Pedosphere **21**(1): 37–45, 2011
ISSN 1002-0160/CN 32-1315/P

Published by Elsevier B.V. and Science Press

PEDOSPHERE

www.elsevier.com/locate/pedosphere

^{137}Cs Redistribution in Thin Stony Soil of a Carbonate Rock Slope in Southwest China*[1]

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(Received April 26, 2010; revised July 22, 2010)

ABSTRACT

The fallout radionuclide cesium-137 (^{137}Cs) has been widely employed as a tracer for assessment of soil loss from thick uniform soils; however, few studies have been conducted on thin stony soils on slopes underlain by carbonate rocks which are widely distributed in karst areas. Information derived from ^{137}Cs measurement of soil samples collected along a carbonate rock slope with thin stony soil where neither soil erosion nor deposition occurred was used to investigate the characteristics of ^{137}Cs redistribution in a karst area of Southwest China. The results indicated that the ^{137}Cs inventories of the surface soil on the slope studied were much lower than that of the local ^{137}Cs reference inventory and the ^{137}Cs activities were much higher than those on slopes with thick uniform soils. The spatial distribution of ^{137}Cs inventories was characterized by considerable variation. The high ^{137}Cs depletion in the stony soil of the slope studied was mainly because a considerable proportion of the fallout input of ^{137}Cs could be lost with runoff and the dissolution of carbonate particles in the soil promoted the loss of ^{137}Cs. These demonstrated that the rates of soil loss could not be estimated from the degree of depletion of the ^{137}Cs inventory relative to the local reference inventory for the thin stony soil of the rocky slope underlain by carbonate rocks in the study area in the way that has been widely used in areas with thick uniform soils.

Key Words: carbonate dissolution, ^{137}Cs fallout, ^{137}Cs inventory, karst area, runoff

Citation: Li, H., Zhang, X. B., Wang, K. L. and Wen, A. B. 2011. ^{137}Cs redistribution in thin stony soil of a carbonate rock slope in Southwest China. *Pedosphere*. **21**(1): 37–45.

Cesium-137 (^{137}Cs) is an artificial radionuclide originating from the nuclear bomb tests that took place between the mid l950s and the l970s. ^{137}Cs has a half-life of 30.17 years and peak fallout on the earth's surface occurred in 1963. ^{137}Cs was released into the stratosphere and distributed globally, and then mostly deposited as fallout with precipitation. ^{137}Cs reaching the land surface was rapidly and strongly adsorbed by the fine particles in the topsoil. Its subsequent redistribution is primarily associated with movement of the soil particles because ^{137}Cs resists downward leaching and plant uptake (Walling, 1998; Zapata *et al.*, 2002; Zapata, 2003; Mabit and Fulajtar, 2007; Mabit *et al.*, 2008). Therefore, ^{137}Cs provides an effective tracer of soil redistribution and it has been widely used for assessing the rates of soil loss in recent years (de Jong *et al.*, 1983; Walling and Bradley, 1988; Zhang *et al.*, 1994, 1998, 2003). The rate of soil loss can be estimated from the degree of reduction of the ^{137}Cs inventory in the soil at a sampling point, *i.e.*, a comparison of the measured inventory at the sampling point with the local reference inventory. However, the ^{137}Cs method can not be used for evaluation of soil loss in strongly acid soils such as red soils and peat soils with a pH value of 4–5 because of the limited adsorption capacity of these soils for ^{137}Cs (Livens and Baxter, 1988; Livens and Loveland, 1988; Hird *et al.*, 1996). Because the spatial distribution of the fallout input of ^{137}Cs to soils can be assumed to be spatially uniform over small areas, the redistribution of ^{137}Cs will directly reflect the redistribution of soil particles caused by physical processes such as erosion and tillage. Therefore, the ^{137}Cs technique has been widely used for estimating soil losses from slopes with thick uniform soils, *e.g.*, loess, Regosol, Oxisol, clay soil, and black soil (Zhang *et al.*, 1990; Quine and Walling, 1991; Guimaraes *et*

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*[1] Supported by the Western Action Program of the Chinese Academy of Sciences (No. KZCX2-XB2-08) and the National Basic Research Program (973 Program) of China (No. 2006CB403200).

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al., 2003; Soto and Navas, 2004).

Karst landforms are found in areas underlain by carbonate rocks, such as limestone and dolomite, and are frequently associated with a fragile ecological environment. Indeed, karst environments constitute one of the most important landscape types of the world. Karst areas cover an estimated 12% of the total land area of the globe, and are mainly located in the Mediterranean, Eastern Europe, the Middle East, Southeast Asia, Southeast North America, and the Caribbean. Specifically, with an area of 55×10^4 km^2, Southwest China is one of the largest continuous areas of karst in the world. At present, most of the karst mountain areas of Southwest China are suffering from serious land desertification and degradation caused by soil losses. Land desertification and degradation have important impacts on the local population and result in both social and economic problems, particularly in the areas developed on pure carbonate rocks. There is therefore an urgent need to obtain reliable information concerning contemporary soil erosion rates in such areas. However, information on soil erosion in these areas is still very limited. Classical investigation methods, such as runoff plots and hydrological monitoring stations, are insufficient in this area, which results in reliable data being unavailable within a short timescale. Therefore, the ^{137}Cs technique is expected to obtain retrospective information on soil erosion more quickly.

