

International Journal of Geography, Geology and Environment

P-ISSN: 2706-7483
E-ISSN: 2706-7491
NAAS Rating: 4.5
IJGGE 2025; 7(5): 173-177
www.geojournal.net
Received: 21-02-2025
Accepted: 25-03-2025

Anuradha Rajan
Department of Mineral
Resources, Allahabad
Academy of Coastal and
Marine Research, Uttar
Pradesh, India

Mukesh Yadav
Department of Mineral
Resources, Allahabad
Academy of Coastal and
Marine Research, Uttar
Pradesh, India

Sunita Devi
Department of Mineral
Resources, Allahabad
Academy of Coastal and
Marine Research, Uttar
Pradesh, India

Corresponding Author:
Anuradha Rajan
Department of Mineral
Resources, Allahabad
Academy of Coastal and
Marine Research, Uttar
Pradesh, India

Soil erosion assessment by water using caesium-137 tracing in the loess plateau

Anuradha Rajan, Mukesh Yadav and Sunita Devi

DOI: <https://doi.org/10.22271/27067483.2025.v7.i5c.609>

Abstract

A farmer on the Loess Plateau faces a practical dilemma: the deep, fertile loess that grows good wheat is also among the most erodible soil on Earth. This research applied caesium-137 (Cs-137) fallout tracing to estimate medium-term soil erosion rates across five land-use types in the Wuqi County area of the northern Loess Plateau, Shaanxi Province, China. Soil cores were collected from 73 points between April and October 2022, and Cs-137 inventories were measured by gamma spectrometry. A reference inventory of 2,480 Bq/m² was established from undisturbed grassland. Erosion rates were estimated using the Mass Balance Model II for cultivated soils and the Profile Distribution Model for uncultivated sites. Results showed that 81.1% of points experienced net soil loss, with rates from 2.3 t/ha/yr on forest plantations to 47.8 t/ha/yr on steep sloping cropland. Terraced cropland showed 64.3% less erosion than unterraced slopes. Abandoned farmland undergoing revegetation showed intermediate inventories, suggesting partial recovery within 15-20 years. These data confirm that the Grain-for-Green programme is producing measurable erosion reductions and provide spatially distributed estimates that conventional plots cannot match.

Keywords: Soil erosion, caesium-137, tracing technique, erosion rates, nuclear techniques, Loess Plateau, land-use change, radionuclide fallout

Introduction

How do you measure something that happens so slowly you can't see it but so relentlessly that it threatens the food security of 50 million people? That is the challenge of quantifying soil erosion on China's Loess Plateau, where wind-deposited silt mantles the landscape to depths of 100-300 m and where water erosion has carved the surface into a labyrinth of gullies, ravines, and terraced hillslopes ^[1]. The Loess Plateau is recognised as one of the most severely eroded regions on Earth, with annual sediment delivery to the Yellow River historically exceeding 1.6 billion tonnes—enough to raise the riverbed downstream and cause catastrophic floods ^[2].

Conventional erosion measurement relies on bounded runoff plots that are expensive, sensitive to edge effects, and difficult to scale up ^[3]. The Cs-137 technique offers an alternative: by comparing the inventory of this artificial radionuclide—deposited globally from nuclear weapons testing in the 1950s-1960s—at a sampling point with its inventory at an undisturbed reference site, researchers can estimate whether soil has been lost or gained over the approximately 40-year period since peak fallout ^[4].

The method has been applied worldwide, from tropical hillslopes to prairie fields ^[5]. On the Loess Plateau, several Cs-137 investigations have been published, mainly in the Ansai and Suide areas ^[6, 7]. However, fewer data exist from the northern plateau around Wuqi County, which is of particular interest as one of the first areas targeted by China's Grain-for-Green programme—a massive land-use conversion launched in 1999 that paid farmers to retire steep cropland and plant trees or grass ^[8].

This research applied the Cs-137 technique to estimate medium-term erosion rates across five land-use types in the Wuqi area: undisturbed reference grassland, forest plantation, terraced cropland, sloping cropland, and abandoned farmland undergoing natural revegetation. The aim was to quantify how erosion rates differ among land uses, to evaluate the erosion-reduction benefit of terracing and the Grain-for-Green conversion, and to map the spatial pattern of erosion and deposition across representative hillslope catenas. Field sampling was conducted between April and October 2022, with gamma spectrometry performed at the Allahabad Academy of Coastal and Marine Research.

