

March 6th, 2019

Editor-in-Chief

SOIL

Dear Editor and Reviewers:

First of all, please let us transfer our most sincere thanks to your valuable comments for our manuscript. After receive the suggestions and comments, we have checked the whole paper thoroughly and revised it according to the constructive comments. The comments pointed out by the reviewers have been carefully treated. I hope all our efforts can make this paper more suitable for the publication level.

We uploaded the revision notes for the reviewers and the new version of the manuscript.

Thank you for your consideration and I looking forward to the further comments of reviewers to our study.

Sincerely,

Yang Yu

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Revision Note for Reviewer 2

This paper aims to quantify the erosion and sediment deposition rates in the Karst region of Southwest China using ^{137}Cs tracing technique. Further, the authors evaluated the relationships between ^{137}Cs and selected soil properties (soil pH, total nitrogen, total phosphorus, and SOC content) by PCA analysis. The purpose of this study is worth giving the intensity of soil erosion in the area. However, I have many concerns about the conclusions:

Dear reviewer 2, also, thanks a lot for your time invested in our manuscript. We highly appreciate your comments and suggestions. We tried to do our best in order to improve our research and clarify all your concerns.

1. The authors only sampled 10 soil cores (nine along 3 transects and one from the depression). I think the size of samples is inadequate for obtaining a catchment-scale conclusion, e.g. Line 20 “the sediment delivery ratio summarized 0.82 in the whole catchment according to the square of hillslope and depression bottom”. Given the complexity of topography of the study area showing in Fig. 1, erosion rates and soil properties can be highly variable.

Response: Thank you very much for your comments. Of course, understanding the high heterogeneity of soils need an elevated number of plot sites to increase the precision. The depression we choose is a small closed watershed. We chose different hillslope positions for sampling in order to decrease the heterogeneity. We consider that it can be adequate to get the small catchment-scale conclusion as other authors also found karst areas (Bai et al, 2010; Zhang et al, 2010, etc.). However, we included this idea as also suggested the reviewer 1.

2. Statistic relationship between ^{137}Cs and soil properties cannot be obtained by PCA (Line 25). The angle between two variables in PAC Biplot just indicates a tendency of correlation. The authors should perform simple correlation analysis to confirm the statistic results. Further, PCA is a technique for reducing the dimensionality of complex datasets, increasing interpretability. I can't see the necessity to perform PCA in this paper in its present form. I would suggest authors try to 1) explain the first two components 2) combine PCA with PERMANOVA to examine how do measured variables differ between slope positions. Then reconsider the necessity of using PCA.

Response: Thank you very much for your comments. We used an Anova for distinguishing the soil properties at different slope positions. We also performed the correlation analysis of the soil properties. However, we would want to conserve the use of the PCA in this paper, because it was really useful to observe and reduce the number of parameters able to explain the interactions among soil processes at the hillslope scale. As we included a new analysis (linear correlation and Pearson correlation), we will wait for your new valuable evaluation to observe if you find now interesting this new approach. If not, we will delete it.

3. §3.2 Authors presented the variation of ^{137}Cs and soil physicochemical properties for selected hillslope at different soil depths. It is not clear which slope position you selected for such comparison? Only shoulder position or plus foot slope? Why?

Response: Thank you very much for your comments. Sorry, we did not express it clearly. The

three hillslope positions were compared and now included in the text. We deleted the confused words.

4. §5 In conclusions (Line 295), authors mentioned that “on the shoulder and backslope, the maximum of ^{137}Cs appears in the soil subsurface layers, whereas at the footslope, the maximum appears in the topsoil parts “. I will doubt this conclusion unless the SD value can be reported in Fig. 2. Its important because what I can see from Fig. 2 is that there might be no difference (if high SD) between 0-5 cm (topsoil) and 5-10 cm (subsurface) at backslope and footslope. From my point of view, it's reasonable that no difference of ^{137}Cs values between 0-5 cm and 5-10 cm because of the mixed effect of tillage practice.

Response: Thank you very much for your comments. We added the SD values in Fig.2 because we agree with your valuable opinion. There are no differences of ^{137}Cs values between 0-5 cm and 5-10 cm unless that we include more data such as SD.

5. Please report the slope gradients in Table 2, then we can see the rationality of your explanations for the factors driving erosion rates (§Conclusions, Line 297).

Response: Thank you very much for your comments. We added the slope gradient in Table 2.

