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Estimation of soil erosion in the Xihanshui River Basin by using ^{137}Cs technique

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Abstract

The Cesium-137 technique was used to estimate soil erosion in the Xihanshui River Basin. More than 100 samples were taken from 10 sites and 20 hillslopes with a 10cm diameter hand-operated core driller. Each sample was 60 cm long. The ^{137}Cs activity was analyzed by gamma spectrometry. The simplified mass balance model and the profile distribution model were used to calculate soil erosion and deposition rate. The local ^{137}Cs reference ranged from 1,600 to 2,402 Bq m^{-2}. The data shows an exponential decrease of mass concentration and amount with depth in an undisturbed soil profile. Soil erosion in the river basin is moderate or severe on cultivated land with annual erosion rates of 2,000-6,000 t km^{-2} yr^{-1}. In general, very severe or severe soil erosion occurred at the upper slope sections, moderate or severe soil erosion at the middle section, and moderate or slight soil erosion at the lower slope sections. On the slopes with natural vegetation, consisting of herbaceous and wood species, the erosion rate is much lower or not detectable. On the lower section of slopes with well-developed vegetation however, there was no soil loss, instead deposition occurred at a rate of more than 300 t km^{-2} yr^{-1}. The slope gradient and vegetation cover affected soil erosion and deposition rates. In general, the rate of soil erosion was proportional to the slope gradient and inversely proportional to the degree of vegetative cover.

Key Words: Soil erosion, ^{137}Cs technique, Cultivated land, Vegetation, Xihanshui River Basin

1 Introduction

The ^{137}Cs technique has been used in soil erosion studies since the 1960s. ^{137}Cs is an artificial radionuclide with a half-life of 30.17yr. It was released into the stratosphere and globally distributed following thermonuclear weapon tests in the late 1950s and early 1960s. As a by-product of nuclear fission, ^{137}Cs fell on the earth with rainfall and was strongly fixed by surface soil and sediment. Since the subsequent redistribution in the soil profile is mainly caused by soil detachment and deposition or soil tillage, the migration characteristics of ^{137}Cs can be used as an effective sediment tracer that can provide a basis for estimating soil erosion and deposition rates (Estrany et al., 2010; Philip et al., 1996). In most parts of China, ^{137}Cs deposition mainly occurred in the 1950-1970s. Although the Chernobyl nuclear accident of April 1986 in the Soviet Union caused the first settlement peak of ^{137}Cs in most regions of the globe, it contributed to little fall-out in China which territory is located in East Asia, far away from the site of the accident. Europe and West Asia were very severely affected (Qi et al., 2006).

The ^{137}Cs technique has been used in many regions for estimating soil erosion (Li et al., 2003; Kosmas et al., 2001; Zhang et al., 2006; Taijiro et al., 2005; Zhang et al., 2008; Saito-Kokubu et al., 2008; Yang et al., 2006). Research conducted in many worldwide environments has demonstrated that this technique is

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accurate in estimating soil loss and sediment deposition rates. Moreover, this technique presents many advantages over conventional monitoring techniques (Loughran, 1989), including the potential for deriving retrospective estimates of erosion and deposition rates based on a single site visit, and the potential for assembling distributed information for individual points in the landscape that can be used to study spatial patterns of soil redistribution. Thus, in watersheds situations where there is a lack of sediment data over a long term, the ^{137}Cs technique can be used to quickly and accurately quantify soil erosion and redistribution rates.

The focus of this study is to use the ^{137}Cs technique for estimating soil erosion in the Xihanshui River Basin, a tributary to the Upper Yangtze River Basin and one of its major sediment sources. This is of special interest. Sediment production due to soil erosion in the Xihanshui River Basin directly affects the service life-span and normal operations of the Three Gorges Dam, the biggest hydro-power project in the world. The sediment sources are from three representative land uses that include cultivated land, vegetated land, and revegetated land. These are discussed in this study, and general characteristics of typical soil erosion were obtained for the Xihanshui River Basin.

2 Study area

The Xihanshui River Basin is located in the south-eastern part of Gansu Province, China, and covers an area of 1.02×10^4 km^2. The Xihanshui River, an upstream tributary of the Jialing River, has its source in the Qishou Mountains near Tianshui City, Gansu. This river crosses the Longnan regions, that include Lixian, Xihe, Chengxian, and Kangxian, then enters Shaanxi Province and joins the Jialing River at Lueyang (Fig. 1). The area north of the Xihanshui River drains the southwestern edge of the Loess