To date, few studies have attempted to use the ^{137}Cs method to assess the rates of soil erosion in the karst areas of Southwest China. Furthermore, there is a great difference between the available information provided by ^{137}Cs measurements and that provided by runoff plots. For example, Zhang *et al.* (2007) undertook a study on the rates of soil loss from slopes developed on carbonate rocks using the ^{137}Cs technique at Nanchuan County, Chongqing City. Their results showed that the rates of soil erosion on the gentle sloping cultivated land with a gradient of 11.2° and the steep sloping cultivated land with a gradient of 25.4° were 565.5 and 2 264.8 t km^{-2} year^{-1}, respectively. However, the estimates of the rates of soil loss provided by the runoff plots in the Chengqi gully catchment in Puding County, Guizhou Province, China, were very low, with a mean value of 7.8 t km^{-2} year^{-1} in 2007 (Bai *et al.*, 2009). This apparent discrepancy raises a question of whether the ^{137}Cs technique is suitable for estimating the rates of soil loss on rocky slopes in karst areas. Slopes developed on carbonate rocks with thin stony soils are widely distributed in the karst mountain areas of Southwest China. Several factors, including the large area of bare bedrocks, the discontinuous soil cover, the variable soil depth, and the varying proportion of gravels, result in strong heterogeneity in the soils on these slopes. It is recognized that the characteristics of the soil and soil loss associated with carbonate rock slopes with thin stony soils are different from those of slopes with thick uniform soils in non-karst areas, and the ^{137}Cs absorption and redistribution processes may be also different for the two types of soils. Therefore, this study was carried out to establish the basis for ^{137}Cs redistribution in thin stony soils on carbonate rock slopes, in order to confirm the applicability of the ^{137}Cs method for estimating soil losses from such slopes.

MATERIALS AND METHODS

Study area

The catchment of the Huanjiang Experimental Station of Karst Ecosystems, Chinese Academy of Sciences (24° 44′ N, 108° 19′ E) in Huanjiang County, northwest Guangxi Province, China, is located in a transitional zone between the Guizhou Plateau and the Guangxi Hilly landforms. The study area is in the southern subtropics, with a warm and humid climate. The average annual temperature is 19.9 °C and the annual precipitation is 1 389 mm (1957–1990), 70%–80% of which occurs in the wet season from May to September, with less than 90 mm in the dry season.

The catchment has a drainage area of 1.46 km^2, characterized by a typical karst hill peak cluster-valley landform (Fig. 1). Most of the catchment is underlain by dolomite of late Carboniferous age, except for the eastern hill, which is underlain by late Carboniferous clasolite. The elevation of the valley and the carbonate rock slope in the catchment ranges between 270 and 519 m. The carbonate rock slope with thin stony soil in the western part of the catchment can be divided into four segments (Fig. 2): 1) a flat hill peak segment, where weathered gravels are widely distributed, black rendzina soils are found in the cracks of the bedrock and between the gravel patches, and the ground vegetation is composed of sparse grasses and shrubs; 2) a bare steep slope segment, where the upper part is bare and extremely steep, with an average gradient of > 50°, rockfalls occur frequently after the rocks are weathered, and the cracks in the rock are filled with black rendzina soil which supports a few shrubs; 3) a talus slope segment, which is in the middle and lower parts of the study slope covered with an accumulation of rock debris ranging from several centimeters to several meters, with a steep head at an average gradient