6. This paper showed that soil erosion was greater in either upper and lower hillslope parts than in the middle one (Line 235), and authors attribute these patterns to the slope gradient. I think another possible reason is that the coexisting of tillage erosion and water erosion. Typically, tillage erosion is the main cause of soil loss at the concave position (ref. to Lobb D.A. 1999), i.e. shoulder position (upper parts), while water erosion leads to serious soil loss at lower slope position (these areas received maximum runoff concentrations).

Response: Thank you very much for your comments. It is a great idea! We included this in the discussion part. Thanks.

Technical comments:

7. Line 23: “.....play the most important role in WHAT?”

Response: “in influencing ^{137}Cs ”.

8. Line 113: is there inorganic C from the soil samples? If so, how did you remove it?

Response: There is inorganic C. But our research only paid attention to soil organic matter.

9. Line 160: add SD to ^{137}Cs concentration.

Response: We added the SD.

10. Line 175: Fig.2 rather than Fig.3?

Response: we revised it.

11. Line 242: please add a reference

Response: We added.

12. Line 245-246: what you mentioned here is not correct according to Fig. 2. Please check it carefully.

Response: Revised it.

13. Line 261: please add ref. here to show where is this data from

Response: We added it.

14. Line 297: check spell of letters.

Response: We checked and revised them.

Evaluating soil erosion and sediment deposition rates by the ^{137}Cs fingerprinting technique at different hillslope positions to assess a karst gaben basin in Yunnan Province, southwest China

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Abstract. Soil erosion is a global environmental issue that can lead to the loss of nutrients in topsoil layers, particularly in fragile karst environments where the low contents of organic carbon and steep slopes used to be key pedological and geomorphological factors. Researching the erosion and deposition rates at the hillslope scale in small watersheds is important for designing efficient soil and water conservation measures. In this research, the Dapotou closed watershed, a representative depression in karst gaben basin, located in the Yunnan province, Southwest China, was selected to assess the variation of soil erosion and sediment mobilisation at different hillslope positions using the ^{137}Cs tracing technique. The results showed that the soil erosion rates in the shoulders, backslopes and footslopes were 0.87, 0.35 and 0.49 cm a^{-1} , respectively, meanwhile the soil sediment rate in depression bottom was 2.68 cm a^{-1} . The average annual soil erosion modulus of the complete hillslope was 632 $\text{t km}^{-2}\text{a}^{-1}$, which confirmed the serious gradation according to karst soil erosion standards. The soil deposition modulus reached up to 3216 $\text{t km}^{-2}\text{a}^{-1}$. The sediment delivery ratio would summarize 0.82 in the whole catchment according to the square of hillslope and depression bottom. To identify which factor could play the most important role in influencing the estimations using ^{137}Cs , a linear correlation and Principal Component Analysis were conducted. The results showed ^{137}Cs concentration of different soil depth at different hillslope positions were significantly correlated with soil organic matter (SOM) and total nitrogen (TN) ($P < 0.05$). As the typical karst geomorphological types, these findings are expected to provide data support for the whole watershed soil erosion management and ecological restoration in this fragile karst ecosystem.

1 Introduction

Soil erosion has been identified as a global geo-environmental hazard (Prise et al., 2009; Panagos et al., 2014). Due to the nutrient-poor characteristics of carbonate-rock parent materials, the effects of soil erosion have been greater in the karst areas, which occupy approximately 12% of global continental terrains (Febles-González et al., 2012). Considering the 22 million km^2 of global karst areas, a total of 15.6% is located in China, amounting approximately 3.44 million km^2 (36% of China). Karst areas in China are mainly concentrated in eight southwest provinces, including Yunnan, Guizhou, Guangdong,

35 Chongqing, Hunan, Hubei, Sichuan and Guangxi (Jiang et al., 2014).

In karst areas, gaben basins and mountains usually coexist because of specific geological processes such as subsidence and dissolution of fault blocks induced by Cenozoic tectonic uplift among others (Wang et al., 2017). These differences in geomorphological characteristics, in addition to severe anthropogenic disturbance (e.g., agriculture), often produce a series of environmental problems (e.g., runoff, erosion). In the gaben basins of China, studies on soil erosion and sediment yield
40 considering small catchments (10–10,000 ha) remains absent, although they are particularly interesting for the understanding of the linkages between soil erosion on hillslopes and sediment transport in large watershed and their potential impacts on the ecological services and human activities (Schuller et al., 2004).

