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Investigating the spatial distribution of soil erosion and deposition in a small catchment on the Loess Plateau of China, using ^{137}Cs

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Abstract

An understanding of the spatial distribution of soil erosion and deposition in a catchment is important for designing soil and water conservation measures. Traditional monitoring techniques provide limited information on the spatial patterns of erosion and deposition. The fallout radionuclide ^{137}Cs was used to document rates and patterns of soil redistribution within a small (0.17 km^2) gully catchment located near An'sai in Shaanxi Province, representative of the Loess Plateau of China. The local reference inventory was estimated to be 2266 Bq m^{-2} and the ^{137}Cs inventories of 198 soil cores collected from the catchment, ranged from 0 to 3849 Bq m^{-2}. The coefficient of variation of the inventories of the individual cores was 0.85, reflecting the complex pattern of ^{137}Cs redistribution by soil erosion and deposition. Estimates of erosion rates derived from ^{137}Cs measurement ranged from less than 25 to 150 Mg ha^{-1} year^{-1}, with about 70% of the net soil loss from the catchment coming from the gully area. The ^{137}Cs technique was shown to provide an effective means of documenting the spatial distribution of soil erosion and deposition within the small catchment.

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Keywords: ^{137}Cs; Soil erosion; Deposition; Small catchment; Spatial distribution; Loess Plateau; China

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1. Introduction

The Loess Plateau of China is well known as one of the most rapidly eroding areas of the world. Soil conservation measures are needed to control soil and water loss and to improve productivity. An understanding of the spatial distribution of soil erosion and deposition is important for designing soil and water conservation programs, targeting remediation measures and for evaluating the benefits of catchment management. In addition, spatially distributed soil erosion data are needed for validating physically based erosion prediction models and to provide an improved understanding of soil erosion dynamics. Traditional

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monitoring techniques for establishing soil erosion rates provide little or no information on the spatial distribution of soil erosion and deposition. Runoff plots have been widely used for determining erosion rates, but the data obtained from such uniform slopes are unrepresentative of natural landforms, where slope lengths may be longer, and greater opportunities for deposition exist.

Tracers provide a means of obtaining spatially distributed information on soil redistribution rates and various types of tracer have been used for this purpose in recent years. Most tracer studies have, however, employed the bomb fallout radionuclide ^{137}Cs (e.g. Brown et al., 1981; Ritchie and McHenry, 1990; Martz and De, 1991; Walling and He, 1999; Walling, 2003) and such work has commonly focused on investigating rates and patterns of soil redistribution on agricultural fields (Ritchie and McHenry, 1990; Walling, 1998; Walling et al., 2003). To date, a number of soil erosion studies employing ^{137}Cs have been undertaken in the Loess Plateau of China (e.g. Feng et al., 2003; Zhang et al., 1989), but these studies have generally focused on very small areas and have not aimed to provide an integrated assessment of the spatial distribution of soil erosion and deposition within a small catchment. The objective of the study reported in this contribution was to explore the potential for using ^{137}Cs measurements to document the rates and patterns of soil redistribution within the complex assemblage of landforms associated with a typical small catchment located on the Loess Plateau of China. Such information is needed to design and target effective soil and water conservation measures in this rapidly eroding terrain.

