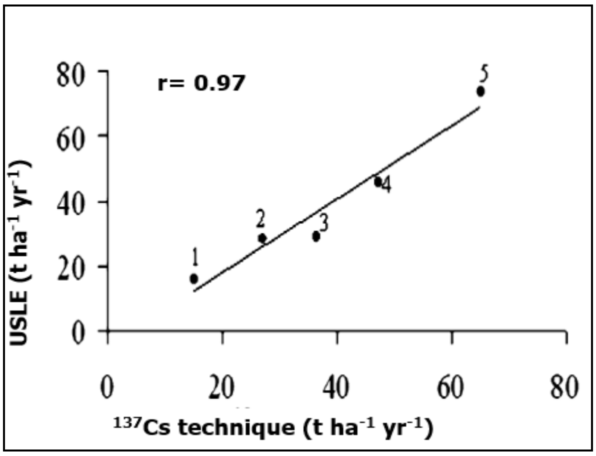


Figure 6: Relative Agreement of Soil Erosion Rate Estimated Through ^{137}Cs Techniques and USLE Method

According to Belyaev et al. (2005), the ^{137}Cs technique outperforms more established techniques including soil geomorphological mapping and the USLE method for determining soil redistribution rate. Although the exact figures range greatly from 8.7 to 24.1 t ha^{-1} year^{-1} for gross erosion, 6.4 to 63.8 t ha^{-1} year^{-1} for within-slope redeposition, which is gross erosion, and 2.2 to 12.2 t ha^{-1} year^{-1} for net erosion, all the techniques used to measure soil redistribution show significant rates of soil redistribution (Fig. 7). The results for estimations of sediment redeposition on slopes and lower areas reported by ^{137}Cs measurements and the soil-morphological technique differ significantly. While both ^{137}Cs calibration models provided reasonable results, soil geomorphological mapping showed substantially greater rates of redeposition (63.8 t ha^{-1} year^{-1}) (6.4 t ha^{-1} year^{-1} from the proportional model and 11.8 t ha^{-1} year^{-1} from the mass balance model). The primary causes of this apparent discrepancy are most likely: (a) a shift in the spatial-temporal pattern of soil redistribution towards decreased deposition and increased erosion after the change in land use in the early 1950s; (b) selective deposition of coarser particles in the bottom, with the finer particles carrying the highest ^{137}Cs activities being transported further to the main valley bottom; and (c) the possible influence of deep linear erosion features, such as ephemeral gullies, mobilizing subsoil material bearing no atmospheric fallout radionuclide content; (d) the insufficient depth of the bulk ^{137}Cs sampling within depositional locations.