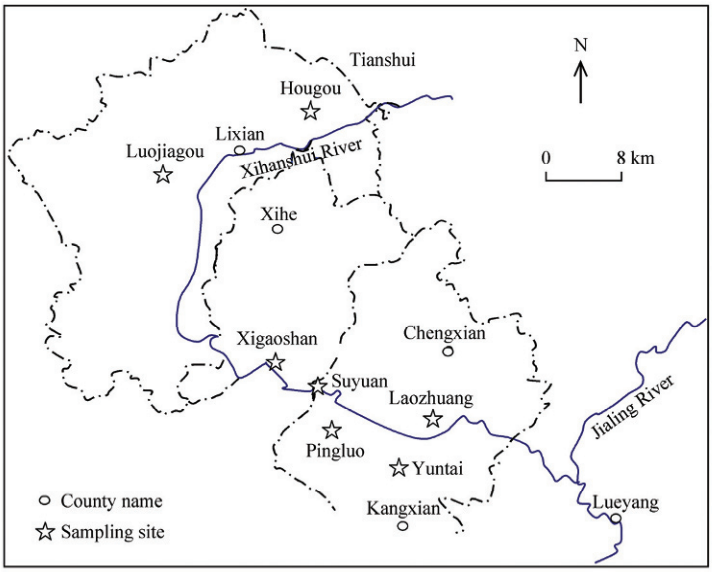


Fig. 1 Distribution of sampling sites in the Xihanshui River Basin

Plateau. The Xihanshui watershed borders the Yellow River Basin in the north. The basin has an annual precipitation ranging from 400 to 800 mm, and rainstorms occur mostly from July to September. Therefore, these rainstorms readily cause serious erosion in the loess region. For example, the basin north of the Daqiao Hydrological Station covers an area of 6,491 km^2. It has an annual sediment yield of 21.2 million tons and an annual sediment transport rate of 3,260 t km^{-2} yr^{-1}. Therefore, this basin has been one of the largest producing sediment yield areas of China. The sources of soil loss in the Xihanshui River Basin are gully erosion, soil mass movement, debris flow, freeze-thaw erosion, wind erosion, and erosion caused by gold mining. Knowledge of these soil losses is essential for determining sediment budgets which would allow the distribution of sediment in different parts of a river basin (Wang et al., 2007). This study discusses the fundamental aspects of sediment budgeting as applied to the Xihanshui River Basin, using the ^{137}Cs technique.

3 Methods

The ^{137}Cs technique was used to estimate soil erosion (deposition) by comparing ^{137}Cs content of the eroded (deposited) site with a reference site (non-eroded and non-deposited site). Through this comparison, a determination could be made whether erosion (less ^{137}Cs present than at the reference site) or deposition (more ^{137}Cs present than at the reference site) has occurred. The ^{137}Cs technique was applied in three steps: field sampling, nuclide content determination, and erosion rate calculation.

3.1 Field sampling and nuclide content determination

Soil cores were collected along the slopes of representative sections of the selected cultivated and vegetated fields. The fields selected, were representative of the range of gradients, slope lengths, and land use in the basin. The distribution of sampling sites is shown in Fig. 1. The sampled locations on the hillslopes were representative positions of the sampled land use to be studied and soil cores were obtained at regular intervals along the slope. For flat areas, such as the reference sites, soil cores were taken following a "S"-shaped sampling pattern. Soil samples were collected with a 10-cm diameter hand-operated core driller. Before sampling, the site was cleared of weeds and crop residue, and then the sampler was vertically drilled into the soil profile to extract soil cores at a specified depth. After the withdrawal of the sampling drill, soil samples were taken and packed into bags, which were labeled both inside and outside. Bulk soil cores and sectioned cores taken at 10-cm intervals were both collected to depths of 30-60cm. The maximum sampling depth was one of a predetermined parameter that ensured that all soil containing ^{137}Cs had been obtained. Samples were collected from November to December in 2008, and more than 100 soil cores were taken from 10 sites and 20 hillslopes within the Xihanshui River Basin.

Soil samples were air-dried, gently disaggregated, sifted, and weighed. 250g of soil with a grain size <2mm were taken out with quartiles (because ^{137}Cs usually occurs in the soil with the grain size <2mm), then put into organic glass containers and sealed to meet measurement requirements. Measurements of ^{137}Cs were made at the Institute for Application of Atomic Energy, Beijing, using γ spectrometry with BE5030-type detector. Laboratory Sourceless Object Calibration Software (LabSOCS) was used for sample efficiency calibration. Cesium-137 content of samples was detected at 661.65KeV peak and using a counting time between 8-24h.

3.2 Erosion rate calculation

The original laboratory determined ^{137}Cs data were obtained on a per unit mass basis (Bq kg^{-1}), These data were multiplied by the soil sample mass obtained from the soil cores (grain size <2mm) and divided by the cross-sectional area of the cores to compute the ^{137}Cs on a per unit surface area basis .

The calculation model used for cultivated soil that is commonly used in the ^{137}Cs technique, is usually referred to as the mass balance model, of which, there are two: the simplified mass balance model and the complex mass balance model. From a practical application standpoint, both models meet the determination accuracy requirements. However, the complex model is more accurate, but some of the parameters in this model are difficult to determine for certain areas, such as the relaxation depth, the ^{137}Cs deposition amount in a particular year, and the loss rate of the freshly deposited ^{137}Cs-fallout prior to its incorporation into the plough layer by cultivation.

There are two types of calculation models for uncultivated soil: the profile distribution model and the diffusion-migration model. The profile distribution model is a fairly simple model and is easy to use. However, it does not take into account the time-dependent behavior of both the ^{137}Cs fallout input and the progressive development of the depth distribution of the ^{137}Cs within the soil profile following deposition from the atmosphere. In the diffusion-migration model, the time-dependent behavior of both the ^{137}Cs fallout deposition and its subsequent redistribution in the soil profile are taken into account, which represents somewhat an improved over the profile distribution model. It does require the computation of complex parameters, such as relaxation depth, which are difficult to determine with reliability in some area. (Walling and He, 1997; 1999; Poreba and Bluszcz, 2008).

This work used the simplified mass balance model for cultivated soil, and the profile distribution model for non-agricultural vegetated lands. Meanwhile, this work used the simplified mass balance model for studying the revegetated lands, as there does currently not exist a specific model or any other practical calculation method for revegetated land. Moreover, the two revegetated areas considered in this study had been used as cultivated lands for 50 and 80 years, respectively, before they were returned to natural vegetation lands 4-5 years ago.

3.2.1 Simplified mass balance model (for cultivated soils)

Zhang et al. (1990) have proposed a simplified mass balance model that assumes that the total ^{137}Cs fallout occurred in 1963 instead of over a longer period that extends from the mid 1950s to the mid 1970s. In its original form, this simplified mass balance model did not take into account particle size effects, though a correction factor P was introduced that reflected this effect.