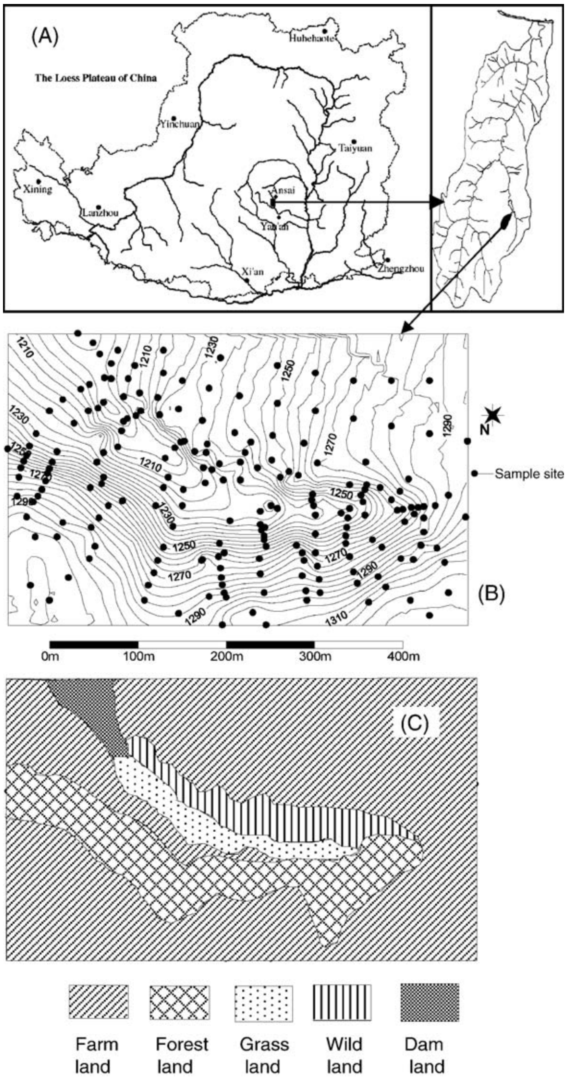

Fig. 1. The location of the study area near An'sai, Shaanxi Province, China (A), the topography (B) and landuse (C) of the catchment.

2. The study area

The study catchment, located at an elevation of 1190–1305 m near An'sai in Shaanxi Province (Fig. 1), is typical of the gullied-hilly area of the Loess Plateau. Gully slopes in this region are very steep, and are characterized by a 70% slope over a vertical elevation change of 100 m. The small (0.17 km^2) catchment comprises two nearly equal sized areas, namely the gully area and the surrounding interfluve and ridge. The climate is characterized by cold dry winters and warm moist summers. The mean annual temperature is 9 °C, with a mean monthly temperature of 22 °C in July and −8 °C in January. The mean annual precipitation is 549 mm, with maximum and minimum recorded values of 958 mm (1964) and 351 mm (1986). Most precipitation occurs in a few large storms, with 75% of the annual precipitation falling during the flood season from June to September. The maximum recorded daily precipitation occurred on July 16, 1989. A total of 137 mm of precipitation, with a maximum intensity of 45 mm in 30 min, was recorded for this event.

A check dam constructed downstream from the study catchment outlet has created a depositional area near the catchment outlet, which has in turn stabilised the steep gully slopes within the catchment. As a result, mass movement activity on the gully slopes has been rare over the past 50 years and surface wash represents the dominant erosion process. The ^{137}Cs technique for estimating erosion rates assumes progressive surface lowering by surface erosion processes and it is inappropriate to use the technique in areas where mass movement processes are important. Its use in the study catchment to estimate rates of surfaced lowering and deposition within the gully area is judged to be appropriate. The interfluve area has been cultivated for several centuries, the main crops being beans, millet and corn. A sparse cover of gum Arabic trees was planted on one gully slope in the late 1970s, but after that date no permanent erosion control measures were applied to the catchment. The soils in the study catchment are typical loessial soils, with over 60% of the material being smaller than 0.25 mm and an organic matter content of less than 2.5%. Under cultivation, the bulk density of this soil averages about 1.1 g cm^{-3}, but this increases to an average around 1.3 g cm^{-3} under other land uses.

3. Methodology

The sampling sites (Fig. 1) were chosen to represent all landform types in the catchment. Samples were mainly collected along downslope transects, although some sampling points were selected on the main gully bed to be representative of this landform. Most soil samples were collected using a 9 cm diameter core tube. Three types of core were obtained. In the first the cores were sectioned into 5 cm increments, in the second they were sectioned into 10 cm increments, whilst for the third type the whole core was retained as a bulk sample. Additional cores collected to a depth of 30 cm and sectioned into 5 cm increments were taken at the bottom of slopes where deposition was expected. Sectioned samples were used to determine both the depth distribution and the inventory or total amount of ^{137}Cs in the soil at the sampling site. Bulk cores were used to determine the ^{137}Cs inventory of the soil at the sampling site.

At the sampling sites, cores were taken at each corner of a 1 m equilateral triangle and where the cores were sectioned, the individual sub-samples for a specific depth increment were mixed to provide a composite sample for that depth increment. Bulk cores were also composite. In general, the three cores types were randomly distributed. However, the proportion of sectioned cores was increased in the flatter areas on the tops of ridges and on interfluve areas, whereas more bulk cores were collected in sloping areas. Table 1 provides information on the distribution of sampling sites between the different landform units.