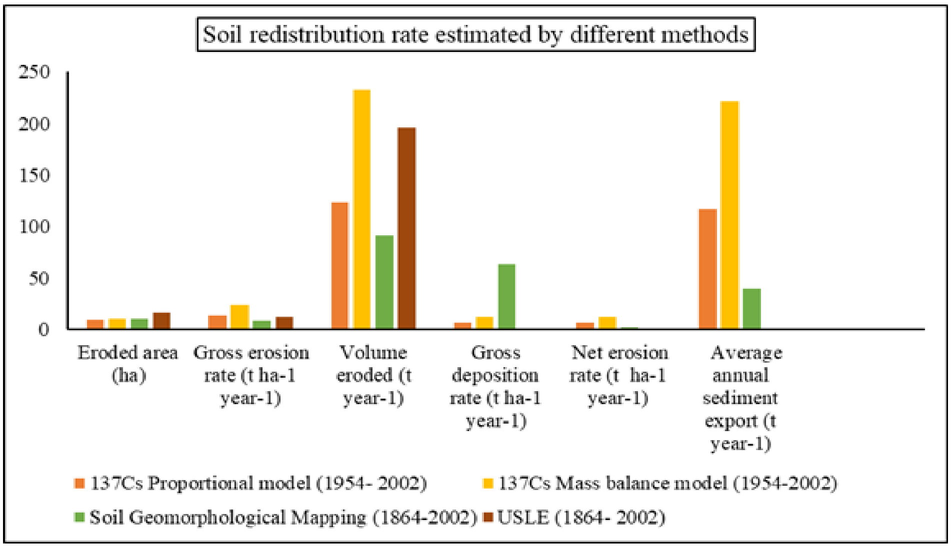


Figure 7: Soil Redistribution Rates Estimated by Different Methods

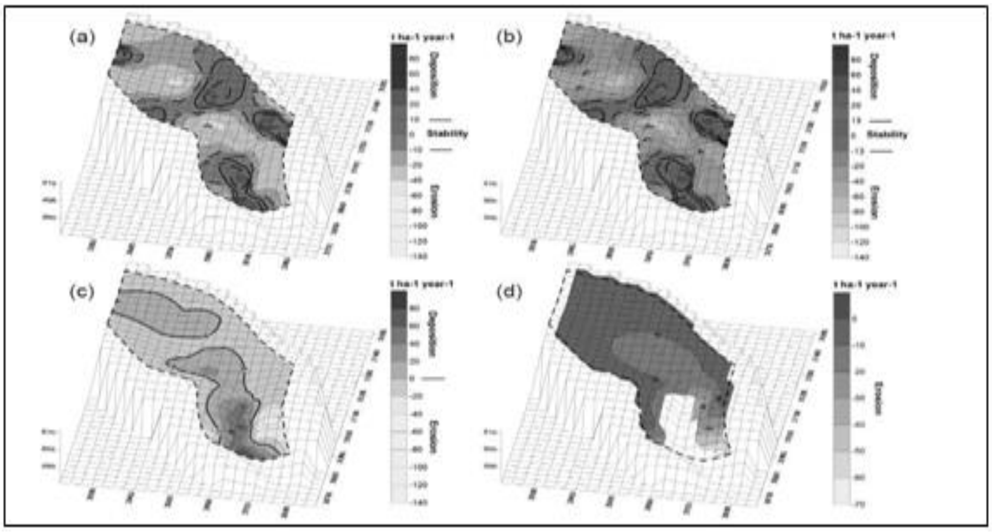


Figure 8: The Spatial Patterns of Soil Redistribution Provided by the ^{137}Cs and Soil-Morphological Methods

Use of ^{137}Cs as a tracer for assessment of soil-induced carbon loss

$$\textbf{CAR (Carbon amplification ratio)} = \frac{\textit{SOC content in sediment}}{\textit{SOC content in original soil}}$$

$$\textbf{EICL or C-erosion (kg ha}^{-1}\textbf{ yr}^{-1}\textbf{)} = \frac{Erosion \times SOC \times CAR \times 1000}{100}$$

In the Doon Valley in India, Mandal et al. (2019) converted ^{137}Cs inventory data to soil loss using a proportional model and compared the results to actual field scale evaluation. Even though there was a 3-4% overestimation in mildly and moderately eroded phases, the accuracy ranged from 96% to 97%. (Table 6). Because of this, using ^{137}Cs technology to study soil erosion in highly intensive croplands is preferable. Compared to other conventional methods, it provides more accurate results for all types of erosion studies, including erosion brought on by water, wind, and gravity. soil erosion loss, CAR, and SOC values with erosion-induced carbon loss (EICL). CAR values ranged from 2.96 in the phase with minor erosion to 2.69 in the phase with severe erosion. In the current study, EICL was derived from erosion rate, SOC concentration, and CAR, which ranged from 136.68 to 383.84 kg ha^{-1} year^{-1} for different erosion phases (Table 7). This resulted in 27.33–76.76 kg C ha^{-1} year^{-1} as a net C source to the atmosphere. The formula below was used to determine the amount of carbon erosion: Because it ignores within-slope redeposition, the USLE-based model fails to adequately represent the spatial pattern of soil redistribution while providing accurate estimates of sediment mobilization from slopes.

Table 6: Accuracy percentage calculated for erosion rate using ^{137}Cs over actual field scale assessment

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

Table: 7 Estimation of erosion-induced carbon loss (EICL) through ^{137}Cs technique

Erosion phases	**% ^{137}Cs loss**	**Erosion (t ha^{-1} year^{-1})**	**SOC (%)**	**CAR**	**EICL (kg ha^{-1} year^{--1})**
Slightly erodedphase	21.88	7.90	0.59	2.96	136.88
Moderately eroded phase	32.51	12.23	0.55	2.85	188.77
Severely erodedphases	49.89	19.26	0.49	2.76	261.96
Very severelyeroded phase	81.48	31.46	0.46	2.54	383.84

Use of multi-radionuclide for soil erosion studies: While ^{137}Cs is the radioisotope that is most frequently employed in studies of soil erosion and sedimentation, there is an urgent need to move on to 239+ 240Pu suitable because more than 60% of ^{137}Cs has already decayed and because it also has some additional benefits because of the following traits: For ^{239}Pu and ^{240}Pu, respectively, the half-life is 24,110 and 6,561 years. It is also an emitter and decays to U-236. It is simple to evaluate using ICP-MS. Alewell et al. (2014) and Meusburger et al. (2016) conducted two distinct tests in Switzerland and Korea and discovered that there is a significant correlation between ^{137}Cs and $^{239+\ 240}$Pu, with r^2 values ranging from 0.91 in Switzerland to 0.99 in Korea (Fig.9)