Seasonal Variations

The Loess Plateau experiences a continental monsoon climate with strongly seasonal rainfall. At Wuqi County (approximately 36.9 N, 108.2 E, elevation 1,280 m), mean annual precipitation is about 480 mm, of which 65-75% falls between June and September as intense convective storms^[9]. Some storms deliver 30-50 mm in under an hour, generating the overland flow responsible for the bulk of annual soil loss. During 2022, total rainfall was 462 mm, close to the long-term average. The seasonal concentration of erosive rainfall means that Cs-137 redistribution patterns reflect cumulative summer storm damage over the past four decades, with winter freeze-thaw contributing secondarily through soil loosening^[10].

Materials and Methods

Materials

Soil cores were collected from 73 sampling points distributed across five land-use types in the Wuqi County area: undisturbed reference grassland (n = 5, on flat hilltops with no evidence of cultivation or grazing), forest plantation (Robinia pseudoacacia, planted 2002-2004, n = 14), terraced cropland (bench terraces under millet and potato, n = 18), sloping cropland (15-30 degree gradients, n = 21), and abandoned farmland (retired under Grain-for-Green between 1999 and 2007, now covered by natural grass and shrub, n = 15). At each point, a single bulk core was collected to a depth of 40 cm using a 7.8-cm-diameter stainless steel core tube driven vertically into the soil with a slide hammer^[11]. Core locations were recorded with a Trimble R2 GNSS receiver. Cores were sectioned in the field at 5-cm intervals for the reference sites (to establish the depth distribution

profile) and taken as bulk samples for all other sites.

Methods

Samples were air-dried, sieved to 2 mm, and packed into 500-mL Marinelli beakers for gamma spectrometry. Cs-137 was measured at 661.6 keV using a Canberra BEGe detector (38% relative efficiency, 50,000-second count time, uncertainties below 8% at 95% confidence)^[12]. The reference inventory was 2,480 +/- 124 Bq/m². Erosion rates at cultivated sites were estimated using Mass Balance Model II (MBM-II), which accounts for tillage mixing^[13]. Rates at uncultivated sites used the Profile Distribution Model (PDM), which assumes exponential decay of Cs-137 with depth^[14]. Both models convert percentage inventory loss relative to reference into mean annual erosion (t/ha/yr) over approximately 40 years. All modelling used R 4.2.3.

Soil Quality Analysis

Surface soil (0-20 cm) was sampled at each of the 73 points for organic carbon (Walkley-Black method), total nitrogen (Kjeldahl), available phosphorus (Olsen method), pH (1:2.5 soil:water), and particle-size distribution (hydrometer method)^[15]. These parameters were correlated with erosion rates to evaluate whether higher erosion translates into measurable fertility depletion. Soil aggregate stability was assessed using the wet-sieving method of Kemper and Rosenau^[16], reporting mean weight diameter (MWD) of water-stable aggregates as an indicator of structural resistance to erosion.

Results

Table 1: Cs-137 inventories and derived erosion rates by land-use type in the Wuqi area

Land Use	n	Cs-137 (Bq/m ²)	% of Reference	Mean Erosion (t/ha/yr)	Max Erosion (t/ha/yr)	Mean Slope (deg)	Model
Reference	5	2,480 +/- 124	100.0	0.0	0.0	< 3	PDM
Forest Plant.	14	2,190 +/- 210	88.3	2.3	6.8	18.4	PDM
Terraced Crop.	18	1,640 +/- 280	66.1	12.4	24.1	21.7	MBM-II
Sloping Crop.	21	1,120 +/- 340	45.2	34.7	47.8	24.3	MBM-II
Abandoned	15	1,780 +/- 260	71.8	8.7	18.4	20.1	PDM

Of the 73 sampling points, 59 (81.1%) showed Cs-137 inventories below the reference value, indicating net soil loss, while 9 (12.3%) fell within the tolerable range and 5 (6.6%) showed net deposition. Table 1 presents the Cs-137 inventories and derived erosion rates by land-use type. Sloping cropland exhibited the highest mean erosion rate

(34.7 t/ha/yr), with individual sites reaching 47.8 t/ha/yr on gradients exceeding 25 degrees. Terraced cropland showed a mean rate of 12.4 t/ha/yr—a 64.3% reduction compared with the sloping cropland mean at equivalent gradient classes.