Assuming a constant erosion rate R (m m^{-2} yr^{-1}), the total ^{137}Cs inventory (A, Bq m^{-2}) at year t (yr) for an eroded site ($A(t)<A_{ref}$) can be expressed as:

$$A(t) = A_{ref}(1 - P\frac{R}{d})^{t-1963} \quad (1)$$

Equation (1) can be rearranged to obtain the following expression for the annual erosion rate:

$$Y = \frac{10dB}{P}\left[1 - \left(1 - \frac{X}{100}\right)^{1/(t-1963)}\right] \quad (2)$$

where A_{ref} = local reference inventory (Bq m^{-2}); Y = mean annual soil loss (t ha^{-1} yr^{-1}); d = depth of plough or cultivation layer (m); B = bulk density of soil (kg m^{-3}); X = percentage reduction in total ^{137}Cs inventory (defined as $(A_{ref}-A)/A_{ref}\times 100$); P = particle size correction factor.

For a deposition site ($A(t)>A_{ref}$), with a constant deposition rate R' (kg m^{-2} yr^{-1}), the sediment deposition rate can be estimated from the ^{137}Cs concentration of the deposited sediment $C_d(t')$ (Bq kg^{-1}) according to:

$$R' = \frac{A_{ex}(t)}{\int_{1963}^{t} C_d(t')e^{-\lambda(t-t')}dt'} = \frac{A(t) - A_{ref}}{\int_{1963}^{t} C_d(t')e^{-\lambda(t-t')}dt'} \quad (3)$$

where $A_{ex}(t)$= the excess ^{137}Cs inventory of the sampling point over the reference inventory at year t (defined as the measured inventory minus the local reference inventory) (Bq m^{-2}); $C_d(t')$= ^{137}Cs concentration of deposited sediment at year t' (Bq kg^{-1}); λ = decay constant for ^{137}Cs (yr^{-1}); P'= particle size correction factor.

Generally, the ^{137}Cs concentration $C_d(t')$ of deposited sediment can be presented as the weighted mean of the ^{137}Cs concentration of sediment moved downslope from the upslope contributing area. $C_d(t')$ can therefore be calculated using the following equation:

$$C_d(t') = \frac{1}{\int_S RdS}\int_S P'C_e(t')RdS \quad (4)$$

where S (m^2) is the upslope contributing area, and $C_e(t')$ (Bq kg^{-1}) is the ^{137}Cs concentration of sediment detached and transported from an eroding point, that can be calculated from Eq. (1) according to:

$$C_e(t') = P\frac{A(t')}{d} = \frac{P}{d}A_{ref}(t')\left(1 - P\frac{R}{d}\right)^{t'-1963} = \frac{P}{d}A_{ref}(t)e^{\lambda(t-t')}\left(1 - P\frac{R}{d}\right)^{t'-1963} \quad (5)$$

where $A_{ref}(t)$=A_{ref}.

3.2.2 Profile distribution model (for uncultivated soils)

In many situations, the depth distribution of ^{137}Cs in an undisturbed stable soil would exhibit an exponential decrease with depth, which may be described by the following function (Zhang et al., 1990):

$$A'(x) = A_{ref}(1 - e^{-x/h_0}) \quad (6)$$

where $A'(x)$ = amount of ^{137}Cs above the depth x (Bq m^{-2}); A_{ref} = ^{137}Cs reference inventory (Bq m^{-2}); x = depth from soil surface (kg m^{-2}); h_0 = coefficient describing profile shape (kg m^{-2}).

If it is assumed that the total ^{137}Cs fallout occurred in 1963 and that the depth distribution of the ^{137}Cs in the soil profile is independent of time, the erosion rate Y for an eroding point (with total ^{137}Cs inventory A_u (Bq m^{-2}) is less than the local reference inventory A_{ref} (Bq m^{-2})) and can be expressed as:

$$Y = \frac{10}{(t-1963)P} \ln(1 - \frac{X}{100}) h_0 \tag{7}$$

where Y = annual soil loss (t ha^{-1} yr^{-1}); t = year of sample collection (yr); X = percentage ^{137}Cs loss of total inventory according to the local ^{137}Cs reference value (defined as $(A_{ref}-A_u)/A_{ref}\times 100$); A_u= measured total ^{137}Cs inventory at the sampling point (Bq m^{-2}).

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

$$R' = \frac{A_{ex}}{\int_{t_0}^{t} C_d(t') e^{-\lambda(t-t')} dt'} = \frac{A_u - A_{ref}}{\frac{P'}{\int_S RdS} \int_S A_{ref}\left(1 - e^{-R/h_0}\right) dS} \tag{8}$$

The soil erosion (deposition) rate is calculated in this study with the Radionuclide Inventories Conversion software proposed by Walling et al. (1997). Parameters, such as soil mass, ^{137}Cs activity, cross-sectional area of soil drilling, sampling time, ^{137}Cs reference inventory, soil bulk density, tillage depth, year of tillage commencement, are required in the model calculation.

4 Results and analysis

4.1 Establishing ^{137}Cs reference inventories

The local ^{137}Cs reference sites were chosen at the top of the hills where no erosion or sediment deposition had taken place (Li et al., 2003; Walling et al., 2002). In this study, undisturbed grassland was chosen at the top of a hill (The reference site of Hougou was a grain storage site built before the foundation of the People's Republic of China, that had not been used and had become flat grassland for at least 55 years), a for many years old reclaimed terrace (Luojiagou, which is an abandoned 90 years old terrace at the top hill), and land that had been for many years in forests (Sites in Xigaoshan, Suyuan, Pingluo and Yuntai, which have not been disturbed for at least 50 years). Four to five soil cores were collected at each reference site, including at least one core that was into slices of 60 cm thickness.

With sample measurements and calculations, the local ^{137}Cs reference inventories at sampling sites are shown in Table 1.