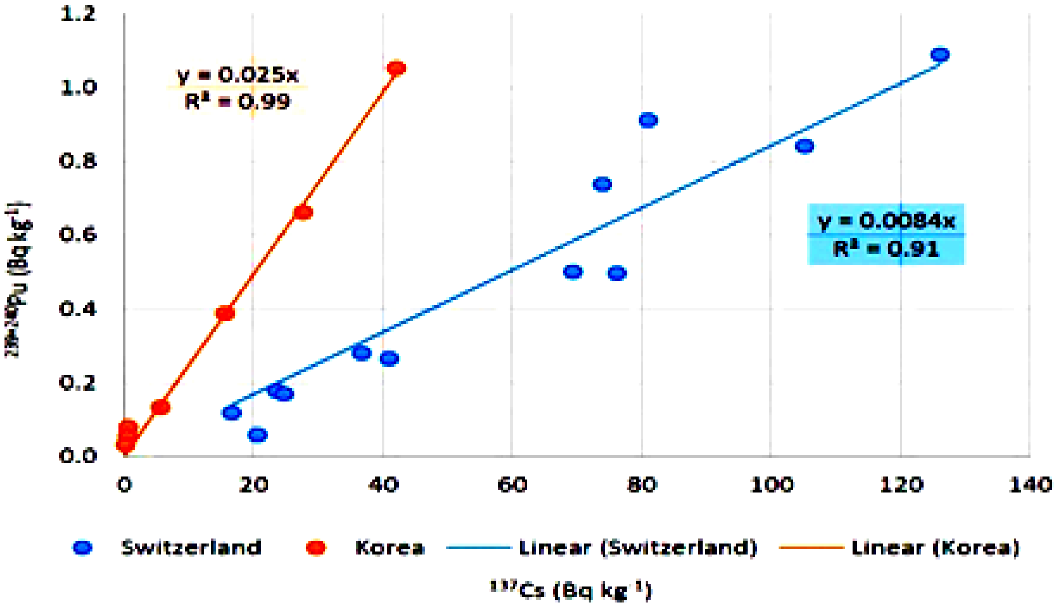


Figure 9: Correlation between 239+240Pu and 137Cs Content in Soils of Two Swiss Alpine Grasslands and One Catchment from the Republic of Korea

Although other fallout radionuclides have some limitations, such as the difficulty in detecting 210Pb excess and the short half-life associated with 7Be, the majority of the experiment involves other FRNs, and the results were also compared with the Cs technique. 137Cs, however, can predict the erosion pattern for decades, up to 50 years. Meusburger et al. (2016) estimated soil redistribution using the 137Cs and 239+240Pu approaches in two separate fields, namely a recently harvested maize field, and a cabbage field. They discovered that the results from these two procedures are quite close and perfectly match one another (Fig. 10). The only difference that was observed at the downslope may be related to the different ways the low land in the cabbage field is configured, which prevents FRN from building up, or to differences in the fallout pattern.

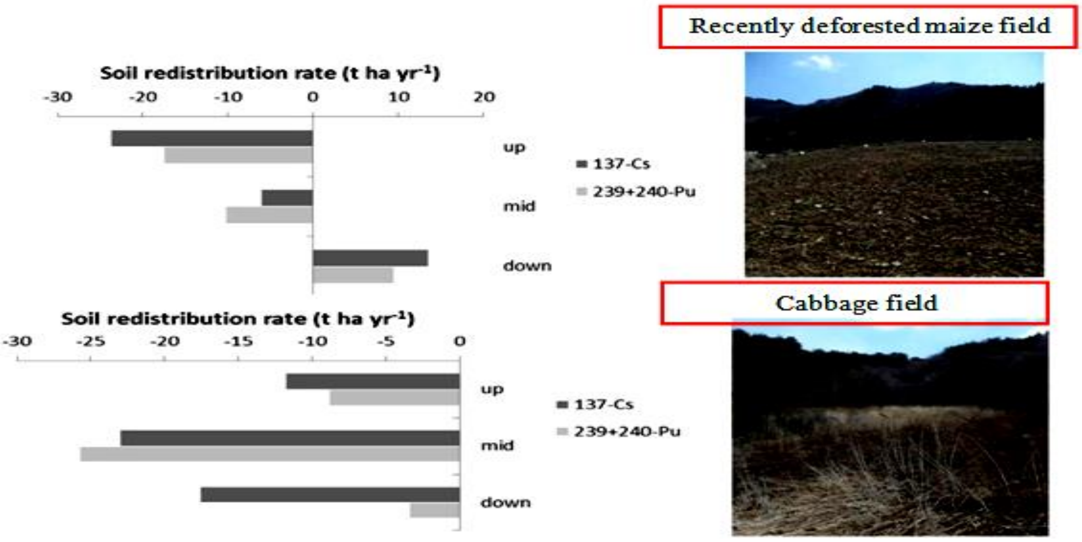


Figure 10: Soil Redistribution Assessment for Three Specific Transects With ^{137}Cs and 239+240Pu

Technique: 2

VI. USE OF ARTIFICIALLY LABELLED RADIONUCLIDE APPROACH FOR SOIL EROSIONSTUDIES

In comparison to the initial application (100%), Syversen et al. (2001) demonstrated relative changes in ^{134}Cs activity levels (%) at specific sites in the tilled area throughout the trial. The erosion of ^{134}Cs-containing particles is indicated by a decrease in ^{134}Cs activity's initial value at specific locations on the surface of contaminated soil (Fig. 11). In contrast, the activity percentage in the buffer zone rose above the background level. It implies that there was significant soil displacement inside the field, which ^{134}Cs might have accurately determined.

