Investigation of Erosion Rates and Sediment Sources by Using ^{137}Cs Technique in the Loess Plateau of China

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Abstract: ^{137}Cs reference inventories ranged between 1,652—2,741Bq/m^2 (1993s' level), and had a tendency to increase from northwest to southeast as annual precipitation increase in the Loess Plateau. The average ^{137}Cs inventories on cultivated slopes (19°—29°) ranged from 557.2 Bq/m^2 to 1,068.0 Bq/m^2 which accounted for 21.94% and 42.05% of the local ^{137}Cs reference inventory, respectively, and corresponding erosion rates ranged from 8,409.4 t/(km^2 • yr) and 4,856.6 t/(km^2 • yr), respectively. The average ^{137}Cs inventories on steep grass and forest slopes (24.1°—43.5°) ranged from 1,770 Bq/m^2 to 2,310Bq/m^2 which accounted for 68.0 % and 88.9 % of the local ^{137}Cs reference inventory, respectively, and corresponding erosion rates ranged from 136 t/(km^2 • yr) to328 t/(km^2 • yr). It was apparent that soil erosion was severe on cultivated slopes and slight on the forest and grass slopes. More than 70% of sediment in rivers comes from the gully area in the Loess Plateau region although soil erosion is severe on the cultivated slopes in the inter-gully area.

Keywords: ^{137}Cs, erosion rates, sediment sources, loess plateau

1 Introduction

The Yellow River is well known for its extremely high suspended sediment load, which is reported to be of the order of 1.6 $\times 10^9$ t/yr and therefore accounts for nearly 10 percent of the total annual sediment flux of the world's rivers to the oceans (Walling and Webb, 1987). Most of the sediment transported by the lower Yellow River originates from the Loess Plateau region, which is located in the middle reaches of the river basin. The dominant landforms of the plateau are rolling hills (rolling plateau) or high plains (high plain plateau) dissected by deep gullies. Soil erosion is very severe throughout the region. Sheet and rill erosion is severe on cultivated slopes, which are extensively distributed over the plateau. Gully erosion and active mass movements predominate in the gully areas. Since the 1960s, an extensive program of soil conservation and sediment control measures has been carried out over the plateau, and this has been associated with a significant reduction in the sediment load of the Lower Yellow River since 1970(Mou, 1991). In order to evaluate the precise impact of the various soils conservation and sediment control measures on sediment delivery there is a need for an improved understanding of the erosion behavior of the plateau.

Classic methods to monitor soil losses on slopes and sediment loads in rivers such as runoff plot and hydrological monitoring station has been used over the plateau. Those methods are costly and can not solve all scientific questions of erosion and sedimentation in the plateau(Campell *et al.*,1988). The Loess Plateau is the first region to use the ^{137}Cs technique to study soil erosion and sedimentation in China in 1986, because the loess soil has a fine and uniform texture (Zhang *et al.*, 1987). Since then, studies have been carried out over the plateau. This paper reports the achievements in using the ^{137}Cs technique to investigate soil erosion rates and sediment sources in the plateau.

2 Basis of the ^{137}Cs technique

^{137}Cs is an artificial radionuclide with a half-life of 30.17 years which released into the environment as a result of atmospheric testing of thermo-nuclear weapons primarily during the period from 1954-mid-

1970s. ^{137}Cs fallout is strongly and rapidly adsorbed by fine particles in the surface horizons of the soil, when it falls down on the ground mostly with precipitation. Subsequent redistribution of the radiocaesium reflects the movement of soil particles since the ^{137}Cs moves in association with the soil particles(Quine.1989). ^{137}Cs is concentrated in the upper horizons of few centimeters in depth and declines rapidly, and the maximum ^{137}Cs distribution depth is less than 20 cm under uncultivated land where soil is undisturbed. It is quite evenly distributed to plough depth (15cm—25cm) under cultivated land, where tillage mixes the ^{137}Cs fallout with plough soils. ^{137}Cs distribution depths in profile on accumulative sites are greater than at no accumulation sites . If it is assumed that the initial distribution of the ^{137}Cs fallout input was uniform then deviations in the measured distribution of ^{137}Cs from local fallout inventory represent the net impact of soil redistribution during the period since ^{137}Cs deposition. It will be possible to estimate rates of soil erosion and accumulation from ^{137}Cs measurements, if a relationship between ^{137}Cs loss and gain and soil loss and gain can be established. The sediments delivered from the inter-gully area, where the land has been extensively cultivated, contain a considerable amount of ^{137}Cs, while those delivered from the gully area, where gully erosion and active mass movements are predominated, contain no or very little ^{137}Cs, in the Loess Plateau. By comparison of the ^{137}Cs contents between the plough soil of cultivated slopes in the inter-gully area, and the products of gully erosion and mass movements in the gully area, and the suspended sediment of floods or deposited sediment in reservoirs, in a watershed, the relative contributions from the inter-gully area and the gully area can be estimated.