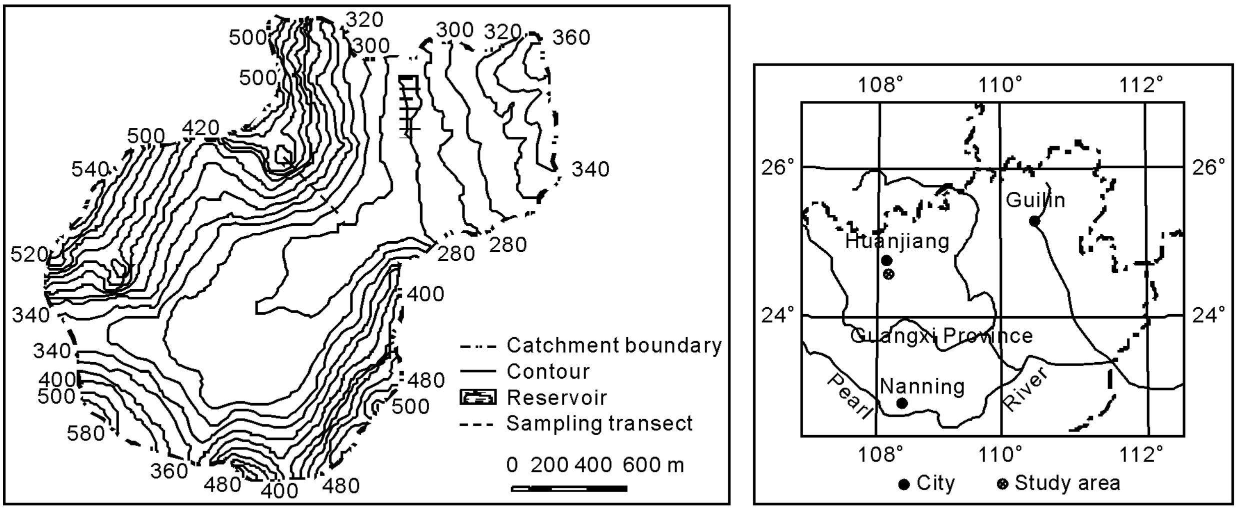

Fig. 1 A sketch map of the study area and the location of sampling transect along the carbonate rock slope studied.

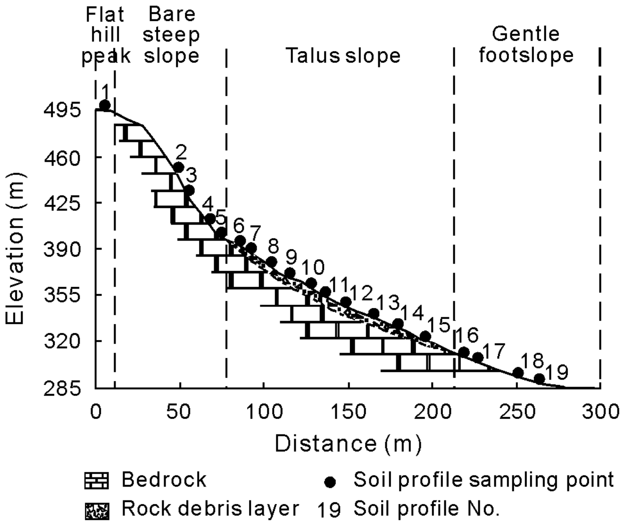

Fig. 2 A sketch map of the topography and geology of the carbonate rock slope studied.

of 37°, a gentle bottom at an average gradient of 20°, where the composition of the surface of the downslope accumulation zone varies from coarse boulders and gravels with a mean particle size of 10–20 cm at the top to fine sand and gravels with a mean particle size of < 10 cm at the bottom, most of the rendzina soil with a thickness of < 5 cm is found either on the surface of the rock debris layer or on the bedrock itself, the soil is very heterogeneous with both the ratio of the soil covered area to the total area and the proportion of coarse particles showing a high degree of variation, and the vegetation varies from sparse grasses at the top to dense woody shrubs at the bottom; and 4) a gentle footslope segment, where bedrock is exposed and yellow soil is found in the solution grooves.

Based on contacts with local farmers, it is known that the vegetation on the hill peak and bare steep slope segments of the carbonate rock slope has not recovered after the original evergreen forest was removed, and the vegetation has regenerated with a succession of secondary shrubs on the talus slope segment and the gentle footslope segment. Short-term cultivation was carried out from the 1960s to 1970s on the lower parts of the slope, but this has been abandoned since the 1980s. Large runoff plots for monitoring runoff and sediment yields under different land use types were constructed on the middle and lower parts of the slope studied in 2005 by the staffs of the Huanjiang Experimental Station. They have found that few runoff events occur and that these are restricted to the periods of heavy or extremely heavy rainfall. The plots had a low runoff and sediment yield, with a runoff coefficient of $< 5\%$ and a specific sediment yield of < 10 t km^{-2} year^{-1} in 2005–2007.

Sampling and measurements

Soil samples, including bulk samples and depth incremental profile samples were collected from the carbonate rock slope in May 2007. The core sampling method, which has been commonly used for sampling thick uniform soils, cannot be employed on the heterogeneous thin stony soils due to the limited surface area of the core, which is unlikely to be representative. Therefore, a sampling transect with a width of 3 m, parallel to the runoff plots was established, extending from the top to the bottom of the slope (Fig. 1), and sampling was undertaken over a large area, to overcome, as far as possible, the problem of lack of representativeness caused by the heterogeneity of the soil. The length and average gradient of the transect were 350 m and 36.8°, respectively. The ground vegetation within the transect was completely cleared, in order to facilitate the sample collection. Bulk samples from 19 profiles and 7 profiles (Profiles 4, 5, 6, 8, 11, 16, and 19) were collected along the transect at intervals of 30 and 10 m (Fig. 2, Table I). The soil profiles were collected by excavating soil pits. Soil pits were dug across sampling transect at the positions with thin uniform soil. The soil profiles were then divided into 3 cm depth intervals and samples were collected from the pit wall, with an area of 10 cm × 30 cm and a depth of 30 cm. The bulk samples were collected by the method of large-area sampling. All the surface soil was dug out and collected from the sampling transect from an area of 1 m × 3 m and a depth of 30 cm. In most cases, however, the sampling depths were less than 30 cm, due to the thin soil containing a great deal of gravel. All bulk soil samples were passed through a 20-mm sieve and then weighed. After that, $<$ 20 mm soil fractions were mixed well and about 3 000 g soil was placed into sample bags for subsequent laboratory measurements. For Profiles 2 and 3 on the upper part of the slope, which was very steep and bare, the soil samples were collected from the cracks.