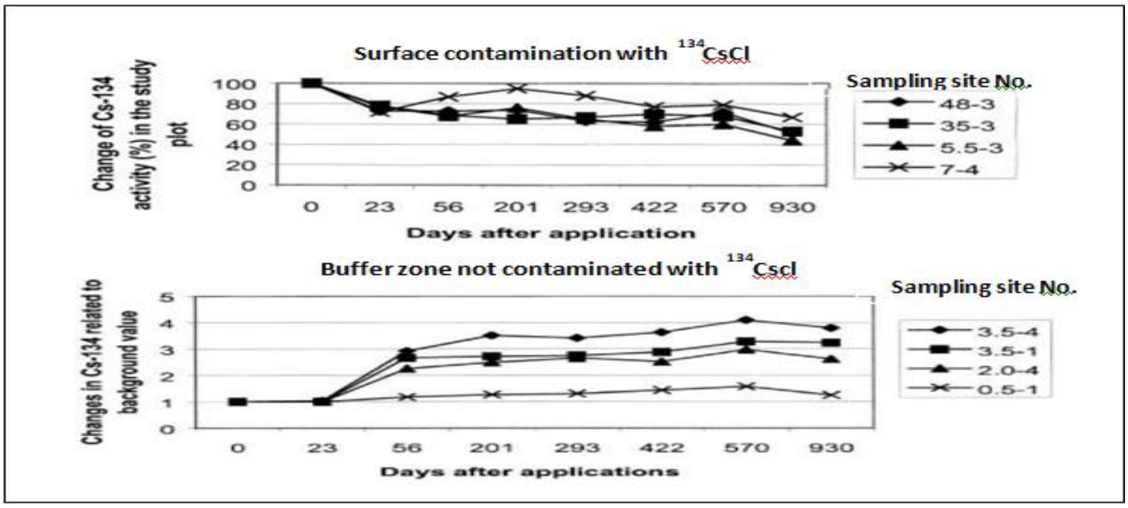


Figure 11: Tracing Particle Transport Processes within a Small Catchment with a Buffer Zone Using ^{134}Cs

Technique: 3

VII. FINGERPRINTING TECHNIQUE USED FOR SEDIMENT TRACING BY COMPOUND-SPECIFIC STABLE ISOTOPE (CSSI) APPROACH

1. The **CSSI approach**, a forensic technique, locate soil erosion causes in landscapes with various land uses.
2. All plants that grow in a specific land use produce a variety of organic biomarkers, such as fatty acids, with a carbon chain containing between 14 and 24 carbon atoms.
3. These organic biomarkers each have a distinct $\delta^{13}\mathbf{C}$ isotopic signature that is distinctive to the plant they come from.
4. The efficient tracing of sediments is made possible by variations in carbon isotope fingerprints.

In contrast to the geochemical fingerprinting method, Blake et al. (2012) employed the CSSI-assisted sediment tracing methodology in agricultural watersheds. The geochemical fingerprinting approach was unable to discriminate between the sediment yield from the two cultivated fields, winter wheat, and maize, but this method was able to do so. Sediment yield per hectare was significantly higher in winter wheat (0.44 t ha^{-1}) than in maize fields (0.14 t ha^{-1}). Both instances had a somewhat similar total sediment production in t ha^{-1} (Table 10)

Table 8: Crop-Specific Sediment Sources in Agricultural Catchments with Compound-SpecificStable Isotope (CSSI) Sediment Tracing Approach

Source type	Area (ha)	Sediment yield	
		Total (t)	(t ha^{-1})
CSSI Technique (CSSI)			
Maize stubble	24	3.4	0.14
Winter wheat	16	7.0	0.44
Grassland	85	11.0	0.13
Geochemical fingerprinting (GC)			
Cultivated	40	13.3	0.34
Pasture	85	8.9	0.10
Woodland	5	0.5	0.10

CSSI signatures revealed pasture soil was the main sediment source. Geochemical fingerprints appear to overestimate contributions from the cultivated source (Fig. 12), where CSSI-based cultivated loadings represent the sum of predicted maize and wheat loads.