Since the last decades, many scholars are trying to use ^{137}Cs to evaluate long-term soil erosion or soil sediment mobilization in karst areas, whose studies focused on karst peak cluster depression and karst plateau (Bai et al., 2010; Feng et al., 2016; Luo
45 et al., 2018). The ^{137}Cs is an artificial radionuclide with a half-life of 30.17 years, which is released into the atmosphere as a result of thermonuclear weapon testing between the 1950s and 1970s (IAEA2014). Traces of ^{137}Cs enter the earth's soils through dry and wet deposition, with the maximum deposition rate occurring in 1963 (Zhang et al., 2008). ^{137}Cs has been a cost- and time-effective tool to evaluate soil redistribution due to erosion and can complement the information provided by conventional erosion measurements (Lizaga et al., 2019), for example *in situ* experiments such as rainfall, runoff or wind
50 simulations (Marzen et al., 2019; Rodrigo-Comino et al., 2017) and soil erosion plots (Cerdà et al., 2018; Kinnell et al., 2016). ^{137}Cs can provide retrospective estimates of long-term soil erosion and deposition rates without disturbing the soil environment by installing measuring equipment (Porto and Walling, 2012). Besides, it can also be used to obtain detailed analyses of sediment migration on hillslopes (Evans et al., 2019; Zebari et al., 2019).

In the small watershed of eastern Yunnan, where it has been adversely impacted by soil erosion, there is an urgent need to
55 assess the sediment delivery ratio based on soil erosion and sediment rates to inform the policymakers and stakeholders about the potential land degradation processes and possible control measures that should be included. Therefore, using ^{137}Cs , we aimed to quantify the hillslope soil erosion, soil sediment mobilisation and sediment delivery in this closed depression watershed of the gaben basin. Generally, the concentrations of deposited ^{137}Cs are usually uniform in a small area, which has similar latitude and rainfall characteristics (Song et al., 2018). Our study pretends to detect the variations of ^{137}Cs and soil
60 properties under different positions on karst hillslopes, which could be considered representative geological structure in southwest China. Also, we attempt to quantify the impact of soil depths and positions on soil erosion rates and to analyze the relationship between soil property variations and erosion rates using multivariate statistical techniques. We hypothesize that the results obtained from this research will support the necessary information required to protect the whole watershed of the Yunnan karst gaben basin.

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2 Materials and methods

2.1 Study area

The Dapotou depression is located in the Yangjie Town, Kaiyuan County, situated in the Yunnan Province from China (103° 17' 25.63"-103°18' 3.40" E, 23° 36' 48.04"-23° 37' 28.10"N) (Figure 1). This territory is a closed watershed with a drainage area of about 1.97 km². Its elevations range from 1267 to 1413 m a.s.l. The underlying bedrock of the depression is a Triassic carbonate rock, which consists of Gejiu Group (T₂g³) and Falang Group (T₂f¹) limestone. Most soils in this watershed have a soil texture of clay-limestone materials.