Sampling to determine the local ^{137}Cs reference inventory was undertaken at Luoyang Town adjacent to the study area in November 2006. A flat cultivated site which had experienced neither soil erosion nor sediment deposition was selected for the study. 31 bulk core samples and one depth incremental profile were collected from a grid with a spacing of 2 m × 1.2 m.

The ^{137}Cs activities of the soil samples were measured in the Isotope Laboratory of the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, China. All samples were air dried, disaggregated, passed through a 2-mm sieve, and weighed prior to assay. The ^{137}Cs activity of the $<$ 2 mm fraction of each sample ($\geq$ 250 g) was measured by gamma spectrometry using a hyperpure coaxial germanium detector coupled to a multichannel analyzer system. ^{137}Cs was detected at 662 keV using counting time of more than 33 000 s, provided results with an analytical precision of approximately ± 5% at the 90% level of confidence. The grain size composition of the soil samples was measured in the Soil Laboratory of the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences. The method of hydrochloric acid dissolution was used for removing the carbonates in the $<$ 2 mm soil fractions. The acid-insoluble residue was weighed after drying, and then the particle size of the residue was measured by pipette settling analysis.

RESULTS AND DISCUSSION

Variation of surface soil particle size along the carbonate rock slope

The particle size of the surface layer of the bulk samples collected from the slope studied is illustrated in Table II and Fig. 3. The surface soil on the flat hill peak was coarsest, with a high content (620 g kg^{-1}) of coarse gravel ($>$ 20 mm), a lower content (140 g kg^{-1}) of fine gravel (2–20 mm), and a content of sand, silt, and clay ($<$ 2 mm) of 240 g kg^{-1}. The particle size of the soil samples collected from Profile 4 of the bare steep slope segment was nearly identical to that of the flat hill peak, with a content of coarse gravel of 504 g kg^{-1}, a fine gravel content of 300 g kg^{-1}, and a content of sand, silt, and clay of 19.6 g kg^{-1}. The soil samples collected from the rock cracks (Profiles 2, 3, and 5) had a finer particle composition, with a mean

TABLE I

Gradients and slope lengths of positions where the soil profiles were taken at the segments of the carbonate rock slope studied

Slope segment											
Flat hill peak			Bare steep slope			Talus slope			Gentle footslope		
Profile No.	Gradient	Slope length	Profile No.	Gradient	Slope length	Profile No.	Gradient	Slope length	Profile No.	Gradient	Slope length
	°	m		°	m		°	m		°	m
1	2	0.0	2	61	66.7	6	28	132.5	16	17	286.6
			3	63	85.7	7	28	141.2	17	20	296.6
			4	50	109.0	8	19	157.2	18	18	323.3
			5	38	122.1	9	28	168.2	19	12	337.3
						10	28	185.7			
						11	30	196.5			
						12	23	210.2			
						13	16	229.1			
						14	10	244.8			
						15	15	263.2			

TABLE II

Particle size of the surface layer, content of acid-insoluble residue (AIR) in the < 2 mm fraction, and fine particle (< 0.005 mm) content of the < 2 mm acid-insoluble residue in the soil samples from the segments of the carbonate rock slope studied

Slope segment	Profile No.	Content of coarse gravel (> 20 mm)	Content of fine gravel (2–20 mm)	Content of sand, silt, and clay (< 2 mm)	Content of AIR in the < 2 mm soil fraction	Fine particle content in the < 2 mm AIR
		g kg^{-1}				
Flat hill peak	1	619.8	139.8	240.4	-	-
Bare steep slope	2	155.3	412.7	432.0	253.6	640.5
	3	0.0	463.5	536.5	-	-
	4	504.4	300.2	195.4	468.8	401.8
	5	165.9	419.2	414.9	524.2	453.3
Talus slope	6	271.0	459.9	269.1	590.8	646.0
	7	174.0	542.1	283.9	614.3	556.7
	8	403.9	385.8	210.3	679.0	574.3
	9	241.2	448.7	310.1	761.3	622.3
	10	262.4	405.0	332.6	782.8	819.1
	11	230.8	522.7	246.5	466.9	387.6
	12	80.7	654.5	264.8	562.7	591.3
	13	98.0	698.0	204.0	732.0	772.0
	14	61.0	721.7	217.3	879.8	864.7
	15	35.6	664.4	300.0	955.0	839.2
Gentle footslope	16	213.3	585.8	200.9	727.5	610.3
	17	138.9	641.1	220.0	883.6	698.0
	18	156.6	592.5	250.9	854.9	709.7
	19	112.6	669.1	218.3	962.6	793.5