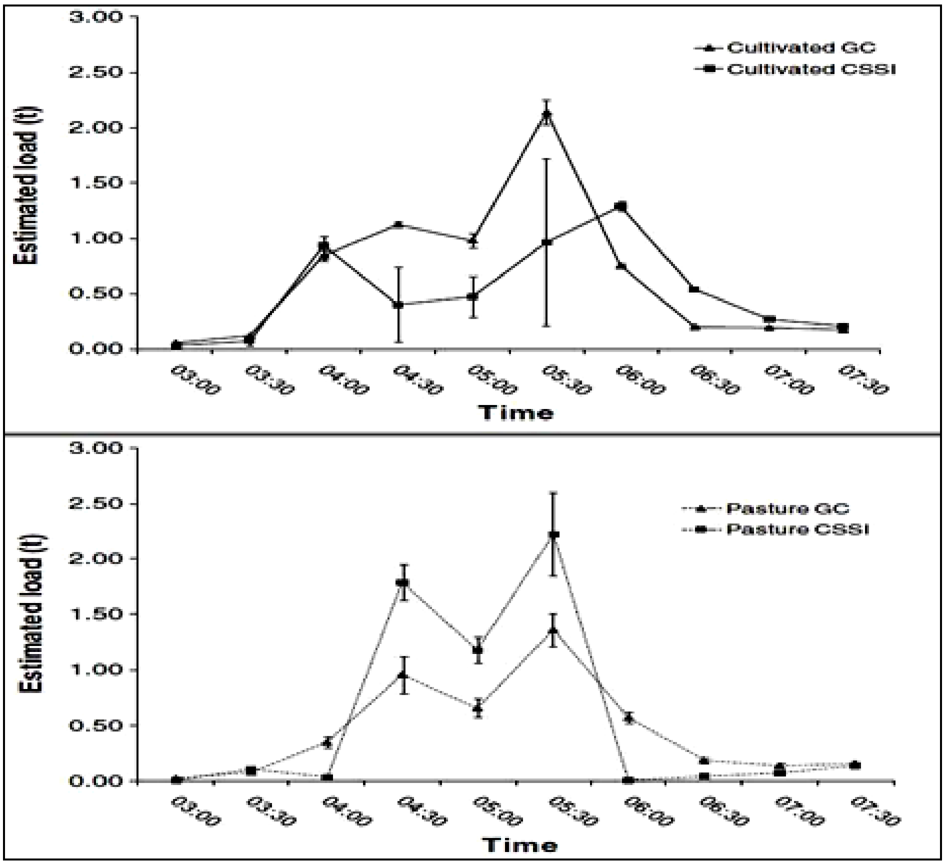


Figure 12: Results from Geochemical Fingerprinting and CSSI are Compared.

VIII. RESEARCH INTO PRACTICE-LINKING RADIOISOTOPE INVENTORY TO LANDMANAGEMENT POLICY

Utilization of 137Cs to evaluate the conservation effectiveness of terracing: The effectiveness of conservation measures was evaluated by Zhang et al. (2014) using the ^{137}Cs method. The Dingjiagou catchment's sloping farmland showed ^{137}Cs concentrations that ranged from highest in the upper position to lowest in the lower position. The sampling sites in the sloped farmland had lower, middle, and upper concentrations of ^{137}Cs, respectively. On the higher, middle, and lower slope sites, respectively, there were ^{137}Cs inventories of 1079.1, 862.4, and 296.3 Bq m^{-2} (Fig. 13). On the upper, medium, and lower slope sites, the ^{137}Cs conversion model yields the appropriate soil erosion rates of 23.6, 27.1, and 36.3 Mg per hectare per year. The amounts of ^{137}Cs of sampling sites on the terraced farmland are not significantly different from those on the sloping farmland at various locations. The ^{137}Cs inventories on the higher, middle, and lower positions, respectively, were 1183.5, 947.8, and 831.8 Bq m^{-2}. Accordingly, the erosion rates marginally increased in the following order: upper, middle, and lower, with rates of 21.9, 25.7, and 27.6 Mg per hectare per year, respectively. The terrace measure decreased soil erosion on the upper, middle, and lower slope positions by 7.7, 5.4, and 31.5% when compared to the sloping farmland. For the entire slope, the terrace measure decreased soil erosion by 15.7% in total.