Table 1 Summarizes the local ^{137}Cs reference inventories at the various sampling sites

Sampling time /（month/day/year）	Sampling sites	Latitude and longitude	Annual rainfall /（mm）	Range of local ^{137}Cs inventories /（Bq m^{-2}）	Local ^{137}Cs inventories /（Bq m^{-2}）
11/25/2008	Hougou	34°15.454'N 105°34.899'E	471	1,817～2,987	2,402
11/26/2008	Luojiagou	34°05.967'N 105°04.950'E	451	1,628～2,126	1,943
11/28/2008	Xigaoshan	33°44.975'N 105°21.660'E	600	1,152～3,343	2,124
11/29/2008	Suyuan	33°40.482'N 105°25.173'E	647	2,206～2,233	2,219
12/01/2008	Pingluo	33°35.346'N 105°26.480'E	671	1,587～1,612	1,600
12/02/2008	Yuntai	33°31.283'N 105°39.403'E	787	1,567～1,996	1,843

The changes in ^{137}Cs concentration with depth at the reference sites and their variations are shown in Fig. 2.

If the average ^{137}Cs concentration for each layer of the profiles in Fig. 2 is set to be representative for that depth, then the relationship between the representative ^{137}Cs concentration and the depth is as shown in Fig. 3. The best fitting regression equation thus obtained, shows that the ^{137}Cs concentration exponentially decreases with the increased depth, and that the ^{137}Cs concentration of the topsoil is 25Bq kg^{-1}. At the 20cm depth, the ^{137}Cs concentration had decreased to 1.58Bq kg^{-1}; while at the 30cm depth, the ^{137}Cs concentration is less than 0.4Bq kg^{-1}. At the 40cm depth, the ^{137}Cs concentration is close to 0, indicating that ^{137}Cs contents at 6 selected reference sites are mainly distributed in the soil layer within the 20cm depth. Little ^{137}Cs is found at a depth greater than 20cm, and almost no ^{137}Cs is found at the depth greater than 40cm.

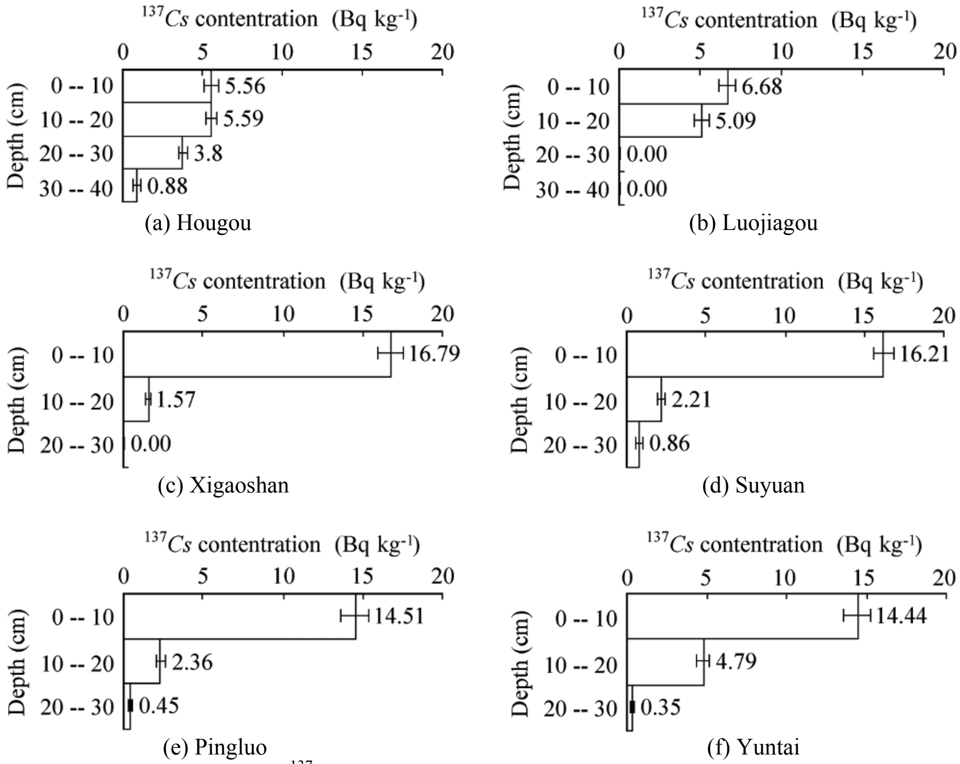


Fig. 2 The ^{137}Cs concentrations and depths for the reference sites

4.2 ^{137}Cs distribution on typical hillslopes of the Xihanshui River Basin

4.2.1 ^{137}Cs distribution in cultivated areas

The following six cultivated fields were selected for the determination of the ^{137}Cs distribution along the banks of the Xihanshui River: Hougou, Luojiagou, Suyuan, Pingluo, Laozhuang and Yuntai. The cultivated areas have average slope gradients of 0°-10° (Hougou), 10°-20° (Suyuan, Pingluo, and Yuntai), and more than 20° (Luojiagou and Laozhuang) respectively. The slope length is 20-40m in Luojiagou and Suyuan, 10m-20m in Hougou, and less than 10m in Pingluo, Laozhuang and Yuntai. The soil type at the sampled sites is brown or yellow soil, representing typical soil types of the Xihanshui River Basin.

The ^{137}Cs distribution in the soil profiles of these cultivated sites are shown in Figs. 4, 5, and 6. The data indicate that ^{137}Cs occurs in the soil to a depth of 0-60cm, though the largest proportion occurs in 0-40cm depth. At the upper slope sections in Luojiagou and Laozhuang (Fig. 4), ^{137}Cs of the soil profiles have a relatively constant distribution in the 0-10cm depth and 0-20cm depth. At the middle slope sections, the ^{137}Cs concentration of the soil profiles was relatively constant in the depth of 0-20cm in Suyuan, 0-30cm in Luojiagou and Yuntai, and 0-40cm in Hougou and Pingluo (Fig. 5). At the lower slope sections (Fig. 6), ^{137}Cs of the soil profiles have a relatively constant distribution in the depth of 0-30cm or 0-40cm, and ^{137}Cs content in the 40-60cm depth is significantly higher than the corresponding layers of the soil profiles at the upper and middle slope sections.