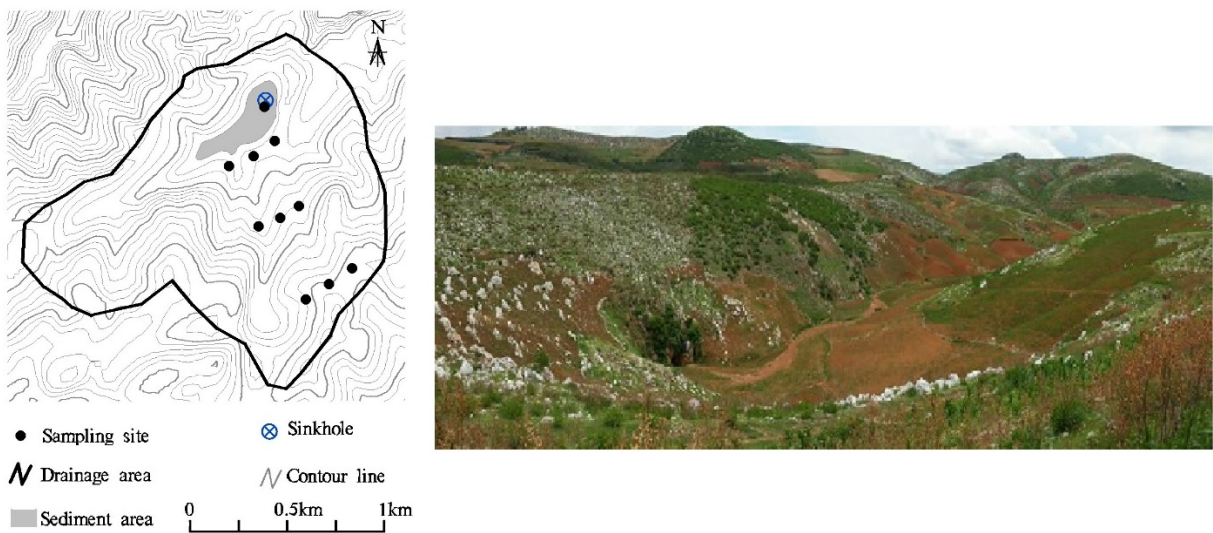
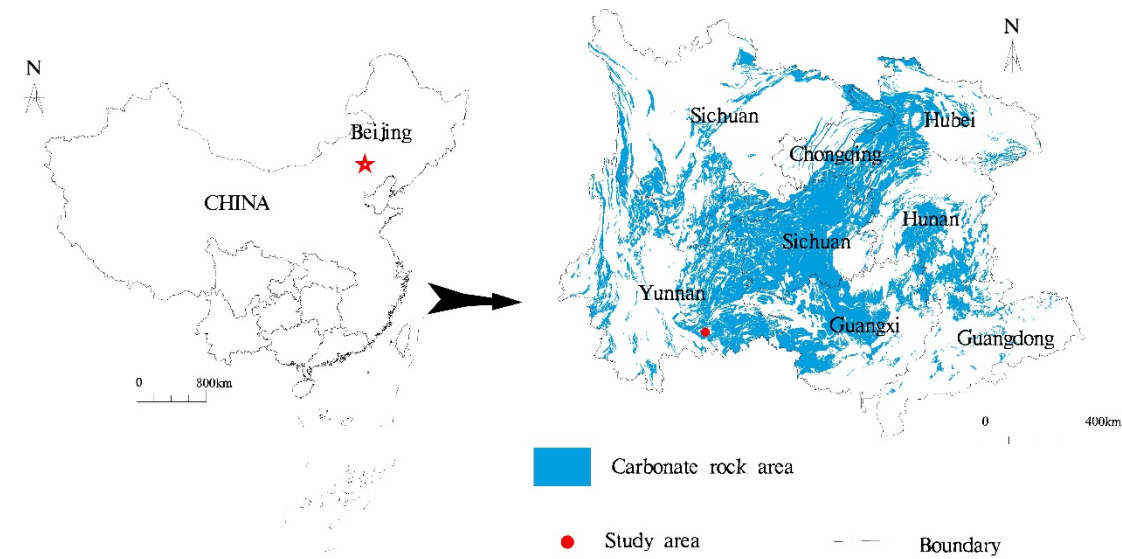


Figure 1: Localisation of the study area, sampling points and panoramic image of one selected plot.

This territory experiences a subtropical monsoonal climate with two main seasons: a rainy season from June to September and a dry season from October to May (Jiang, 2012). The mean annual precipitation is 904 mm with a unimodal rainfall regime.

The rainy season precipitation accounts for 80% of the annual precipitation. The average annual temperature is 18.3°C (the coordinates of the climate station is 103°19'12.76"E , 23°37'17.25"N).

The study area has a depression bottom with a length of about 1000 m and an average width of about 60 m. The hillslopes and depression bottom itself are once-a-year cultivated with maize. There is a sinkhole in the northeast of the bottom of depression (Fig. 1). Some steep slope areas are dominated by calcicole shrub and drought-tolerant herbs. When experiencing heavy rain, the bottom of the depression is submerged because the sinkhole is not able to canalize the total amount of runoff. Some part of the surface water infiltrates to the soil and some other flow into the subterranean stream through the sinkhole. It uses to be at least once or twice flooded events every rainy season.

2.2 Sampling tools and sampling design

In this study, samples in nine cultivated hillslopes at three different hillslope positions (shoulder, backslope and footslope) and one at the depression bottom were collected in July 2017. Soil samples were taken considering the depth of 40 cm on each hillslope position (although in one site of backslope was sampled only to 30 cm deep because of the soil depth) and 240 cm at the depression bottom to ensure that the full radionuclide soil content was taken into account. To establish the vertical distribution of ^{137}Cs , the samples were collected by using a scraper with 5 cm increments. A total of 70 soil samples from the hillslope and 48 soil samples from the depression. The bulk density of soil samples was measured by using a cutting ring. Geographical coordinates and elevation of each sampling point were recorded by using a GPS device. After that, soil samples were transported to the laboratory and were sieved through 2 mm sieve to remove plant roots before air drying and performing the radionuclide and physicochemical property analyses.