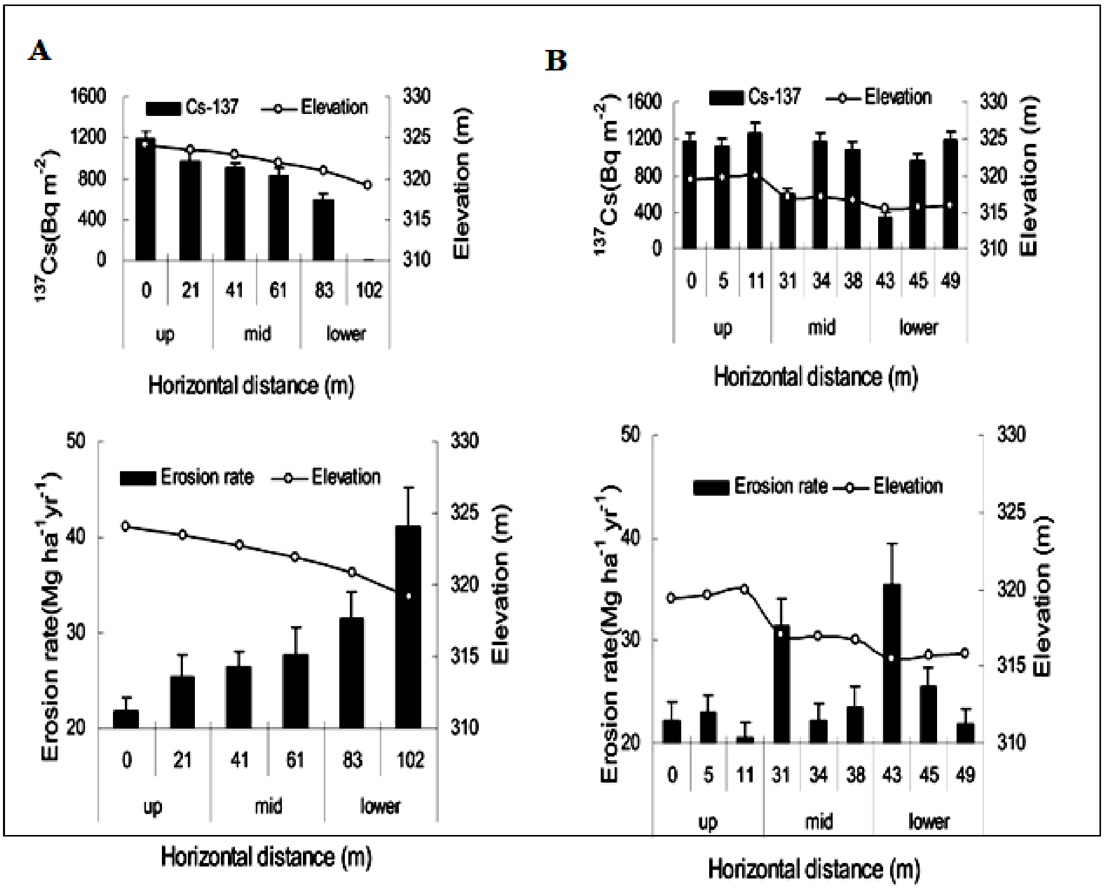


Figure 13: Inventory of ^{137}Cs and Erosion Rates at the Different Slope Positions on the (A) SlopeFarmland and (B) Terrace Farmland in the Dingjiagou Catchment

While the middle position in the Xingsheng catchment had a lower inventory of ^{137}Cs due to the sloping farmland, the upper and lower positions in the catchment contained higher amounts. On the upper, middle, and lower slope positions, the inventories of ^{137}Cs were 809.4, 612.4, and 929.3 Bq m^{-2}, respectively. On the top, middle, and lower slope sites along the downslope, respectively, erosion rates were calculated to be 32.5, 39.9, and 31.5 Mg ha^{-1}year^{-1} (Fig. 14). The amount of ^{137}Cs and the rates of soil erosion did not significantly differ across the various slope positions on the contour-cropped farms. On the top, middle, and lower slope sites, the concentrations of ^{137}Cs were 1052.7, 1190.4, and 1196.5 Bq m^{-2}, respectively. On the upper, middle, and lower slope positions, respectively, soil erosion rates on the contour cropping farmland were calculated to be 23.1, 21.8, and 22.9 Mg ha^{-1}year^{-1}. On the upper, middle, and lower slope sites, respectively, contour cultivation reduced soil erosion by 40.9, 83.5, and 37.6% when compared to slope farmland. For the entire slope, contour cultivation reduced soil erosion by a total of 53.5%.

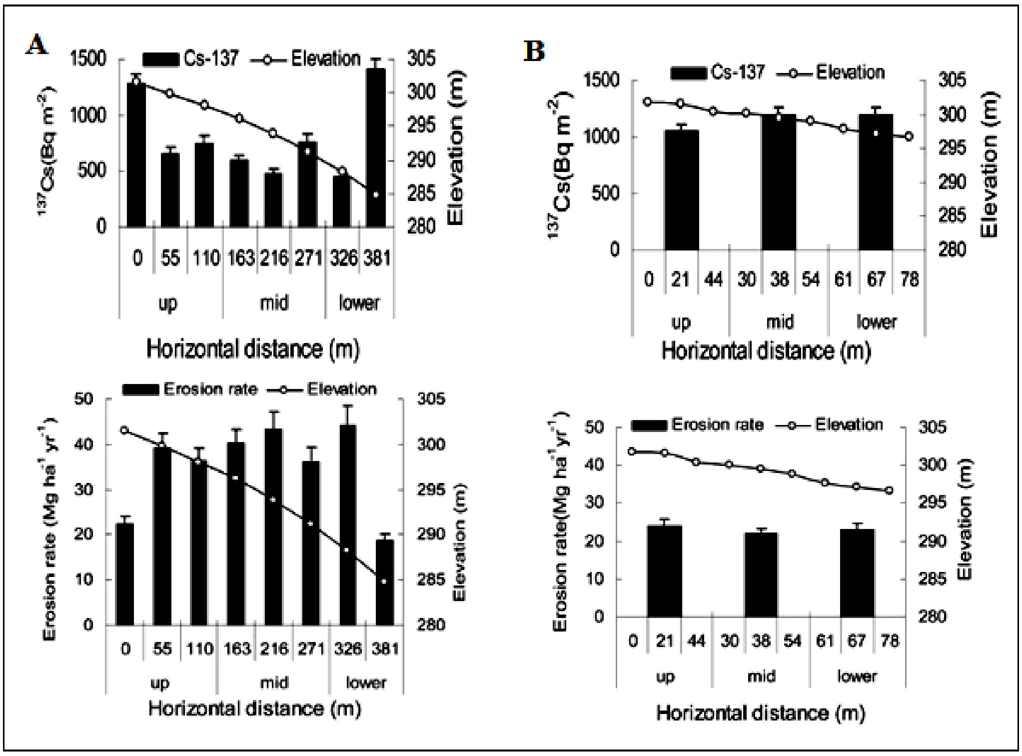


Figure 14: ^{137}Cs Inventory and Erosion Rates at the Different Slope Positions on the Slope (A)Farmland and (B) Contour Farming in the Xingsheng Catchment.