Two flat artificial terraces in the catchment were selected to provide sampling sites for assessing the local ^{137}Cs reference inventory. These terraces were constructed in the mid 1950s, prior to the main period of bomb fallout. Ten sampling sites were selected randomly on these terraces.

All samples were air-dried, ground, passed through a 2 mm sieve, mixed and weighed. The ^{137}Cs content of the <2 mm fraction of each sample was measured by low background gamma spectrometry, using a hyperpure coaxial germanium detector linked to a multi-channel digital analyzer system (EG&G, ORTEC). All sample weights exceeded 400 g and ^{137}Cs was measured at 661.6 keV. Count times were typically about 28,800 s, providing a measurement precision of ca. ±6% at the 95% level of confidence.

Table 1
The distribution of sampling sites between different landform units

Sample sites	Mound area				Gully area	
	Top of mound crests	Mound slopes	Top of ridge	Ridge slopes	Gully slopes	Gully beds
Sectioned (5 cm intervals)	5	9	5	6	4	2
Sectioned (10 cm intervals)	4	15	5	6	26	22
Bulked	2	41	3	8	26	9
Total	11	65	13	20	56	33
Sum	109				89	

4. The local reference inventory

The ^{137}Cs inventories measured in the cores collected from the sampling sites on the two flat terraces averaged 2266 Bq m^{-2}, with a maximum value of 2789 Bq m^{-2}, a minimum value of 1898 Bq m^{-2} and a standard deviation of 338 Bq m^{-2}. 2. The mean inventory of 2266 Bq m^{-2} was used to represent the local ^{137}Cs reference inventory.

5. The vertical distribution of ^{137}Cs in soils

Fig. 2 shows the ^{137}Cs depth distribution associated with three typical sectioned cores collected from the study area. For core A, which was collected from an undisturbed (uncultivated) site, there is a broad peak in the ^{137}Cs profile close to the surface, and the maximum concentration is found at a depth of 4 cm below the surface. Concentrations of ^{137}Cs decrease gradually below the peak. For the two sectioned cores collected from the cultivated study field, the ^{137}Cs concentrations are relatively uniform within the plough layer. Core B was collected from an eroded location, and the total ^{137}Cs inventory of 1153.5 Bq m^{-2} is substantially lower than the estimated local reference inventory. Core C was collected from a depression area near the base of the interfluve slope, and in this core the ^{137}Cs extends below the plough layer, indicating that deposition of sediment containing ^{137}Cs eroded from upslope has occurred at this location. The occurrence of deposition at this site is further confirmed by the total inventory for core C (2740 Bq m^{-2}), which is substantially greater than the local reference inventory. The ^{137}Cs depth distributions presented in Fig. 2 confirm that the behaviour of radiocaesium in the study catchment conforms to the normal expectations, when using ^{137}Cs measurements to estimate rates of soil redistribution (e.g. Zapata, 2002).

6. Estimation of erosion rates from ^{137}Cs data

Two different conversion models were used in this study to derive estimates of soil redistribution rates from the measured inventories for individual sampling sites, depending on the local site conditions. These were applicable to cultivated soils and undisturbed soils, respectively.

6.1. The conversion model for cultivated soils

A number of approaches have been proposed for deriving estimates of soil redistribution rates from ^{137}Cs measurements obtained from cultivated areas (e.g. Walling and Quine, 1990; Walling and He, 1999). Mass balance models have been frequently used to simulate ^{137}Cs loss and gain for specified erosion and deposition rates and to establish calibration relationships. Walling and He (1999) have developed a mass balance model that has provided reliable erosion rate estimates for an eroding point ($A(t) < A_{\mathrm{ref}}$).

$$\frac{\mathrm{d}A(t)}{\mathrm{d}t} = (1-\Gamma)I(t) - \left(\lambda + P\frac{R}{d}\right)A(t) \qquad (1)$$

where $A(t)$ is the cumulative ^{137}Cs activity per unit area (Bq m^{-2}), R the erosion rate (kg m^{-2} year^{-1}), d the cumulative mass depth representing the average plough depth (kg m^{-2}), λ the decay constant for ^{137}Cs (year^{-1}),