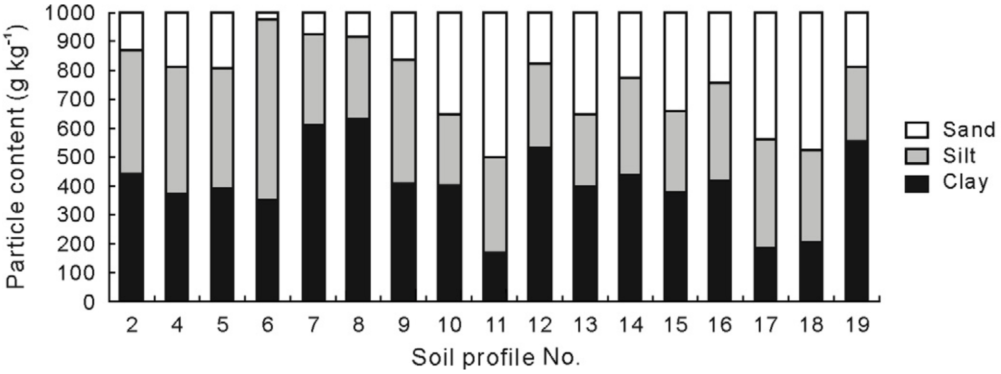

Fig. 3 Particle size of the < 2 mm fractions in the bulk soil samples of the carbonate rock slope studied.

content of coarse gravel of 107 g kg^{-1}, fine gravel of 432 g kg^{-1}, and sand, silt, and clay of 461 g kg^{-1}. The particles of the surface soil on the talus slope segment were finer than those of the flat hill peak and bare steep slope segments, with a mean content of coarse gravel of 186 g kg^{-1}, fine gravel of 550 g kg^{-1}, and sand, silt, and clay of 264 g kg^{-1}. The content of coarse gravel ranged from 174 to 271 g kg^{-1} at the top of the talus slope segment (Profiles 6–11), whereas it was far lower at the bottom (Profiles 12–15), ranging from 36 to 98 g kg^{-1}, except for Profile 8 (403.9 g kg^{-1}), which was adjacent to a small gully. The content of sand, silt and clay in the soil samples collected from the talus slope segment showed no major variation, with a range from 204 to 333 g kg^{-1}, but the content of fine gravel in soil on this segment showed a tendency to increase downslope, from 400–500 g kg^{-1} at the top to 600–700 g kg^{-1} at the bottom, which reflected the origin of the talus slope segment produced by rockfalls and accumulation. The content of coarse gravel on the gentle footslope segment ranged between 113 and 213 g kg^{-1}, being slightly higher than those of the bottom of the talus slope segment. It is likely that the gravels in the soil of the gentle footslope segment originated from the adjacent bedrock. The contents of fine gravel and sand, silt, and clay of the gentle footslope segment ranged from 586 to 669 g kg^{-1} and from 201 to 251 g kg^{-1}, respectively, which showed no obvious differences with those of the bottom of the talus slope segment.

The content of acid-insoluble residue in the < 2 mm soil fraction showed a tendency to increase downslope (Table II). The content of acid-insoluble residue for the bare steep slope segment ranged from 254 to 524 g kg^{-1}, with a mean of 416 g kg^{-1}; for the talus slope segment, the content increased from 591 g kg^{-1} at the top to 955 g kg^{-1} at the bottom, with a mean of 702 g kg^{-1}. For the gentle footslope segment, it ranged from 728 to 963 g kg^{-1}, with a mean of 857 g kg^{-1}. The trend of downslope increase for the acid-insoluble residue content in the $<$ 2 mm soil fraction reflected the downslope enhancement of chemical dissolution, which suggested a greater abundance of shallow groundwater at the bottom of the slope. The content of fine particle ($<$ 0.005 mm) in the $<$ 2 mm acid-insoluble residue also demonstrated a trend to increase downslope. For the bare steep slope segment, the content of fine particle in the acid-insoluble residue ranged from 402 to 641 g kg^{-1}, with a mean of 499 g kg^{-1}; for the talus slope segment, it increased from 646 g kg^{-1} at the top to 839 g kg^{-1} at the bottom, with a mean of 667 g kg^{-1}. For the gentle footslope segment, it ranged from 610 to 794 g kg^{-1}, with a mean of 703 g kg^{-1}. The tendency for the content of fine particle in the $<$ 2 mm acid-insoluble residue to increase downslope was probably related to the greater intensity of chemical dissolution at the bottom of the slope and the destruction of the cement binding individual particles. However, there was an exception. The content of acid-insoluble residue in the $<$ 2 mm soil fraction and the fine particle ($<$ 0.005 mm) content of the residue for Profile 11 were 466.9 and 387.6 g kg^{-1}, respectively. The reason for these reduced contents in Profile 11 relative to those in the adjacent profiles was probably related to the thinner soil layer associated and the greater incidence of broken bedrock fragments incorporated into the soil during sampling of this profile.