We also select a control plot as a reference for the inventory site. Ideally, the land for the reference inventory should be flat and undisturbed. However, it is difficult to find any completely flat land which has not been cultivated since the mid-1950s. Therefore, local reference samples of ^{137}Cs were collected in a relatively flat shrub-grassland site, located several kilometres from the study area (103°26'48.37"E, 23°29'20.15"N). The reference site is well vegetated and protected (undisturbed by the residents). Five soil samples were then collected in this reference site and the average soil thickness of the reference profile was estimated close to 20 cm.

2.3 Laboratory analysis

The ^{137}Cs analyses were performed in the Institute of Mountain Hazard and Environment, Chinese Academy of Sciences. The ^{137}Cs content of the <2 mm fraction of each sample was measured by γ spectrometry using a hyper pure coaxial germanium detector and multichannel analyzer system. The samples have a weight of 300 g. ^{137}Cs was detected at 662 keV and counting times were more than 50 000 s, providing results with an analytical precision of approximately $\pm 5\%$ at the 95% level of

confidence.

Also, soil physicochemical properties were measured in the Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences. Soil organic matter (SOM) was determined by dry combustion at 500 °C (Davis, 1974). Total nitrogen (TN) and total phosphorus (TP) concentration were measured by using a persulfate digestion method. Total potassium (TK) was quantified by using flame photometry method. Finally, soil pH was analyzed by using Mettler Toledo Seven Excellence pH meter.

2.4 Conversion models

The ^{137}Cs inventory of soil profile in different hillslope position was calculated by using the following equation (Zhang et al., 2009b):

$$\text{CPI} = \sum_{i=1}^n C_i \times B d_i \times D_i \times 10 \quad (1)$$

Where CPI is the ^{137}Cs inventory (Bq m^{-2}), represents the total amount of ^{137}Cs in sample; i is the sampling layer sequence; n is the quantity of sampling layer; C_i is ^{137}Cs concentration (Bq kg^{-1}); $B d_i$ is the bulk density of the i layer (g cm^{-3}) and D_i is the depth of i layer (cm).

The reference sample was considered using a bulk sample and the ^{137}Cs inventory was calculated following this equation (Zhang et al., 2009b):

$$\text{CPI} = C_i \times W/S \quad (2)$$

Where W is the weight of fine particles, S is the surface area of the sample plot.

A simplified Mass Balance Model is widely used for the assessment of erosion rates on cultivated lands (Zhang et al., 1990):

$$A = A_0 (1 - h/H)^{N-1963} \quad (3)$$

Where A_0 is the ^{137}Cs reference inventory (Bq m^{-2}); A is the ^{137}Cs inventory at an erosion point (Bq m^{-2}); h is the annual soil loss in depth since the year 1963 (cm); H represents the plough depth (cm), and N means the sampling year.

^{137}Cs has been widely used for dating of undisturbed soil profiles. The excepted ^{137}Cs depth profile characterized by a single peak for the year 1963 which the ^{137}Cs maximum fallout flux occurred. The deposition rate since 1963 can be evaluated by using the following equation (Bai et al., 2010):

$$R = H_m / (n - 1963) \quad (4)$$

Where R is the deposition rate (cm a^{-1}), H_m is the depth of the peak in ^{137}Cs activity (cm), and n is the sampling year.

The deposited sediments used to be mixed into a plough layer by plough activities at the karst depression bottomland. The ^{137}Cs distribution depth at the deposited depression bottom is greater than the local reference inventory. Under the assumption that ^{137}Cs fallout was totally on the ground in 1963, the sediment deposition depth was derived from the equation (Bai et al., 2010):

$$\Delta H = H_m - H_p \quad (5)$$

Where ΔH is the sediment deposition depth since 1963 (cm); H_m represents the total ^{137}Cs distribution in profile (cm); H_p means the plough layer depth (cm).

The modulus of soil erosion is calculated as follows:

$$Y=h \times D \times 10000 \quad (6)$$

Y is soil erosion modulus ($\text{t km}^{-2}\text{a}^{-1}$); D is the soil capacity (g cm^{-3}).