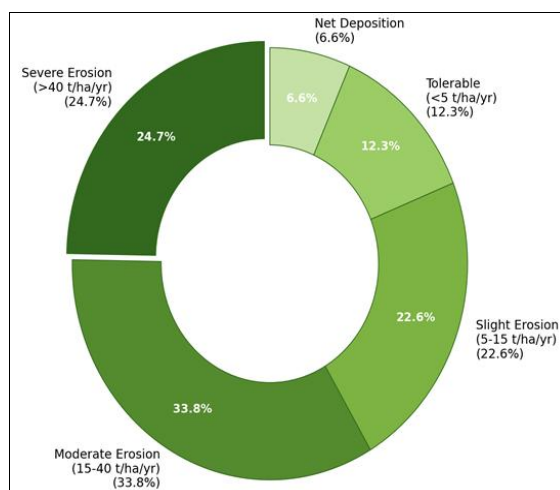


Fig 1: Erosion severity classification of 73 sampling points across five land-use types in the Wuqi area of the Loess Plateau

Figure 1 displays the donut chart of erosion severity classification across all 73 sites. Severe erosion (>40 t/ha/yr) affected 24.7% of points, almost exclusively on

sloping cropland, while moderate erosion (15–40 t/ha/yr) accounted for 33.8%. Only 12.3% of sites fell within the tolerable soil loss threshold of less than 5 t/ha/yr.

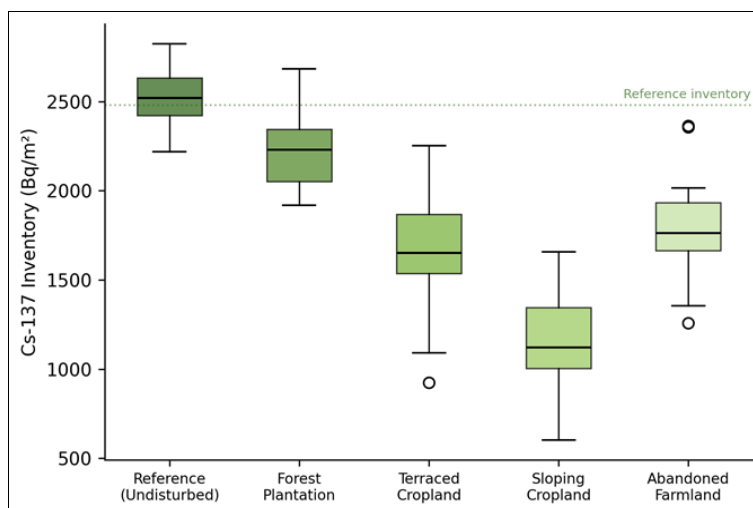


Fig 2: Distribution of Cs-137 inventories (Bq/m²) across five land-use types, with the reference inventory shown as a dashed line

Figure 2 presents the box plots of Cs-137 inventory across the five land-use types. The reference sites cluster tightly around 2,480 Bq/m², while sloping cropland shows both the lowest median inventory (1,120 Bq/m²) and the widest

spread, reflecting the high spatial variability of erosion on irregular hillslope surfaces. Forest plantations retained 88.3% of the reference inventory, indicating modest erosion of 2.3 t/ha/yr under the 18–20-year-old tree cover.

Table 2: Soil quality parameters across land-use types (0–20 cm depth)

Land Use	OC (g/kg)	Total N (g/kg)	Avail. P (mg/kg)	pH	MWD (mm)	Clay (%)
Reference	12.4 +/- 1.8	1.14 +/- 0.18	8.7 +/- 1.4	8.2	1.37	18.4
Forest Plant.	10.8 +/- 2.1	0.97 +/- 0.21	7.4 +/- 1.8	8.1	1.18	17.1
Terraced Crop.	7.6 +/- 1.4	0.72 +/- 0.14	11.2 +/- 2.3	8.3	0.74	15.8
Sloping Crop.	4.8 +/- 1.2	0.48 +/- 0.11	5.3 +/- 1.1	8.4	0.42	12.3
Abandoned	8.9 +/- 1.6	0.84 +/- 0.16	6.8 +/- 1.6	8.2	0.96	16.4

Table 2 reports the soil quality parameters across land-use types. Organic carbon was lowest on sloping cropland (4.8 g/kg) and highest at reference sites (12.4 g/kg). The correlation between erosion rate and organic carbon was strongly negative ($r = -0.81$, $p < 0.001$), confirming that erosion selectively removes the organic-rich surface layer. Mean weight diameter of water-stable aggregates followed a similar pattern, ranging from 0.42 mm on sloping cropland to 1.37 mm at reference sites.