^{137}*Cs reference inventory*

The ^{137}Cs inventories for the 32 sampling points measured for determination of the local ^{137}Cs reference inventory ranged from 754.6 to 1 273.8 Bq m^{-2}, with a coefficient of variation (C. V.) of 13.5% (Fig. 4). Based on these measurements, the average of the 32 values, 997.7 Bq m^{-2}, was used to represent the ^{137}Cs reference inventory for the study area.

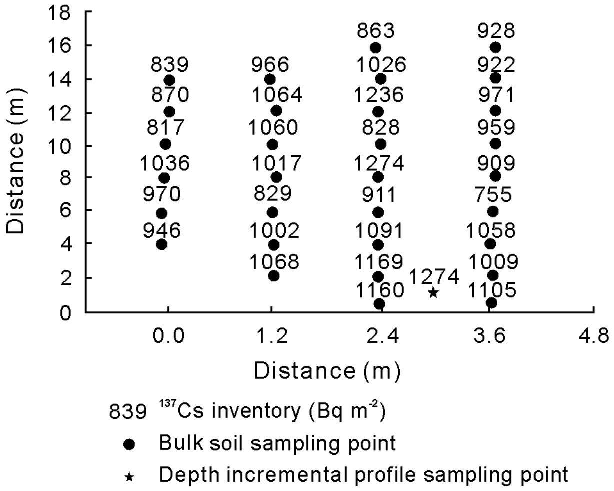

Fig. 4 ^{137}Cs inventories for 32 sampling points at the reference site adjacent to the study area.

^{137}*Cs depth distributions in the soil profiles*

The ^{137}Cs depth distributions for the four soil profiles located within the upper part of the slope (two on the bare steep slope segment and two on the talus slope segment) (Fig. 5) demonstrated patterns typical for uncultivated land. Maximum ^{137}Cs activities occurred in the upper horizon extending to a few centimeters in depth and declined rapidly below this level. No ^{137}Cs was found below 14 and 18 cm in these profiles. For the two profiles collected from the bare steep slope segment, the ^{137}Cs activities were 28.36±2.93 and 27.80±2.88 Bq kg^{-1} in the upper layer of 0–3 cm in depth, respectively. The ^{137}Cs activities in the lowest layer containing ^{137}Cs were low, with a mean of $<$ 2 Bq kg^{-1}. The ^{137}Cs inventories calculated for these

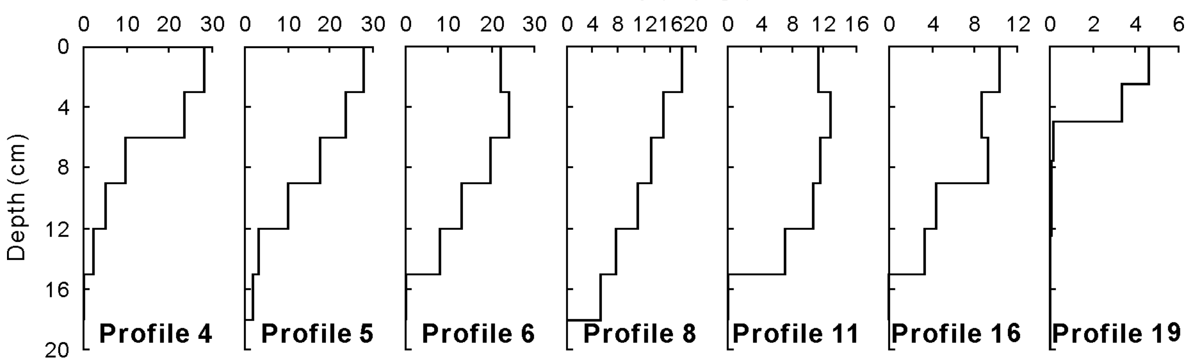

Fig. 5 ^{137}Cs depth distributions in the depth incremental soil profiles on the carbonate rock slope studied.