$$R=1-Q_d/Q_m \quad (7)$$

150 R is sediment delivery ratio; Q_d is the deposition amount(t); Q_m is the erosion amount(t)

2.5 Statistical analysis

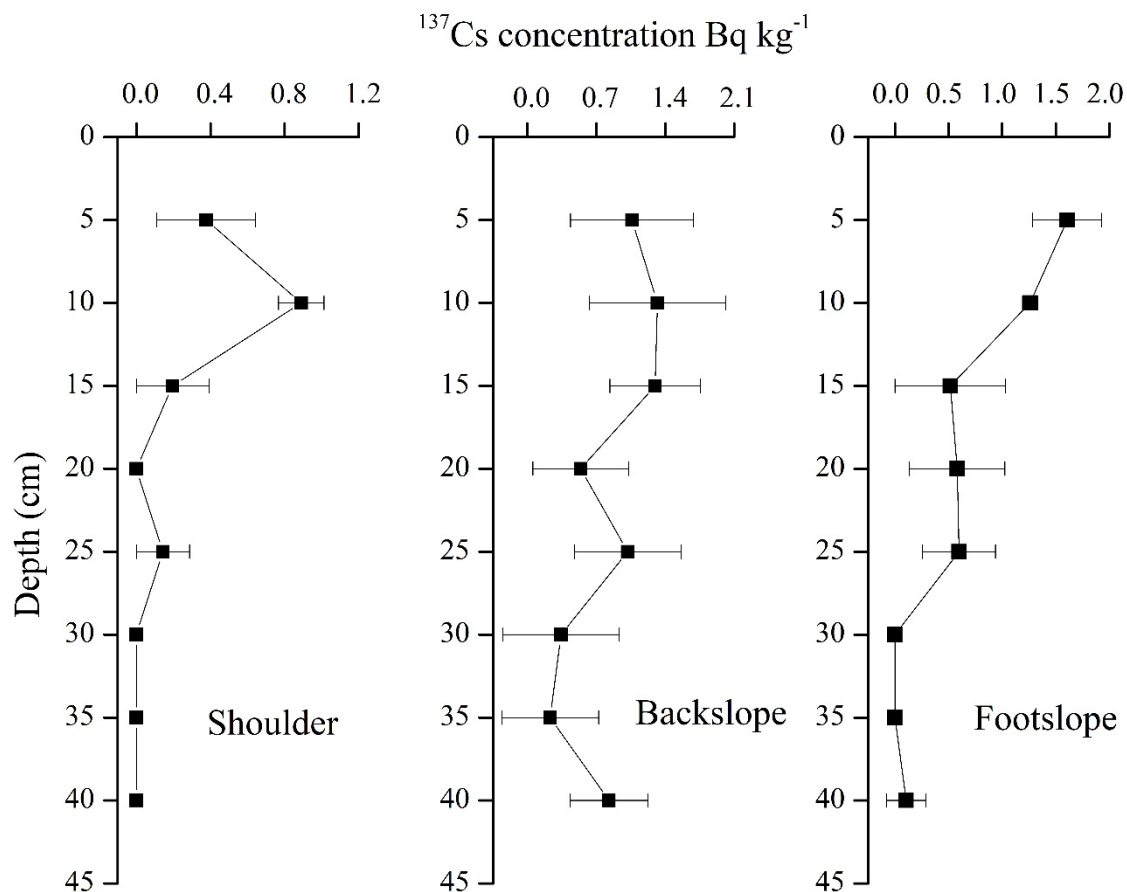
Data on soil pH, SOM, TN, TP and TK were statistically analysed to provide annual averages from each soil depths under different hillslope positions (shoulder, backslope and footslope). First, analysis of variance (ANOVA) was conducted to soil properties and sediment deposition rates, to evaluate their statistical differences at different positions and depths. In the case of obtaining significant differences at $P < 0.05$, the variable means were compared using an LSD (least significant difference) test. All the results were plotted including averages and standard deviation values (SD). Additionally, a Pearson correlation and Principal Component Analysis (PCA) was also performed to determine first correlations among the measured variables and reduce the number of studied factors for observing the possible interaction between soil erosion and properties. The raw datasets were standardized before analyses and all statistical analyses were conducted using the R software version 3.2.4 (R Core Team 2013).

3. Results

3.1 Variation of ^{137}Cs and soil physicochemical properties at different hillslope position

165 Our results showed that ^{137}Cs concentration was significantly different at different hillslope positions ($P < 0.05$) (Fig. 2). The average ^{137}Cs concentration was the highest in the backslope ($0.83 \pm 0.54 \text{ Bq kg}^{-1}$), followed by the footslope ($0.58 \pm 0.23 \text{ Bq kg}^{-1}$) and shoulder ($0.20 \pm 0.09 \text{ Bq kg}^{-1}$). The ^{137}Cs inventories at different hillslope positions were respectively 364.6 Bq m^{-2} , 249.9 Bq m^{-2} and 85.1 Bq m^{-2} , and the mean ^{137}Cs inventories were 226.5 Bq m^{-2} .