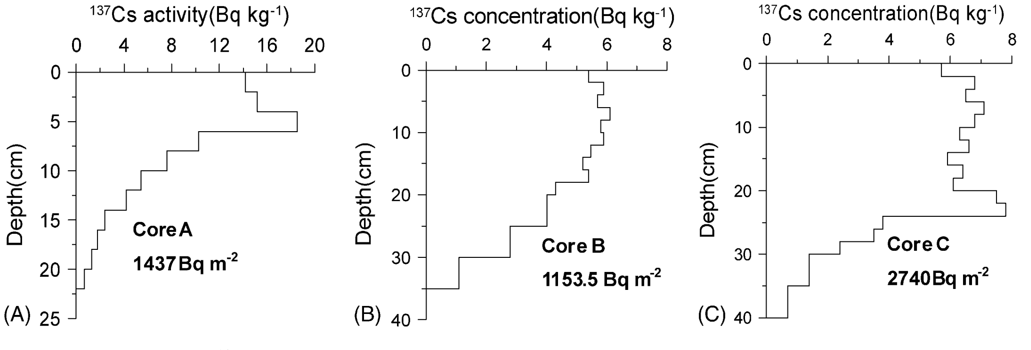

Fig. 2. The vertical distribution of ^{137}Cs associated with soil cores collected from an undisturbed site (A) and cultivated fields (B and C).

$I(t)$ the annual ^{137}Cs deposition flux (Bq m^{-2} year^{-1}), Γ the percentage of the freshly deposited ^{137}Cs fallout removed by erosion before being mixed into the plough layer and P is the particle size correction factor.

For a depositional point ($A(t) > A_{\text{ref}}$), the mean soil deposition rate R' can be calculated from the following equation:

$$R' = \frac{A_{\text{ex}}}{\int_{t_0}^{t} C_{\text{d}}(t')\, \mathrm{e}^{-\lambda(t-t')}\, \mathrm{d}t'} \tag{2}$$

where A_{ex} is the excess ^{137}Cs inventory and $C_{\text{d}}(t')$ (Bq kg^{-1}) is the ^{137}Cs concentration of deposited sediment.

6.2. The conversion model for undisturbed soils

For undisturbed soils, the processes involved in ^{137}Cs redistribution in a soil profile differ from those for cultivated soils, and the ^{137}Cs depth distribution in the soil profile will be significantly different from that in cultivated soils, where it is mixed within the plough layer (He and Walling, 1997). Alternative approaches are therefore required for estimating soil erosion rates for undisturbed soils. Zhang et al. (1990) developed a model for ^{137}Cs distribution in undisturbed soils. This assumed that the depth distribution of ^{137}Cs activity could be represented by a simple exponential function viz.

$$A'(x) = A_{\text{ref}}(1 - \mathrm{e}^{-x/h_0}) \tag{3}$$

where $A'(x)$ is amount of ^{137}Cs above depth x (Bq m^{-2}), A_{ref} the local ^{137}Cs input reference inventory (Bq m^{-2}), x the depth from the soil surface (kg m^{-2}) and h_0 is the coefficient describing profile shape (kg m^{-2}). The erosion rate Y for an eroding point (Mg ha^{-1} year^{-1}) can be estimated from the percentage reduction in the inventory of the sampling point relative to the reference inventory X viz.

$$Y = \frac{10}{t - 1963} \ln\left(1 - \frac{X}{100}\right) h_0 \tag{4}$$

where t is the year of sample collection.

For a depositional location, the deposition rate R' can be estimated from the excess ^{137}Cs inventory $A_{\text{ex}}(t)$ (Bq m^{-2}) and the ^{137}Cs concentration of the deposited sediment C_{d}:

$$\begin{aligned} R' &= \frac{A_{\text{ex}}}{\int_{t_0}^{t} C_{\text{d}}(t')\, \mathrm{e}^{-\lambda(t-t')}\, \mathrm{d}t'} \\ &= \frac{A_{\text{u}} - A_{\text{ref}}}{\frac{P'}{\int_S R\, \mathrm{d}S} \int_S A_{\text{ref}}(1 - \mathrm{e}^{-R/h_0})\, \mathrm{d}S} \end{aligned} \tag{5}$$

where A_{u} is the measured total ^{137}Cs inventory at the sampling point (Bq m^{-2}) and S is the upslope eroding area (m^{-2}).