3 ^{137}Cs reference inventory distribution over the plateau

Flat grassland is usually selected as a ^{137}Cs-reference site in other countries(Quine.1989). But, such grassland is difficult to be found in the Loess Plateau. We also selected a large flat cultivated field as a ^{137}Cs-reference site, if no flat grassland could be found in a study area, ^{137}Cs reference inventories ranged between 1,652—2,741Bq/m^2 (1993s' level), and had a tendency to increase from northwest to southeast as annual precipitation increased .

4 Estimating soil losses from ^{137}Cs measurements

4.1 Cultivated land

The soil loss at a point of a cultivated land was calculated by using the simplified mass balance model (Zhang *et al.*,1990):

$$A = A_0(1 - \Delta H / H)^{N-1963} \tag{1}$$

where: A= the ^{137}Cs inventory (Bq/kg); A_0 = the local ^{137} Cs reference inventory; ΔH = annual soil loss in depth (cm); H= plough soil depth (cm).

The calculated erosion rate using the above model from the ^{137}Cs inventory at a point on a cultivated slope represents the combination of soil losses by water erosion and tillage at the point. The average water erosion rate over a field of a cultivated slopes should be calculated from the area-weighted mean ^{137}Cs inventory, because tillage redistributed the soil within the field and only water erosion removes soil out of the field.

Investigation of erosion rates on cultivated slopes by using the ^{137}Cs technique had been carried out at seven study sites over the plateau. Water erosion rates on cultivated slopes derived from the ^{137}Cs measurements at the Ansai study site, where sampling was undertaken in 1992, are shown in Table 1. The local ^{137}Cs reference inventory was 2,540 Bq/m^2. The average ^{137}Cs inventories over a field ranged from 557.2 Bq/m^2 to 1,068.0 Bq/m^2, which accounted for 21.94% and 42.05% of the local ^{137}Cs reference inventory, respectively. The erosion rates, estimated by using the above formula (γ=1.1g/cm^3, H= 15 cm), ranged from 8,409.4 t/(km^2 • yr) and 4,856.6 t/(km^2 • yr). It was apparent that the steeper the cultivated slopes, the higher the erosion rates. In general, the soil erosion rates from the ^{137}Cs measurements were close to the rates predicted by using the local empirical relationships developed from the runoff plot data. But the rates derived from the ^{137}Cs measurements were considerably higher than the predicted values of the empirical relationships if the slope length was more than 50 m. This is because the soil loss is predominately caused by rill erosion on a cultivated slope and rill erosion is not getting severe if slope length is greater than 50 m. Most of rills reach the plough pan layer during a heavy storm, But the local empirical relationships were developed from the data of runoff plots of less 40m.

Table 1 Erosion rates on cultivated slopes derived from ^{137}Cs measurements at Ansai site

Field		1	2	3	4
Total slope	Slope length(m)	49.23	77.13	62.29	88.82
	Slope gradient(°)	23.98	19.11	28.94	11.21
	Average ^{137}Cs inventory(Bq/m^2)	705.2	771.0	557.2	1,068.0
	Erosion rates (t/(km^2 • yr))	7,132.1	6,646.7	8,409.4	4,856.6
Gentle hill top	Slope length(m)	16.31	21.73	14.97	15.97
	Slope gradient(°)	5.40	8.35	14.49	1.68
	Average ^{137}Cs inventory(Bq/m^2)	1,164.1	937.6	617.6	21,423.9
	Erosion rates (t/(km^2 • yr))	4,379.7	5,570.5	7,853.0	3,260.0
Steep hill slope	Slope length(m)	30.02	55.40	47.32	72.85
	Slope gradient(°)	30.04	22.96	31.87	12.73
	Average ^{137}Cs inventory(Bq/m^2)	548.7	713.5	669.7	1,002.4
	Erosion rates (t/(km^2 • yr))	8,491.8	7,068.8	7,412.6	5,206.6