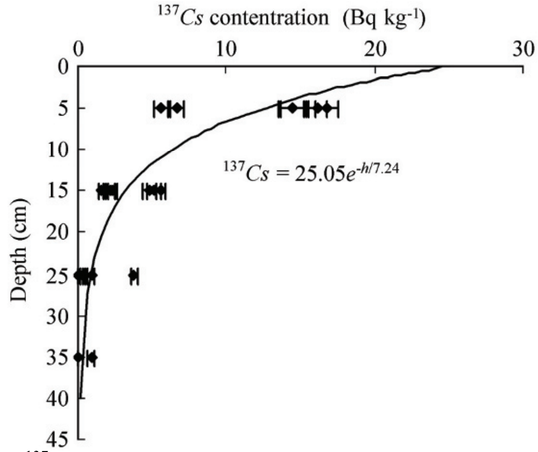
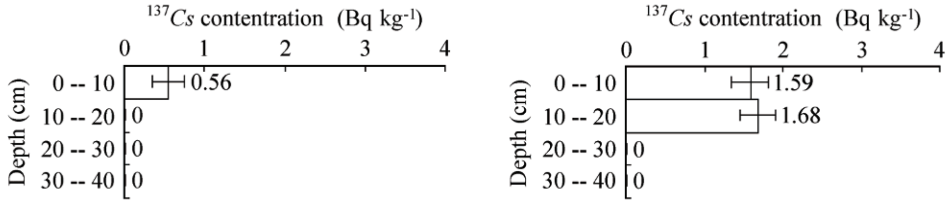
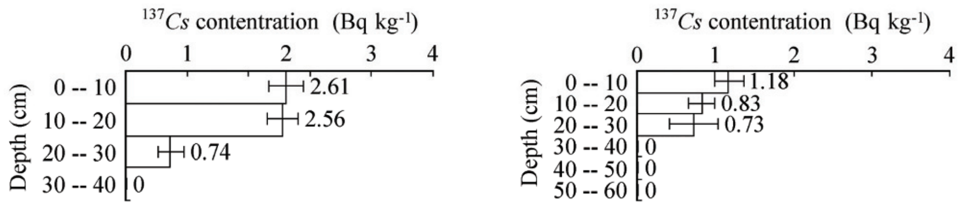


Fig. 3 The ^{137}Cs concentrations and representative depths for the reference profiles

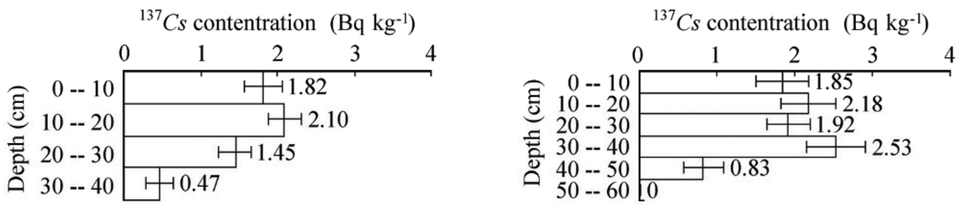


(a) The upper slope section in Luojiagou (b) The upper slope section in Laozhuang

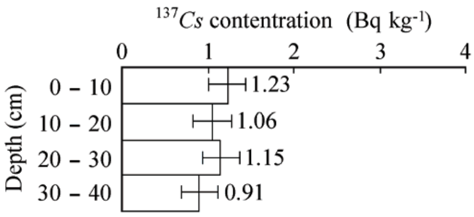
Fig. 4 The ^{137}Cs distribution in the soil profiles at the upper slope sections in Luojiagou and Laozhuang