7. Results and discussion

The ^{137}Cs inventories measured for the sampling sites in the study catchment ranged from 0 to 3849 Bq m^{-2} (Table 2). Even within the same landform group, the variation of ^{137}Cs inventory values was considerable, as shown by standard deviations in excess of median values. The highest coefficients of variation of the ^{137}Cs inventories were

Table 2
The variation of ^{137}Cs inventories within the study catchment

Landform (units)	Interfluve area			Gully area		Entire catchment
	Top of interfluve crests	Top of ridge	Ridge and interfluve slopes	Gully slopes	Gully bottoms	
No. of cases	11	13	85	56	33	198
Minimum (Bq m^{-2})	549	328	0.0	0.0	0.0	0.0
Maximum (Bq m^{-2})	2707	1410	3546	2859	3849	3849
Range (Bq m^{-2})	2158	1083	3546	2859	3849	3849
S.E.	195	96	87	92	121	538
S.D. (Bq m^{-2}).	646	348	806	691	695	743
C.V.	0.49	0.44	0.79	0.96	1.06	0.85
Median (Bq m^{-2})	1126	784	834	487	585	689
Mean (Bq m^{-2})	1329	797	1017	723	654	876

associated with the gully bottoms and the gully slopes, where values of 1.06 and 0.96 were found. Although the slopes are much gentler on the tops of the ridges and interfluves, the coefficient of variation values for these sites still reached 0.49. For the overall catchment, the coefficient of variation was 0.85. These high coefficients of variation values emphasize the importance of soil redistribution within the study catchment.

The spatial distribution of ^{137}Cs inventories in the study catchment was mapped using a spatial interpolation procedure (WINSURFER8.0 Software) constrained by information on the local topography (Fig. 3). The spatial pattern of ^{137}Cs inventories shown in Fig. 3 primarily reflects the distribution of the major landforms in the catchment, namely the ridge, the interfluve and the gully. Overall, the pattern evidences a gradual reduction in the ^{137}Cs inventory, and thus an increase in the erosion rate, from the interfluve area between the gullies to the gullies themselves. In the main gully, ^{137}Cs inventories were higher at the gully head and at the gully mouth than in the middle reaches of the gully. There was evidence of downcutting in the middle part of the main gully. In addition, Fig. 3 also shows that there are some sites where the ^{137}Cs inventories were higher or lower than expected from the general pattern, which suggests that ^{137}Cs redistribution in these areas has been influenced by the microtopography. The sites where ^{137}Cs inventories were higher than expected were located near the gully edge. Because the interfluve area is cultivated and the slope angles at the foot of most interfluve areas are low, sediment has been deposited in the area near the gully edge, increasing the ^{137}Cs inventories in these areas.

The conversion models described above were used to derive estimates of soil redistribution rates from the measured ^{137}Cs inventories and the pattern demonstrated by the estimated soil redistribution rates is shown in Fig. 4. Erosion intensity generally increases from the ridge divide to the main gully bottom. Erosion rates are generally less than 25 Mg ha^{-1} year^{-1} on the interfluve crests, the ridge tops and the upper parts of the ridge and interfluve slopes. Higher erosion rates of 50–75 Mg ha^{-1} year^{-1} are found on the middle and lower portions of the interfluve slopes, and these increase to 75–100 Mg ha^{-1} year^{-1} on the upper parts of the gully slopes. Values of 100–150 Mg ha^{-1} year^{-1} are found on the middle parts of the gully slopes and these values increase to between 150 and 200 Mg ha^{-1} year^{-1} on the lower gully slopes. In addition, high erosion rates (>150 Mg ha^{-1} year^{-1}) were found around the gully heads of both the main and the branch gullies. Gully heads are the key position for controlling soil erosion and sediment delivery. To control erosion around gully heads, runoff needs to be reduced. This could be accomplished by constructing terraces or contour trenches or reducing tillage on the interfluve areas to reduce the runoff reaching the gully head. The values of net soil loss from different landforms shown in Table 3 indicate that most of the sediment is mobilized

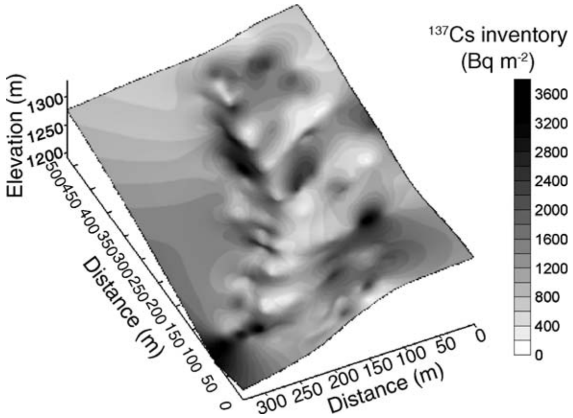

Fig. 3. The spatial distribution of ^{137}Cs inventories within the study catchment.