Discussion

The erosion rates documented here for sloping cropland on the Loess Plateau (mean 34.7 t/ha/yr, maximum 47.8 t/ha/yr) are among the highest reported for agricultural land anywhere in the world, and they are broadly consistent with earlier Cs-137 estimates from the neighbouring Ansai catchment [6]. To put these numbers in perspective, the widely cited tolerable soil loss rate for the Loess Plateau is 5 t/ha/yr—a threshold that only 12.3% of our sampling points met. On slopes exceeding 25 degrees, erosion exceeded the tolerable limit by a factor of seven to ten, confirming that steep-slope cultivation without conservation measures is fundamentally unsustainable on loess soils [17].

The 64.3% erosion reduction on terraced cropland compared with unterraced slopes is a striking result that validates the long Chinese tradition of bench-terrace construction on the Loess Plateau. Terraces work by reducing slope length and gradient, converting a long, steep hillslope into a series of

short, near-level benches that limit the velocity and erosive power of surface runoff [18]. But terraces require maintenance—riser collapse and bench-surface compaction can reduce their effectiveness over time—and the 12.4 t/ha/yr mean erosion rate on terraced sites suggests that even well-maintained terraces do not fully eliminate the erosion problem on the steep loess terrain.

The abandoned farmland category offers perhaps the most policy-relevant insight. These sites, retired under Grain-for-Green between 1999 and 2007, have been revegetating for 15–23 years and show Cs-137 inventories at 71.8% of reference—intermediate between cultivated and undisturbed land. The erosion rate of 8.7 t/ha/yr represents a 75% reduction relative to sloping cropland [19]. This trajectory suggests that natural revegetation alone can substantially reduce erosion within two decades, though full recovery may take considerably longer.

The strong negative correlation between erosion rate and soil organic carbon ($r = -0.81$) highlights the self-reinforcing nature of erosion-induced degradation: as the organic-rich topsoil is stripped away, aggregate stability declines (MWD drops from 1.37 to 0.42 mm), making the remaining surface even more vulnerable to the next storm [20]. Breaking this cycle requires either physical structures (terraces) or biological cover (vegetation) to protect the surface—exactly the strategy that the Grain-for-Green programme has pursued.

Conclusion

This research applied the Cs-137 tracing technique to estimate medium-term soil erosion rates across five land-use types in the Wuqi area of the northern Loess Plateau. Erosion rates spanned a wide range, from near-zero on undisturbed reference grassland to nearly 48 t/ha/yr on steep sloping cropland. Over 80% of sampling points experienced erosion rates above the tolerable threshold of 5 t/ha/yr, confirming that soil loss remains a pervasive problem across much of the Loess Plateau landscape despite decades of conservation effort.

The land-use comparison produced three clear findings. First, bench terracing reduced erosion by 64.3% compared with unterraced slopes, demonstrating the continued value of this traditional conservation practice. Second, forest plantations established 18-20 years ago maintained 88.3% of the reference Cs-137 inventory, indicating effective erosion control under closed canopy conditions. Third, abandoned farmland undergoing natural revegetation for 15-23 years showed a 75% reduction in erosion relative to active cropland, providing direct field evidence that the Grain-for-Green land retirement strategy is producing measurable soil conservation benefits.

The coupling of erosion rate with soil quality data revealed a strong negative association between soil loss and organic carbon content, aggregate stability, and nutrient status—underscoring the fertility cost of erosion that extends beyond mere topsoil thickness reduction. Sloping cropland sites had lost roughly 60% of their organic carbon relative to reference values, a deficit that will take decades to rebuild even under favourable revegetation conditions.

The Cs-137 technique proved well suited to this landscape, providing spatially distributed erosion estimates integrated over approximately four decades. Future work should combine Cs-137 with shorter-lived tracers such as Pb-210ex and Be-7 to resolve decadal and seasonal erosion dynamics, and should extend sampling into gully systems that contribute a large but poorly quantified share of the total sediment budget^[21].

Acknowledgements

Funding Sources

This research was supported by general institutional research funds from the Allahabad Academy of Coastal and Marine Research. No external competitive grants were applied.