(a) The middle slope section in Suyuan (b) The middle slope section in Luojiagou

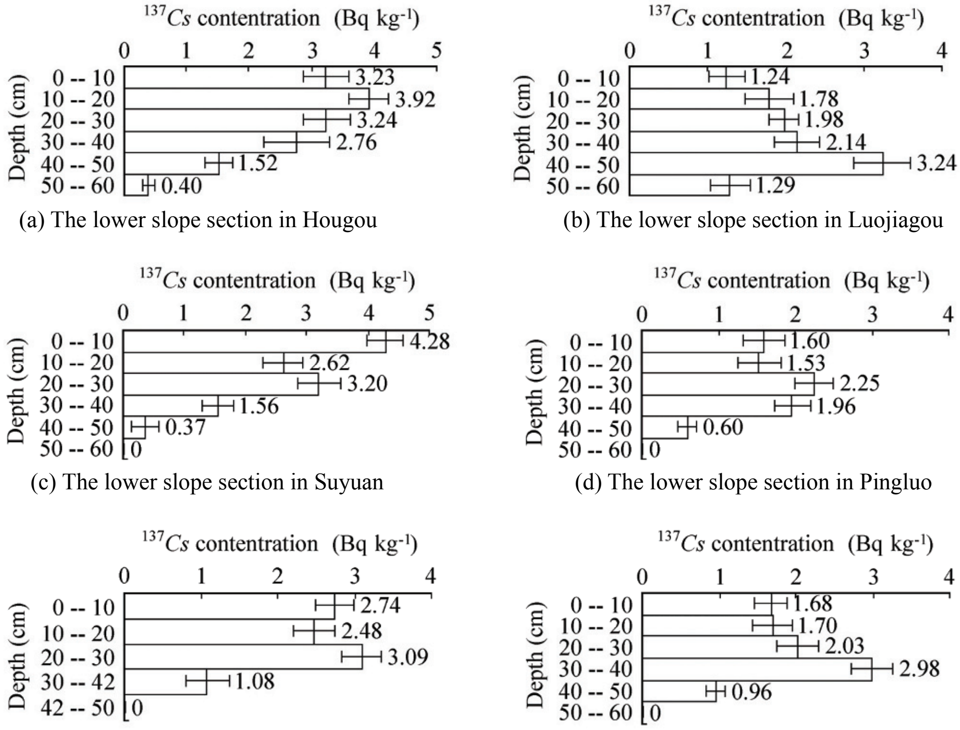


(c) The middle slope section in Yuntai (d) The middle slope section in Hougou



(e) The middle slope section in Pingluo

Fig. 5 The ^{137}Cs distribution in the soil profiles at the middle slope sections in Suyuan, Luojiagou, Yuntai, Hougou and Pingluo



(a) The lower slope section in Hougou (b) The lower slope section in Luojiagou

(c) The lower slope section in Suyuan (d) The lower slope section in Pingluo

(e) The lower slope section in Laozhuang (f) The lower slope section in Yuntai

Fig. 6 The ^{137}Cs distribution in the soil profiles at the lower slope sections in Hougou, Luojiagou, Suyuan, Pingluo, Laozhuang and Yuntai

The rather uniform ^{137}Cs concentration is attributed to frequent tillage and mixing of the soil in farming operations, while the non-even distribution of ^{137}Cs along the slope is caused by water that carries soil from the upper to the lower slope. Due to soil movement by tillage, erosion, transport, and deposition, the total ^{137}Cs content increases as one goes from the upper slope to the lower slope (Fig. 7). The uniform ^{137}Cs distribution depth for all profiles follows the sequence upper slope < the middle and lower slope. For the process of soil movement, the upper slope is simpler than the lower part, because the soil loss due to erosion and the soil mixing induced by farming generally occurs in the upper slope. While in the lower slope, there is not only its own soil redistribution, but also the combination of water erosion and tillage with eroded soil from the upper part; thus, the depth of uniform ^{137}Cs distribution will be larger in the soil profiles of the lower slope. The average depth of uniform ^{137}Cs distribution in the soil profiles of the upper and middle slope is 26cm, and actual tillage depth of the cultivated fields is confirmed as 20-25cm after local investigations, indicating their approximation.

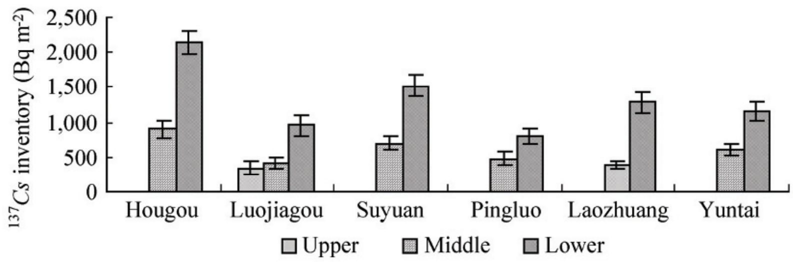
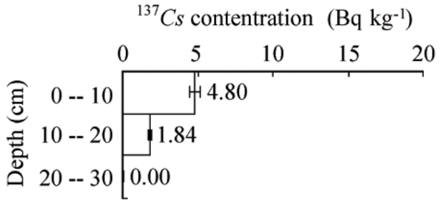


Fig. 7 Comparison of ^{137}Cs inventories at the upper, middle and lower slope sections

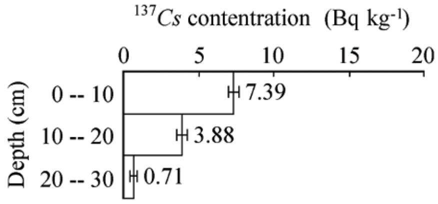
4.2.2 ^{137}Cs distribution in vegetated areas

Samples were taken from several undisturbed forest and grassland sites.

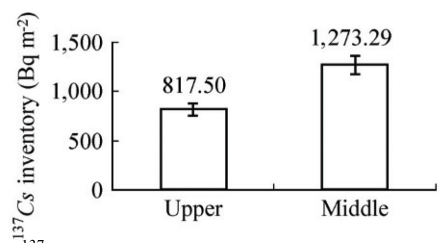
In Xigaoshan, a 60-year old field in grassland was selected. This place had a slope length of 30m, was 9m wide and had an average slope gradient of 26°. The ^{137}Cs concentration of the sampled profiles changed with depth in Figs. 8(a) and (b); ^{137}Cs concentration distribution along the slope is shown in Fig. 8(c). With the ^{137}Cs concentration and a reference concentration of 2,124Bq m^{-2} in Xigaoshan, the computed ^{137}Cs losses are 62% and 40% in the upper and middle slope, respectively, indicating that the sequence of ^{137}Cs loss is the upper slope > the middle.