170 Similar to the ^{137}Cs concentration, we found the maximum values of soil pH, SOC, TN, TP, TK in the backslope. Also, it is important to remark that soil pH, TN, TK were higher in the shoulder than in the footslope, meanwhile, SOC and TP were higher in the lower parts than in the upper ones. Except for SOC, other soil properties (pH, TN, TP and TK) were significantly different at different hillslope positions (Table 1).



175 **Figure 2: ^{137}Cs concentration distribution features at different hillslope positions.**

Table 1: Average variations in ^{137}Cs and soil properties at different hillslope positions.

	^{137}Cs Bq kg^{-1}	pH	SOM g kg^{-1}	TN g kg^{-1}	TP g kg^{-1}	TK g kg^{-1}	Slope gradient ($^{\circ}$)
Shoulder	$0.20 \pm 0.09\text{b}$	$6.87 \pm 0.37\text{b}$	$0.95 \pm 0.72\text{a}$	$0.09 \pm 0.04\text{b}$	$0.02 \pm 0.00\text{b}$	$1.06 \pm 0.21\text{b}$	27
Backslope	$0.82 \pm 0.54\text{a}$	$7.47 \pm 0.74\text{a}$	$1.27 \pm 0.52\text{a}$	$0.14 \pm 0.05\text{a}$	$0.03 \pm 0.01\text{a}$	$1.95 \pm 0.54\text{a}$	20
Footslope	$0.58 \pm 0.23\text{a}$	$6.09 \pm 1.03\text{c}$	$1.05 \pm 0.32\text{a}$	$0.09 \pm 0.03\text{b}$	$0.03 \pm 0.01\text{b}$	$0.95 \pm 0.34\text{b}$	23

Data represent means and standard deviations (SD). Different lowercase letters indicate a significant difference among slope position.

3.2 Variation of ^{137}Cs and soil physicochemical properties for three hillslopes positions at different soil depths

Figure 2 and Table 2 shows the variations of ^{137}Cs and soil properties for the selected hillslopes and different soil depths, respectively. In the shoulder, ^{137}Cs was mainly distributed in the topsoil (i.e., 0.38 Bq kg^{-1} in 0-5 cm and 0.89 Bq kg^{-1} in 5-10 cm soil). Below 10 cm, ^{137}Cs concentration decreased rapidly. There were no ^{137}Cs in 15-20 cm, 25-30 cm, 30-35 cm and 35-40 cm soil depths.

In the backslope, ^{137}Cs concentration ranged from 0.23 Bq kg^{-1} to 1.32 Bq kg^{-1} . ^{137}Cs was mainly distributed within 0-15 cm

soil depth (i.e., 1.06 Bq kg⁻¹ in 0-5 cm, 1.32 Bq kg⁻¹ in 5-10 cm and 1.30 Bq kg⁻¹ in 10-15 cm soil). The mean ¹³⁷Cs concentration of the whole soil profile was 0.83 Bq kg⁻¹.

190 Finally, in the footslope, the ¹³⁷Cs concentration was mainly distributed within 0-10 cm. The peak concentration of ¹³⁷Cs was in the top 5 cm with a concentration of 1.61 Bq kg⁻¹, which was also the maximum concentration of the whole hillslope. From the top 5 cm, ¹³⁷Cs concentration decreased with increasing soil depth. There were no ¹³⁷Cs in the 25-30 cm and 30-35 cm soil depths. The mean ¹³⁷Cs concentration in the foot slope was 0.58 Bq kg⁻¹.

Based on the variance analysis considering the different five soil depths (0-5 cm, 5-10 cm, 10-20 cm, 20-30 cm, 30-40 cm), ¹³⁷Cs concentration was significantly different (P<0.05). Multiple comparisons showed ¹³⁷Cs concentration in 0-5 cm was significantly higher than that below 10 cm. ¹³⁷Cs concentration in 5-10 cm was significantly different with that in 10-20 cm, 20-30 cm and 30-40 cm, but it was not significant with the 0-5 cm. ¹³⁷Cs concentration in 10-20 cm, 20-30 cm and 30-40 cm showed no significant difference.