4.2 Uncultivated land

The soil loss at a point of uncultivated land was calculated by using the following equation(Zhang *et al.*,1990):

$$A = A_0 e^{-\lambda h} \tag{2}$$

where: A= the ^{137}Cs inventory at a point (Bq/m^2), A_0 = the local ^{137}Cs reference inventory (Bq/m^2), λ = coefficient(cm^{-1}), h= depth (cm). Investigation of erosion rates on uncultivated slopes by using the ^{137}Cs technique have been carried out at five study sites over the plateau. Water erosion rates on uncultivated slopes derived from the ^{137}Cs measurements at the Xifeng study site, where sampling was undertaken in 1993, are shown in Table 2. The local ^{137}Cs reference inventory was 2,600 Bq/m^2.The average ^{137}Cs inventories on grass and forest slopes ranged from 1,770 Bq/m^2 to 2,310 Bq/m^2 , which accounted for 68.0% and 88.9% of the local ^{137}Cs reference inventory, respectively. The erosion rates, estimated by using the above formula (γ =1.21g/cm^3 , λ = 0.23 cm^{-1}), ranged from 136 t/(km^2 • yr).

Table 2 Erosion rate derived from ^{137}Cs measurements on uncultivated slopes at Xifeng study site

Field	Vegetation	Slope length (m)	Slope gradient(°)	^{137}Cs ineventory (Bq/m^2)	Erosion rate(t/(km^2 • yr))
1	Grass	23.0	24.1	2,350	167
2	Grass	96.3	38.8	2,000	237
3	Grass	75.0	31.8	2,150	159
4	Grass	31.4	37.0	2,210	136
5	Grass	36.5	33.6	1,950	243
6	Forest	38.5	34.8	1,770	328
7	Forest	29.0	43.5	2,140	163
8	Bare slope	30.0	45.0	60	3,267

to 328 t/(km^2 • yr). It was apparent that soil erosion was limited on the forest and grass slopes although the slopes were very steep (24.1°—43.5°). In contrast, the average ^{137}Cs inventories on the bare slope was very low, 60 Bq/m^2 , only accounted for 2.3% of the local ^{137}Cs reference inventories, the corresponding erosion rate was very high, 3,267 t/(km^2 • yr) (Zhang, *et al.*, 1994).

The studies carried out at other sites had similar results as at the Xifeng site. It was apparent that slope gradients had little effects on erosion rates on uncultivated slopes under good vegetation coverage and the vegetation coverage was the key factor to the soil erosion on uncultivated slopes in the Loess Plateau.

5 Sediment sources

The plough soils of cultivated slopes with a certain ^{137}Cs content in the inter-gully area and the products of gully erosion and mass movements in the gully area with little ^{137}Cs are major sediment sources in the Loess Plateau. It has been suggested that the sediment delivery ratio be close to 1(Jing, *et al.*,1997). The relative contributions of the suspended sediments of the rivers and the deposited sediments in sediment trapping reservoirs from the two areas can be determined by using the simple mixing model:

$$C_d = C_m \quad f_m + C_g \quad f_g \tag{3}$$

$$f_m + f_g = 1 \tag{4}$$

Where: C_d = the ^{137}Cs content of suspended sediment or deposited sediment (Bq/kg); C_m = the ^{137}Cs content of the plough soil in the inter-gully area(Bq/kg); f_m = the relative contribution of the sediment from the inter-gully area (%); C_g = the ^{137}Cs content of the products of gully erosion and mass movements (Bq/kg); f_g = the relative contribution of the sediment from the gully area (%).