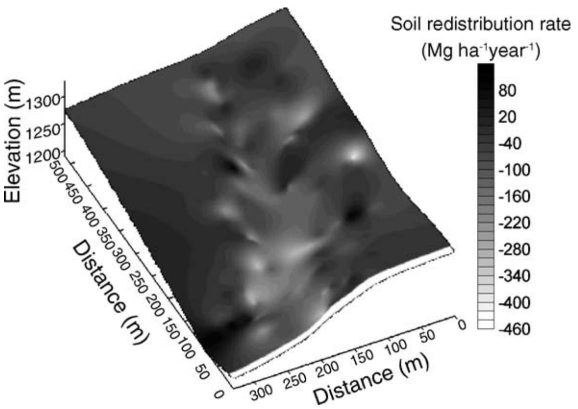

Fig. 4. The spatial distribution of soil redistribution rates within the study catchment.

Table 3
Net soil loss from different landforms within the study catchment

Landform (units)	Mound area			Gully area	
	Top of interfluve crests	Top of ridge	Ridge and interfluve slopes	Gully slopes	Gully bottoms
Area (m^2)	7150	2750	68100	86250	7750
Net soil loss (Mg ha^{-1} $year^{-1}$)	20.95	46.40	78.56	118.74	188.75
Net soil loss (Mg $year^{-1}$)	563			1170	

from the gully area, which contributes ca. 70% of the net soil loss from the catchment. The net soil loss from the gully area could be reduced by constructing a dam at the gully entrance so that a proportion of the sediment output from the catchment would be deposited within the gully. In addition, planting more trees and grass on the gully slopes could also be expected to further reduce soil loss from the gully area.

Although it is not possible to directly validate the magnitude of the erosion rates estimated from the ^{137}Cs measurements, an indication of their likely reliability can be obtained by comparing the estimate of total net soil loss from the study catchment based on the ^{137}Cs measurements and presented in Table 3 (1733 Mg $year^{-1}$) with an estimate of the local specific sediment yield derived from sediment load measurements in larger adjacent river basins. Existing evidence suggests that it is reasonable to assume that sediment delivery ratios in the Loess Plateau of China are close to 1.0 (cf. Mou and Meng, 1982) and that it is therefore possible to make a direct comparison between the value of net soil loss from the study catchment estimated using the ^{137}Cs measurements for the different landform units (see Table 3) and the estimate of the local specific sediment yield. The latter value is estimated to lie in the range 6355–14,000 Mg km^{-2} $year^{-1}$ before 1990 (cf. Jiang and Zheng, 2004). Since the level of erosion control in the larger river basins prior to 1990 was similar to that in the study small catchment, the estimate of net soil loss from the study catchment of 10,076 Mg km^{-2} $year^{-1}$ is seen to be entirely consistent with the measured sediment yields. It can therefore be suggested that the soil redistribution rates estimated from the ^{137}Cs measurements provide a meaningful assessment of the absolute magnitude of rates of soil loss in the study catchment as well as the spatial pattern involved.

8. Conclusion

The results presented in Table 2 and Figs. 2 and 3 clearly confirm the potential for using ^{137}Cs measurements to investigate the spatial pattern of soil redistribution in the study catchment. These results indicate that soil erosion rates increase markedly in moving from the ridge tops and interfluves, to the lower slopes of the interfluves and finally to the steep slopes of the gully. Erosion rates are generally less than 25 Mg ha^{-1} $year^{-1}$ on the interfluve crests, the ridge tops and the upper parts of the ridge and interfluve slopes. Higher erosion rates of 50–75 Mg ha^{-1} $year^{-1}$ are found on the middle and lower interfluve slopes, and these increase still further to 75–100 Mg ha^{-1} $year^{-1}$ on the upper parts of the gully slopes. The gully area accounts for about 70% of the net soil loss from the study catchment.

The ^{137}Cs technique has been successfully used to study the spatial distribution of soil redistribution within a study area and thus offers important advantages over other methods for documenting erosion rates. The resulting data can provide a valuable basis for planning soil conservation and sediment control measures, in areas such as the Loess Plateau of China.

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