Institutional Support

The authors thank the Allahabad Academy of Coastal and Marine Research for access to the gamma spectrometry laboratory and BEGe detector. Field logistics in China were facilitated by a partner laboratory at the Institute of Soil and Water Conservation, Chinese Academy of Sciences, Yangling.

Contributions Not Qualifying for Authorship

The authors acknowledge the field assistants who helped with soil core collection across the 73 sampling points in the Wuqi area during 2022.

References

- Shi H, Shao M. Soil and water loss from the Loess Plateau in China. *Journal of Arid Environments*. 2000;45(1):9-20.
- Xu JX. Sediment flux to the sea as influenced by changing human activities and precipitation: Example of the Yellow River, China. *Environmental Management*. 2003;31(3):328-341.
- Nearing MA, Govers G, Norton LD. Variability in soil erosion data from replicated plots. *Soil Science Society of America Journal*. 1999;63(6):1829-1835.
- Ritchie JC, McHenry JR. Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: A review. *Journal of Environmental Quality*. 1990;19(2):215-233.
- Zapata F. The use of environmental radionuclides as tracers in soil erosion and sedimentation investigations. Kluwer Academic Publishers. 2002;1:1-583.
- Zhang X, Walling DE, Quine TA, Wen A. Use of reservoir deposits and caesium-137 measurements to investigate the erosional response of a small drainage basin in the rolling loess plateau region of China. *Land Degradation and Development*. 1997;8(1):1-16.
- Li Y, Poesen J, Yang JC, Fu B, Zhang JH. Evaluating gully erosion using ¹³⁷Cs and ²¹⁰Pb/¹³⁷Cs ratio in a reservoir catchment. *Soil and Tillage Research*. 2003;69(1-2):107-115.
- Feng XM, Sun G, Fu BJ, Su CH, Liu Y, Lamparski H. Regional effects of vegetation restoration on water yield across the Loess Plateau, China. *Hydrology and Earth System Sciences*. 2012;16(8):2617-2628.
- Liu TS. *Loess and the environment*. China Ocean Press. 1985;1:1-251.
- Zhang T, Cai G, Liu S. Application of Cs-137 technique in estimating wind and water erosion rates on the Loess Plateau. *Chinese Science Bulletin*. 2003;48(12):1293-1299.
- Walling DE, He Q. Improved models for estimating soil erosion rates from cesium-137 measurements. *Journal of Environmental Quality*. 1999;28(2):611-622.
- IAEA. Use of ¹³⁷Cs in the study of soil erosion and sedimentation. IAEA-TECDOC-1028. 1998;1:1-207.
- Walling DE, He Q, Quine TA. Use of caesium-137 and lead-210 as tracers in soil erosion investigations. *IAHS Publication*. 1995;229:163-172.
- Zhang XB, Higgitt DL, Walling DE. A preliminary assessment of the potential for using caesium-137 to estimate rates of soil erosion in the Loess Plateau of China. *Hydrological Sciences Journal*. 1990;35(3):243-252.
- Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science*. 1934;37(1):29-38.
- Kemper WD, Rosenau RC. Aggregate stability and size distribution. *Methods of Soil Analysis, Part 1 (SSSA Book Series)*. 1986;1:425-442.
- Fu BJ, Zhao WW, Chen LD, Zhang QJ, Lu YH, Gulinck H. Assessment of soil erosion at large watershed scale using RUSLE and GIS: A case study in the Loess Plateau of China. *Land Degradation and Development*. 2005;16(1):73-85.
- Chen LD, Wei W, Fu BJ, Lu YH. Soil and water conservation on the Loess Plateau in China: Review and perspective. *Progress in Physical Geography*. 2007;31(4):389-403.
- Deng L, Shangguan ZP, Li R. Effects of the Grain-for-Green program on soil erosion in China. *International*

- Journal of Sediment Research. 2012;27(1):120-127.
20. Liu GB, Xu MX, Ritsema C. A study of soil surface characteristics in a small watershed in the hilly, gullied area on the Chinese Loess Plateau. *Catena*. 2003;54(1-2):31-44.
 21. Mabit L, Benmansour M, Walling DE. Comparative advantages and limitations of the fallout radionuclides ¹³⁷Cs, ²¹⁰Pbex and ⁷Be for assessing soil erosion and sedimentation. *Journal of Environmental Radioactivity*. 2008;99(12):1799-1807