Detailed studies of the relative contributions of deposited sediments from the inter-gully area and gully area were undertaken in five small watersheds with a drainage area of 0.21km^2—2.63km^2 in the rolling plateau. The ^{137}Cs contents of plough soils on cultivated slopes in the inter-gully area varied between 1.6Bq/kg—9.5 Bq/kg (n=232) in the six watersheds. The ^{137}Cs contents ranged from 3.72 Bq/kg to 9.50 Bq/kg with a mean value of 5.70Bq/kg for the relatively gentle slopes of <15° (n=113), from 2.60Bq/kg to 3.98Bq/kg with a mean value of 3.41bq/kg for the relative steep slopes, and from 1.60 Bq/kg to2.30Bq/kg with a mean value of 2.01Bq/kg for the steep slopes. The plough soils for a certain gradient of the cultivated slopes had no significant differences in ^{137}Cs contents among the watersheds. The average ^{137}Cs content of the products of gully erosion and mass movements in the gully area were 0.02 Bq/kg in the Zhaojia Gully and no ^{137}Cs was detected in the surface soils on steep gully walls in the Yangdao Gully (Zhang, *et al.,*1989,199*7).* The ^{137}Cs contents of the deposited sediments in the sediment trapping reservoirs in the five watersheds varied between 0.58 Bq/kg—1.15 Bq/kg. By analysis of the erosion severities and area ratios of the above three types of the slopes to the total area of the inter-gully area, the average ^{137}Cs contents of plough soils on the relative steep slopes were used to calculate the relative contributions of sediment in a watershed. By using the mixing model, the relative contributions of sediment from the gully area ranged from 67% to 80% for the four watersheds in the eastern rolling plateau and 83% for the Qiaozixi Gully in the western rolling plateau.

Table 3 The ^{137}Cs contents of deposited and suspended sediments and relative contribution of the sediment from the gully area in the Loess Plateau

Watershed	Zhaojia Gully	Majia Gully	Yangdao Gully	Yuejia Gully	Qiaozixi Gully	Yellow River (Wupu)	Yellow River (Longmen)	Qingjian River (Zichang)	Qingjian River (Yanchuan)	Tuwei River (Gao jianpu)	Tuwei River (Gaojia chuan)	Fenhe River (Hejing)
Drainage area (km^2)	2.63	0.84	0.21	1.70	1.09	433,514	497,552	913	3,468	2,095	3,253	38,728
^{137}Cs content of sediment (Bq/kg)	0.91	1.15	0.74	0.78	0.58	0.40	1.14	0.74	0.55	0.75	0.48	1.09
Relative contribution of sediment from gully area (%)	73	64	78	77	83	88	67	78	84	78	86	68

Suspended sediment samples were collected at two hydrological stations on the Yellow River and at five stations on its big tributaries in 1993 and 1994(Jing, *et al.*,1997). Three floods sampled at the stations represent the range in magnitude for the year from small to large. The ^{137}Cs contents of the suspended sediment samples ranged from 0 to 2.7Bq/kg and the arithmetic mean content of the samples at each station ranged from 0.40 Bq/kg to 1.14 Bg/kg. The average ^{137}Cs content of the suspended sediment samples at the Wupu Station on the upstream of the Middle Yellow River had the lowest value of 0.40 Bq/kg, while it had the highest value of 1.14 Bq/kg at the Longmen Station on the downstream of the river among the seven stations. The ^{137}Cs contents of the suspended sediments of the five tributaries ranged from 0.55 Bq/kg to 1.09 Bq/kg. Those values were close to the deposited sediments in the sediment trapping reservoirs. The ^{137}Cs contents of the suspended sediments and deposited sediments had a tendency to decrease from the north to the south in the Hekouzhen-Longmen basin. It implied that gully erosion became slight from the north to the south in the basin. The relative contributions of the suspended sediments in the floods at the seven stations from the gully area were estimated between 67% and 88% (C_m=3.41 Bq/kg, C_g= 0.02 Bq/kg). By synthetic analyses of the relative contributions of sediment from the gully area from this and other studies with the erosion environment conditions, the relative importance of the sediment from gully area in the Middle Yellow River Basin can be drawn as following: more than 70% of the sediments comes from the gully area in most of the basin except in the Fenhe River and Weihe River Valley regions. More than 85% of sediment came from the gully area in the high plain plateau and Shaanxi-Shanxi Gorge region of the Yellow River.

6 Conclusions

(1) The ^{137}Cs technique has a great potential for investigation of erosion rates and sediment sources in the Loess Plateau and the fine and uniform texture of the loess soil is favourable for the technique.

(2) More than 70% of sediment in rivers comes from the gully area in the Loess Plateau region although soil erosion is severe on the cultivated slopes in the inter-gully area.

(3) Erosion rates derived from ^{137}Cs measurements are close to the rates predicted by using the local empirical relationships developed from the runoff plot data.

(4) Soil erosion is very slight on steep slopes under good vegetation coverage and very severe on steep bare slopes.

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