(a) The upper slope section



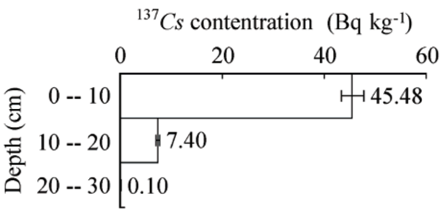
(b) The middle slope section



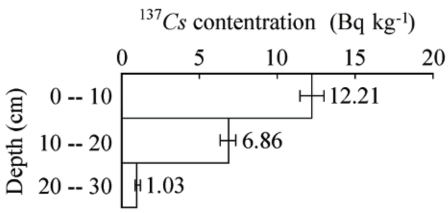
(c) ^{137}Cs concentration distribution along the slope

Fig. 8 The ^{137}Cs distribution on the grassland of Xigaoshan

This study selected an arborvitae forest in Suyuan; and a beech and cypress forest in Yuntai. The arborvitae forest with a slope gradient of 5° was established over an 80-year period. A humus layer of 3cm was found at the topsoil during sampling. The beech and cypress forest dotted with a small number of coriaria and buxus, was never cultivated, and has an average slope gradient of 26°. The ^{137}Cs distributions of these two forests are shown in Figs. 9(a), and (b) respectively. In Fig. 9(a), ^{137}Cs mainly occurs in the top 0-10cm of the profile; ^{137}Cs content at the soil depth of 10-15cm decreased by 84% relative to that at the 0-10cm layer; ^{137}Cs is relatively insignificant at depth greater than 15cm. The small amounts in depth below 15cm were attributed to the physical migration of ^{137}Cs contaminated soil particles. The calculated ^{137}Cs content was 3,092Bq m^{-2} in the arborvitae forest, and 2,519Bq m^{-2} in the beech and cypress forest, respectively, while the Table 1, ^{137}Cs reference values for the two regions were 2,219Bq m^{-2}, and 1,843Bq m^{-2} respectively, ^{137}Cs deposition occurred in the arborvitae forest and in the beech and cypress forest with deposition rates of 39% and 37% respectively.



(a) Suyuan Arborvitae forest

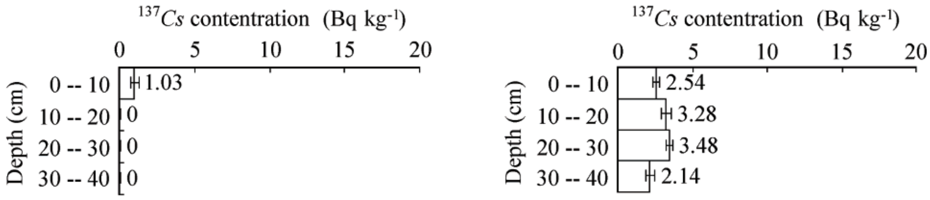


(b) Yuntai Beech and Cypress forest

Fig. 9 ^{137}Cs concentrations on the forest

4.2.3 ^{137}Cs distribution in revegetated areas

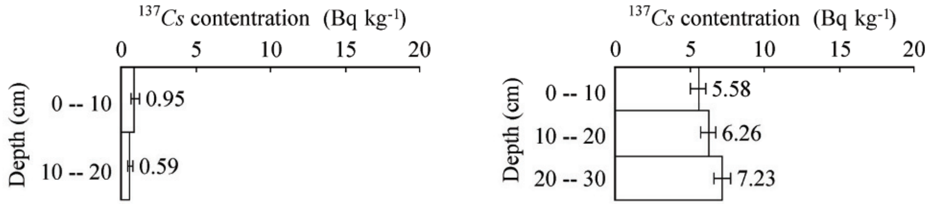
Revegetated land consisted of cultivated land that returned to natural revegetation. The ^{137}Cs distribution of the Luojiagou revegetated area is shown in Fig. 10. This site had been in cultivated condition for more than 50 years before it was returned to forest 4 years ago. After seeds were sowed, the soil was not tilled, and volunteer alfalfa was grazed. The sampled slope site was 31m long, 20m wide, and had an average slope gradient of 5°. Figure 10(a) shows that the low level of ^{137}Cs activity was concentrated in the topsoil 0-10cm depth. Figure 10(b) shows the ^{137}Cs distribution to a depth of 0-40cm. In this case, the ^{137}Cs concentration increases until the 30cm depth and decreases below the 30cm depth. ^{137}Cs activity does not decrease exponentially with depth, but is relatively uniform and is consistent with ^{137}Cs activity distribution observed on cultivated land. Additionally, ^{137}Cs activity at the depth of 20-30cm is greater than that at the surface, suggesting that the sampling site was eroded by water and apparently influenced by tillage erosion. Also the nuclide vertically migrated from the topsoil under the influence of cultivation. ^{137}Cs content in the lower slope section is significantly higher than that of the upper part of the slope, indicating that the erosion intensity in the upper slope was more significant than the lower slope.



(a) The upper slope section (b) The lower slope section

Fig. 10 ^{137}Cs activities in the revegetated land in Luojiagou

The ^{137}Cs distributions on the upper and lower part of the slopes for revegetated land in Laozhuang are shown in Figs. 11(a) and (b), respectively. The sampled slope site is 7m long, 8m wide, and had an average slope gradient of 28°. There is a ridge at the top of the sampled slope, and its distance from the upper and lower sampled profiles are 2m and 5m respectively. This site had been cultivated for more than 80 years, before it was returned to forest five years ago. In Fig. 11(a), the ^{137}Cs content is small and similar for the 0-10cm and 10-20cm depths. Figure 11(b) shows ^{137}Cs content for 0-10cm, 10-20cm, and 20-30cm depths, reflected the cultivated land's pattern of ^{137}Cs profile distribution. With soil tillage, ^{137}Cs was evenly distributed to a certain depth. In the meantime, ^{137}Cs content on the upper slope is much smaller than the lower part of the slope as shown in Fig. 11, indicating that ^{137}Cs loss is larger on the upper slope than the lower part.



(a) The upper slope section (b) The lower slope section

Fig. 11 ^{137}Cs concentrations in the revegetated land in Laozhuang

4.3 Characteristics of soil erosion on typical hillslopes

The ^{137}Cs activities and soil erosion of sampled cultivated areas, vegetated lands, and revegetated lands in the Xihanshui River Basin are shown in Table 2.