two profiles were 1 615.7 and 1 550.0 Bq m^{-2}, respectively, much greater than the local reference inventory of 997.7 Bq m^{-2}. The high inventories for the profiles collected probably suggested downslope transfer of ^{137}Cs fallout contained in rainfall by runoff from the exposed bedrock surfaces in the steep upper part of the slope. For the two profiles collected from the talus slope segment, the ^{137}Cs activities were 21.78±2.30 and 17.80±1.91 Bq kg^{-1} in the top layer of 0–3 cm in depth. However, the ^{137}Cs activities in the lowest layer containing ^{137}Cs were relatively high, being 8.07±0.96 Bq kg^{-1} for Profile 6 and 5.30±0.67 Bq kg^{-1} for Profile 8. There was weathered bedrock containing no ^{137}Cs beneath the soil. The ^{137}Cs inventories of these 2 profiles were 1 280.2 and 869.9 Bq m^{-2}, slightly greater and slightly less than the local reference inventory, respectively. The depth distributions of ^{137}Cs for Profile 11 of the talus slope segment and Profiles 16 and 19 of the gentle footslope segment demonstrated the pattern expected for cultivated land. ^{137}Cs was almost uniformly distributed within the plough layer, but was found only to a limited depth, 12, 9, and 6 cm in the profiles from the bottom of the talus slope segment and the upper and lower parts of the gentle footslope segment, respectively. The depth of the plough layer was significantly less than that reported for cultivated land in other areas with thick uniform soils, where plough depths of > 12 cm are demonstrated by the ^{137}Cs depth distributions (Walling and Quine, 1991; Quine *et al.*, 1994; Zhang *et al.*, 1999; Brígido *et al.*, 2002). There was a little ^{137}Cs in the soil beneath the plough layer, which appeared to reveal either the continuous downward diffusion of ^{137}Cs from the plough layer or a non-uniform tillage depth. The average ^{137}Cs activities for Profiles 11, 16, and 19 on the lower part of the slope were 11.5, 9.4, and 4.0 Bq kg^{-1}, with the ^{137}Cs inventories being 373.5, 297.0, and 56.2 Bq m^{-2}, respectively. ^{137}Cs inventories in these three profiles were far less than the local reference inventory, which might be due to low ^{137}Cs inventories in the soils before cultivation, or the impact of soil loss with cultivation.

Spatial distribution of ^{137}Cs inventories in the bulk samples

For the 19 samples, the mean mass depths of the < 2 mm fraction ranged between 0.89 and 5.10 g cm^{-2}, with a mean of 2.0 g cm^{-2}; the ^{137}Cs activities ranged between 5.48±0.64 and 24.72±2.56 Bq kg^{-1}, with a mean of 12.0 Bq kg^{-1}; and the ^{137}Cs inventories ranged between 120.3 and 992.5 Bq m^{-2}, with a mean of 261.1 Bq m^{-2} (Table III). A large area of bare bedrock was found in Profile 3 and the soil was collected from several cracks, so that the mean mass depth and ^{137}Cs inventory were not calculated for this profile. Because the depth incremental profiles were collected from the positions with thicker soil and limited gravel, the ^{137}Cs inventories of all bulk samples were far lower than those documented for the depth incremental profiles, except in the case of the profile collected from the footslope segment. The ^{137}Cs inventories for the bulk samples and depth incremental profiles all showed a tendency to decrease downslope. However, in contrast to the depth incremental profiles, the ^{137}Cs inventories of all the bulk samples were substantially lower than the local ^{137}Cs reference inventory. The ^{137}Cs activities of the bulk samples from the flat hill peak and bare steep slope segments were greater than those for the talus slope and gentle footslope segments. There was no obvious difference in ^{137}Cs activity between the talus slope and gentle footslope segments.

TABLE III

Mean mass depth, ^{137}Cs activity, and ^{137}Cs inventory of the < 2 mm fraction of the bulk soil samples from the segments of the carbonate rock slope studied

Slope segment	Profile No.	Mean mass depth of < 2 mm soil fraction	^{137}Cs activity	^{137}Cs inventory
		g cm^{-2}	Bq kg^{-1}	Bq m^{-2}
Flat hill peak	1	2.66	15.68	417.24
Bare steep slope	2	5.10	14.47	992.54
	3	-	24.72	-
	4	1.36	19.24	299.72
	5	2.07	20.91	529.38
Talus slope	6	2.12	9.49	228.37
	7	2.36	11.02	294.93
	8	1.89	7.25	144.89
	9	1.85	9.52	174.43
	10	1.69	8.44	161.16
	11	0.96	11.09	122.55
	12	2.20	9.92	237.31
	13	1.81	9.44	203.26
	14	2.24	8.49	192.92
	15	2.12	5.48	120.27
Gentle footslope	16	0.89	16.21	154.98
	17	1.36	9.99	142.45
	18	1.25	10.88	143.40
	19	2.35	5.92	140.20

The mean net soil loss from the slope studied was estimated to be less than 10 t km^{-2} year^{-1} during 2005–2007 from the results obtained from the runoff plots adjacent to the sampling transect. Therefore, the slope studied can be regarded as uncultivated land where neither erosion nor deposition occurred, except for the footslope segment which had experienced a short-term cultivation. Compared with the uncultivated land with thick uniform soils in other areas, the ^{137}Cs redistribution on the slope studied with thin stony soil showed mainly three characteristics. Firstly, the ^{137}Cs inventories were much lower than that of the local reference inventory. In theory, the ^{137}Cs inventory in a sampling plot where neither soil erosion nor deposition occurred should be equal to the local reference inventory. However, the mean value of ^{137}Cs inventory for the slope studied was only 261.1 Bq m^{-2}, which was only 26.2% that of the local reference inventory. Secondly, the ^{137}Cs activities in the < 2 mm fraction of the surface soil were very high. A high value of 12.0 Bq kg^{-1} was recorded for the mean ^{137}Cs activity of the bulk samples. The mean ^{137}Cs activities of surface soils (0–20 cm) in most reference profiles with thick uniform soils, such as loess, sandy loam, Entisol, and clay loam, usually range between 4 and 8 Bq kg^{-1} (Zhang *et al.*, 1990; Porto *et al.*, 2003; Qi, 2006; Schuller *et al.*, 2007), which are much lower than those of the slope studied. Furthermore, the ^{137}Cs inventories of all these profiles were more than 1 000 Bq m^{-2}. Obviously, the reason for the high ^{137}Cs activities of the thin stony soil on the carbonate rock slope was that the surface soil had a coarse particle size and all the ^{137}Cs was adsorbed by a small proportion of fine soil particles. Thirdly, there was considerable spatial variation in the distribution of ^{137}Cs on the slope studied. In general, the ^{137}Cs inventories in the depth incremental profiles collected at the positions with thicker soil were greater than those of the bulk samples. The two profiles on the bare steep slope segment showed the greatest variation. The ^{137}Cs inventories in the bulk samples were only 18.6% and 34.2% those of the depth incremental profiles.