Use of ^{7}Be for short-term assessment of the effect of tillage practices on soil loss: ^{7}Be has a huge amount of potential for short-term evaluation of the impact of tillage practices on soil loss owing to its short half-life. According to Yassin et al. (2017), conventional tillage causes soil loss between 7 to 17 t ha^{-1} year^{-1} at both sites (Machouch and Herchane site), however, no-till systems cause soil loss remains less than 11 t ha^{-1} year^{-1} (Fig. 15)

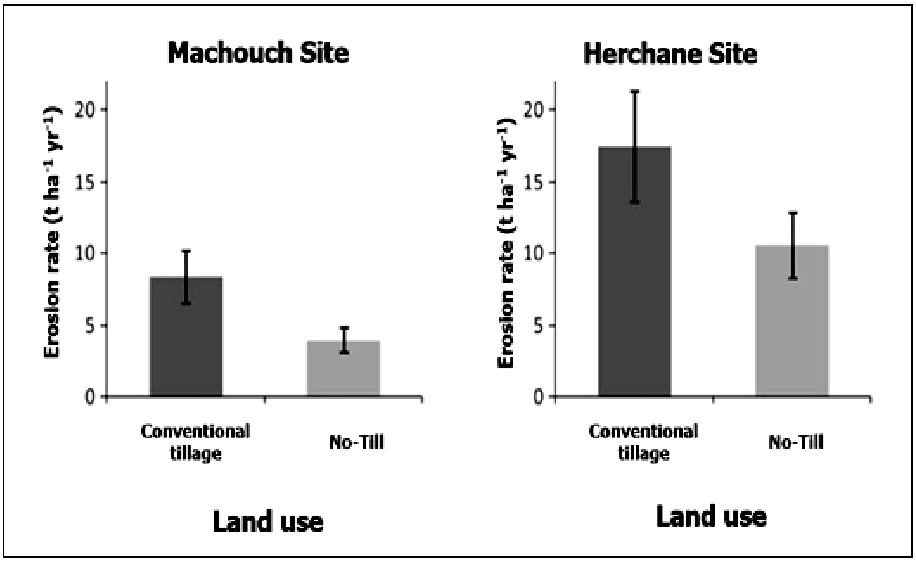


Figure 15: Soil Erosion Rate Due to Different Land uses

IX. CHALLENGES IN IMPLEMENTING RADIOTRACER TECHNIQUES FOR SOILEROSION STUDIES

The main limitations of the use of the radiotracer technique are as follows:
(adapted after Mabit *etal.* 2002)

1. A multidisciplinary team is required for the technique's successful application. This is a particular drawback in most developing nations with a shortage of scientific personnel.
2. It is necessary to use specialized labs with expensive gamma-counting equipment and sample processing capabilities.
3. The technique is essentially limited to documenting sheet erosion and general surface lowering, but it can be used to study rill erosion in cultivated areas.
4. The lack of a universal conversion model and standardized protocol
5. The requirement of the reference site with the same fallout pattern and geomorphological feature
6. The technique needs further standardization of the protocols for its global application. The initial radionuclide fallout was not accurately estimated.
7. The artificially labelled isotope approach for erosion studies involves an additional cost of application and is also not applicable for large catchments.

The significance of these drawbacks, particularly the expense, must be assessed in light of the unique benefits of the ^{137}Cs technology as well as the limits of other approaches.

X. CONCLUSIONS

1. ^{7}Be, ^{137}Cs, and excess ^{210}Pb, respectively, can be used to accurately estimate soil erosion, deposition, and sediment budget on time scales of short-term (a few days or a single storm event), medium-term (about 50 years), and long-term (about 100 years).
2. One of the best models is the **mass balance model-3 (MBM-3)**, which also takes into account soil redistribution brought on by tillage erosion.
3. The accuracy level varied between 96 and 97%, making **^{137}Cs technology** a more accurate method for studying soil erosion in intensive croplands.
4. **^{137}Cs** technique can also be used as a potential environmental marker for assessing **erosion-induced soil organic carbon loss (EICL)**
5. **^{137}Cs** technique can assess the conservation efficiency of erosion control practices
6. Short-term evaluation of the effectiveness of tillage practices can be accurately assessed by **^{7}Be**
7. **Compound-specific stable isotope (CSSI)** techniques can trace the source of sedimentation in landscapes with different land uses