On cultivated areas, according to the intensity standards of soil erosion (The sediment research panel from the office of State Council Three Gorges Project Construction Committee, the professional sediment group of China's Three Gorges Project Development, 2002) and annual erosion rates in Table 2, very severe and severe erosion occur in the upper Luojiagou and Laozhuang slopes. In addition to the severe erosion in the middle part of Luojiagou slope, moderate erosion exists on the middle parts of the slopes of Hougou, Suyuan, Pingluo and Yuntai. On the lower slope, moderate erosion occurs in Luojiagou and Pingluo, and slight erosion exists in Hougou, Suyuan, Laozhuang and Yuntai, indicating that the sequence of erosion intensity is the upper slope>the middle>the lower.

As for sampled grassland, the upper slope of Xigaoshan presents moderate erosion, and the middle and lower parts are slight erosion; thus, the sequence of erosion intensity is the upper > the middle > the lower. With an average erosion rate of 1,676 t km^{-2} yr^{-1}, Xigaoshan is classified as slight erosion. In the other sampled grassland, Hougou is classified as slight erosion with an average annual erosion rate of 1,838 t km^{-2} yr^{-1}.

Table 2 ^{137}Cs activity and soil erosion on typical hillslopes in the Xihanshui River Basin

Land use	Sampling site	Soil type	Slope gradient/ (°)	Vegetation cover/ (%)	^{137}Cs reference inventory/ (Bq m^{-2})	^{137}Cs inventory/ (Bq m^{-2})		^{137}Cs loss rate/ (%)	Annual erosion rate/ (t km^{-2} yr^{-1})	Erosion intensity
Cultivated area	Hougou	Yellow soil	10	—	2,402	Middle	898	63	4755	Moderate
						Lower	2,154	10	531	Slight
						Average	1,526	36	2,643	Moderate
	Luojiagou	Yellow soil	23	—	1,943	Upper	336	83	8,416	Very severe
						Middle	420	78	7,362	Severe
						Lower	948	51	3,479	Moderate
						Average	568	71	6,419	Severe
	Suyuan	Brown soil	17	—	2,219	Middle	693	69	5,616	Severe
						Lower	1,521	31	1,839	Slight
						Average	1,107	50	3,728	Moderate
	Pingluo	Brown soil	20	—	1,600	Middle	476	70	5,846	Severe
						Lower	800	50	3,365	Moderate
						Average	638	60	4,606	Moderate
	Laozhuang	Brown soil	21.5	—	1,843	Upper	374	80	7,662	Severe
						Lower	1,283	30	1,763	Slight
						Average	829	55	4,713	Moderate
	Yuntai	Brown soil	18	—	1,843	Middle	607	67	5,360	Severe
						Lower	1,166	37	2,228	Slight
						Average	887	52	3,794	Moderate
Grassland	Xigaoshan	Brown soil	26	85	2,124	Upper	818	62	2,903	Moderate
						Middle	1,273	40	1,294	Slight
						Lower	1,751	18	831	Slight
						Average	1,281	40	1,676	Slight
	Hougou	Yellow soil	33	80	2,402	Average	1,324	45	1,838	Slight
Forest	Suyuan arborvitae forest land	Brown soil	5	80	2,219	Average	3,092	-39	-330	Deposition
	Yuntai beech and cypress forest land	Purple soil	26	85	1,843	Middle	2,519	-37	-1,068	Deposition
Revegetated land	Luojiagou	Yellow soil	10	40	1,943	Average	651	67	4,805	Moderate
	Laozhuang	Brown soil	28	80	1,843	Average	1,200	35	2,902	Moderate

In the sampled forests, the average annual deposition rate of Suyuan arborvitae forest is 330 t km^{-2} yr^{-1}, and the erosion intensity are described as deposition. In Yuntai, where is the forest land of beech and cypress, the sampled site is located on the middle slope with an average deposition rate of 1,068 t km^{-2} yr^{-1}, and the erosion intensity is classified as deposition, indicating that the eroded sediment of the upper slope deposits on the middle slope.

As for revegetated land, Luojiagou and Laozhuang were returned to forest four years and five years ago respectively with an annual rainfall of 451mm in Luojiagou and about 700mm in Laozhuang. Influenced by rain and climatic conditions, vegetation coverage in Laozhuang has reached 80%, but only 40% in Luojiagou, and the average erosion rate of Luojiagou is 4,805 t km^{-2} yr^{-1}, while 2,902 t km^{-2} yr^{-1} in Laozhuang. It is indicated that although the time interval is only one year between the two lands when they were returned to forests, and Laozhuang has a larger slope gradient than Luojiagou, Laozhuang has a lower erosion rate than Luojiagou due to a better vegetation development in Laozhuang than in Luojiagou.

The comparison of the average soil erosion intensity of different land use shows that among the six cultivated areas, one is severe erosion, and five are moderate erosion; two grasslands are classified as slight erosion; two forest lands are deposition; two revegetated lands are both classified as moderate erosion. Therefore, the lands are shown as follows in sequence of erosion intensity: forest < grassland < revegetated land < cultivated land.

5 Conclusions

The local ^{137}Cs reference in the Xihanshui River Basin ranged from 1,600 to 2,402 Bq m^{-2}. In undisturbed soil the measured ^{137}Cs activity decreases exponentially down according to the soil depth. In cultivated area, however, the distribution is relatively constant within the tillage depth.

The soil erosion in the watershed is moderate or intensive in cultivated area with annual erosion rate in the range of 2,000-6,000 t km^{-2} yr^{-1}. In general, very severe or severe soil erosion occurs at the upper slope sections, severe or moderate soil erosion occurs at the middle slope sections, and moderate or slight soil erosion occurs at the lower slope sections.

On the slopes with vegetation consisting of herbaceous and wood species, the erosion rate is much lower or not detectable. At the lower slope sections with well-developed vegetation, however, no soil loss, instead deposition occurred at a deposition rate of more than 1,000 t km^{-2} yr^{-1}.

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