Applicability of the ^{137}Cs method for estimating soil loss from carbonate rock slopes

With the purpose of assessing the applicability of the ^{137}Cs method for estimating soil loss from carbonate rock slopes, it is important to explain the high ^{137}Cs depletion documented for the carbonate rock slope with thin stony soil in this study although neither soil erosion nor deposition occurred in the slope studied. The main reasons for the high ^{137}Cs depletion in the slope studied are illustrated as follows. Firstly, excluding Profiles 2, 3, and 5 on the bare steep slope segment where the soil samples with a fine particle composition were collected from the rock cracks, the content of sand, silt, and clay in the remaining bulk samples ranged from 218 to 333 g kg^{-1}, with a mean of 248 g kg^{-1}, and the mass depth of the < 2 mm soil fraction ranged from 0.89 to 2.66 g cm^{-2}, with a mean of 1.82 g cm^{-2}. Assuming a dry bulk density of 1.3 g cm^{-3} in the soil, the mean thickness of the slope studied was only 1.4 cm, which confirmed the thin soil covering of the slope studied. The available monitoring data showed that heavy or extremely heavy rains were the dominant form of precipitation in the study area, and that only a few runoff events were produced when heavy rains occurred. During the heavy rains, a large amount of ^{137}Cs fallout was delivered to the land surface with precipitation, but it may not have been be fully adsorbed by the very limited amount of fine soil particles at the surface during the short time available. In the meantime, since heavy rains are responsible for producing runoff, a substantial proportion of the fresh fallout ^{137}Cs is likely to have been lost directly with the runoff before it could be adsorbed by the soils. Therefore, an appreciable amount of the ^{137}Cs fallout was lost with the runoff during the fallout of ^{137}Cs. Secondly, due to the large area of bare rock found in the slope studied, a considerable proportion of the ^{137}Cs fallout reaching the surface land with the precipitation was unable to be adsorbed by the bare rock and was therefore lost *via* runoff. Therefore, a great proportion of the ^{137}Cs fallout produced by nuclear bomb tests was lost from the slope with thin stony soil developed on carbonate rock. Thirdly, the dissolution of carbonate particles in the soils enhanced the loss of ^{137}Cs. The soil on the carbonate rock slopes was rich in carbonate particles, with a mean carbonate content in the < 2 mm fraction of 312 g kg^{-1}. The dissolution of carbonate particles weakened the binding between soil particles and the ^{137}Cs adsorbed to their surface, resulting in increased ^{137}Cs loss with runoff. It was believed that the dominant basis of ^{137}Cs loss from carbonate rock slope with thin stony soil may be the dissolution of carbonate particles in the soil.

In the ^{137}Cs method, as traditionally applied, the magnitude of the rate of soil loss is estimated by comparing the ^{137}Cs inventory of the sampling points with the local reference inventory, *i.e.*, the ^{137}Cs depletion. However, for the study area, the low rate of soil loss from the runoff plots was inconsistent with the high levels of ^{137}Cs depletion found for the sampling points on the slope studied. This implied that the high levels of ^{137}Cs depletion on the slope studied may not correspond to high rates of soil redistribution caused by water erosion. On the basis of this limited evidence, it could tentatively be concluded that the current ^{137}Cs method, which is widely used throughout the world in areas with thick uniform soils, was of limited value for estimating soil loss from slopes developed on carbonate rocks in the study area. More case studies are needed to confirm these preliminary conclusions.

ACKNOWLEDGEMENTS

The authors thank the Huanjiang Experimental Station of Karst Ecosystem, Chinese Academy of Sciences and the State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, for assisting the experiment. The authors are also grateful to Dr. BAO Yu-Hai, Dr. YAN Dong-Chun, and Dr. BAI Xiao-Yong from the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Dr. CHEN Hong-Song, Dr. ZHANG Xiao-Nan, Mr. YI Ai-Jun, Mr. FU Wei, and Mr. ZHANG Wei from the Institute of Subtropical Agriculture, Chinese Academy of Sciences, for their kind assistance in the field survey.

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