XI. FUTURE PERSPECTIVE

1. Development of a new conversion model to extend the timeframe for using ^{7}Be measurements to monitor the redistribution of soil caused by erosive processes throughout the rainy season.
2. There is a huge potential for the application of ^{7}Be and ^{210}Pb$_{ex}$ in erosion studies southern part of India as ^{137}Cs fallout is negligible
3. Development of fallout radionuclide (FRN) inventory data is needed in the potentially erodedland across the country and calibration with actual field scale measurement data

4. Development of a universal conversion model is required that could be applied irrespective ofland use and geomorphological feature
5. For further validation of the use of the radiotracer technique, a large number of databases areneeded in different landscapes and land uses

REFERENCES

[1] Alewell, C., Meusburger, K., Juretzko, G., Mabit, L., & Ketterer, M. E. (2014). Suitability of $^{239+240}$Puand ^{137}Cs as tracers for soil erosion assessment in mountain grasslands. *Chemosphere*, **103**, 274-280.

[2] Belyaev, V. R., Golosov, V. N., Ivanova, N. N., Markelov, M. V., & Tishkina, E. V. (2005). Human-accelerated soil redistribution within an intensively cultivated dry valley catchment in southern European Russia. *International Association of Hydrological Sciences- Publication*, **291**, 11-20.

[3] Blake, W. H., Ficken, K. J., Taylor, P., Russell, M. A., & Walling, D. E. (2012). Tracing crop-specificsediment sources in agricultural catchments. *Geomorphology*, **139**, 322-329.

[4] Blake, W. H., Walling, D. E., & He, Q. (1999). Fallout beryllium-7 as a tracer in soil erosion investigations. *Applied Radiation and Isotopes*, **51**, 599-605.

[5] Lal, R. (2014). Soil conservation and ecosystem services. *International Soil and Water Conservation Research*, **2**, 36-47.

[6] Mabit, L., Bernard, C., Laverdière, M. R. (2002) Quantification of soil redistribution and sediment budget in a Canadian watershed from fallout caesium-137 (^{137}Cs) data. *Canadian Journal of SoilScience* **82**, 4.

[7] Mabit, L., Bernard, C., Lee Zhi Yi, A., Fulajtar, E., Dercon, G., Zaman, M. & Heng, L. (2018). Promoting the use of isotopic techniques to combat soil erosion: An overview of the key role played by the SWMCN Subprogramme of the Joint FAO/IAEA Division over the last 20 years. *Land Degradation & Development*, **29**, 3077-3091.

[8] Mandal, D., Giri, N., Srivastava, P., Sah, C., Bhusan, R., Naregundi, K. & Shrivastava, M. (2019). ^{137}Cs-a potential environmental marker for assessing erosion-induced soil organic carbon loss inIndia. *Current Science (00113891)*, **117**.

[9] Meusburger, K., Mabit, L., Ketterer, M., Park, J. H., Sandor, T., Porto, P., & Alewell, C. (2016). A multi-radionuclide approach to evaluate the suitability of $^{239+}$ ^{240}Pu as soil erosion tracer. *Scienceof the Total Environment*, **566**, 1489-1499.

[10] NRAA (National Rainfed Area Authority) (2008). Harmonization of Wastelands/Degraded Lands Datasets of India. Ministry of Agriculture, Govt. of India, New Delhi.

[11] Syversen, N., Øygarden, L., & Salbu, B. (2001). Cesium-134 as a tracer to study particle transport processes within a small catchment with a buffer zone. *Journal of environmental quality*, **30**, 1771-1783.

[12] Walling, D. E. and He, Q. (1993). Towards improved interpretation of ^{137}Cs profiles in lake sediments. In: Geomorphology and Sedimentology of Lakes and Reservoirs (ed. J. McManus & R. W. Duck), 31-53. Wiley, Chichester, UK.

[13] Yassin, M., Benmansour, M., Chikhaoui, M., Ismaili Alaoui, F. Z., El Bahi, S., Babaou,Y. (2017). Contribution à l'évaluation de l'impact de l'aménagement des bassins versants de l'Oued Mellahet Allal El Fassi au Maroc. *Annales de la Recherche Forestière au Maroc*, **44**, 79–96.

[14] Zapata, F. (Ed.). (2002). *Handbook for the Assessment of Soil Erosion and Sedimentation Using Environmental Radionuclides* (Vol. **219,** 9348054-9). Dordrecht: Kluwer Academic Publishers.

[15] Zhang, Q. W., & Li, Y. (2014). Effectiveness assessment of soil conservation measures in reducing soil erosion in Baiquan County of North-eastern China by using ^{137} Cs techniques. *Environmental Science: Processes & Impacts*, **16**, 1480-1488.

[16] Zupanc, V., & Mabit, L. (2010). Nuclear techniques support to assess erosion and sedimentation processes: preliminary results of the use of ^{137}Cs as soil tracer in Slovenia. *Dela*, **33**, 21-36.