Other soil properties (SOM, TN, TP) showed significant differences (P<0.05), meanwhile, TK and pH showed no significant differences among soil depths. SOM in 0-5 cm (1.89 g kg⁻¹) was significantly higher than other soil depths and, even, SOM in 5-10 cm (1.40 g kg⁻¹) was significantly higher than 20-30 cm (0.88 g kg⁻¹), and 30-40 cm (0.62 g kg⁻¹). TN in adjacent soil depths registered no significant differences. For example, TN in 0-5 cm (0.16 g kg⁻¹) was significantly higher than the soil layers below 10 cm but had no significant difference with 5-10 cm. TP in 0-5 cm (0.033 g kg⁻¹) and 5-10 cm (0.035 g kg⁻¹) were significant higher than the soil depths below 20 cm. Soil TP had no significant difference between two adjacent soil depths.

Table 2. Average variations in ¹³⁷Cs and soil properties at different soil depths.

	¹³⁷ Cs Bq kg ⁻¹	pH	SOM g kg ⁻¹	TN g kg ⁻¹	TP g kg ⁻¹	TK g kg ⁻¹
0-5 cm	1.01±0.67a	6.31±1.02a	1.89±0.87a	0.16±0.05a	0.033±0.007a	1.37±0.63a
5-10 cm	1.16±0.41a	6.49±1.06a	1.40±0.32b	0.13±0.03ab	0.035±0.011a	1.33±0.68a
10-20 cm	0.52±0.54b	6.82±0.95a	1.04±0.27bc	0.10±0.04bc	0.028±0.009ab	1.33±0.62a
20-30 cm	0.35±0.39b	7.06±0.87a	0.88±0.33c	0.09±0.04cd	0.022±0.006bc	1.26±0.60a
30-40 cm	0.09±0.14b	5.73±2.58a	0.62±0.34c	0.06±0.04d	0.018±0.009c	1.07±0.61a

Data represent means and standard deviations (SD). Different lowercase letters indicate a significant difference among different depth (P<0.05).

3.3 ¹³⁷Cs variation of depression bottom in different soil depth

We observed a possible trend in ¹³⁷Cs concentration (Figure 3): first increased with soil depth, and then decreased after 165 cm. The peak of ¹³⁷Cs concentration was in the 165 cm soil layer (2.38 Bq kg⁻¹). The mean ¹³⁷Cs concentration in the whole depression soil profile was 1.25 Bq kg⁻¹, higher than the ¹³⁷Cs concentration of the tested hillslopes.

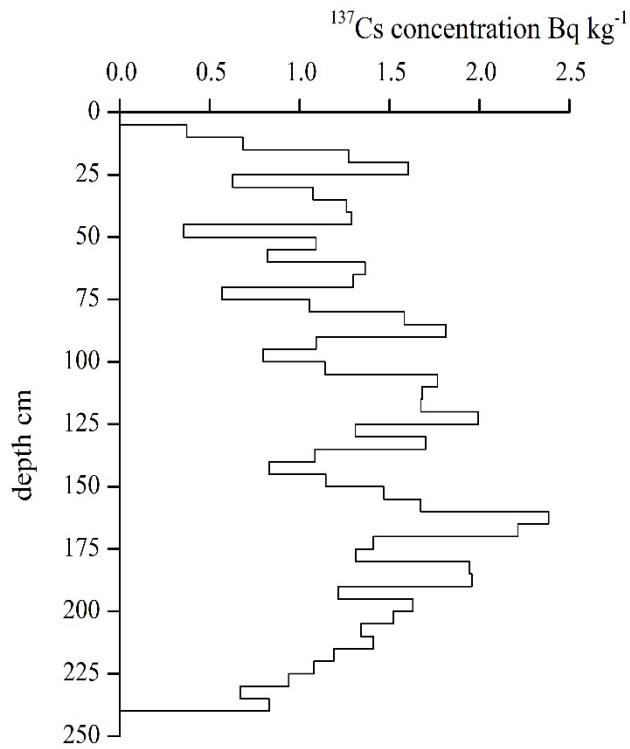


Figure 3: ¹³⁷Cs depth distribution features in depression bottom.

3.4 Potential connection between soil properties and sediment deposition rates

The Pearson correlation and principal component analysis (PCA) were carried out considering the above-mentioned variables related to sediment deposition rates using ¹³⁷Cs. The highest linear correlation was found for SOM (0.669), N (0.643) and P (0.620). Fig. 4 showed a plot of the eigenvector in the plane of the first two components together with the PC scores in the plane of PC1 and PC2. On the first component, which explained 61.4% of the total variance, and the second component explained 23.6%, respectively. Sediment deposition rates (Cs) was significantly affected by hillslope positions, meanwhile, Cs closely related to SOM and TN. We included the linear correlation between soil erosion rates and SOM, where it can be noted the trend and relationship between both variables (Figure 5).

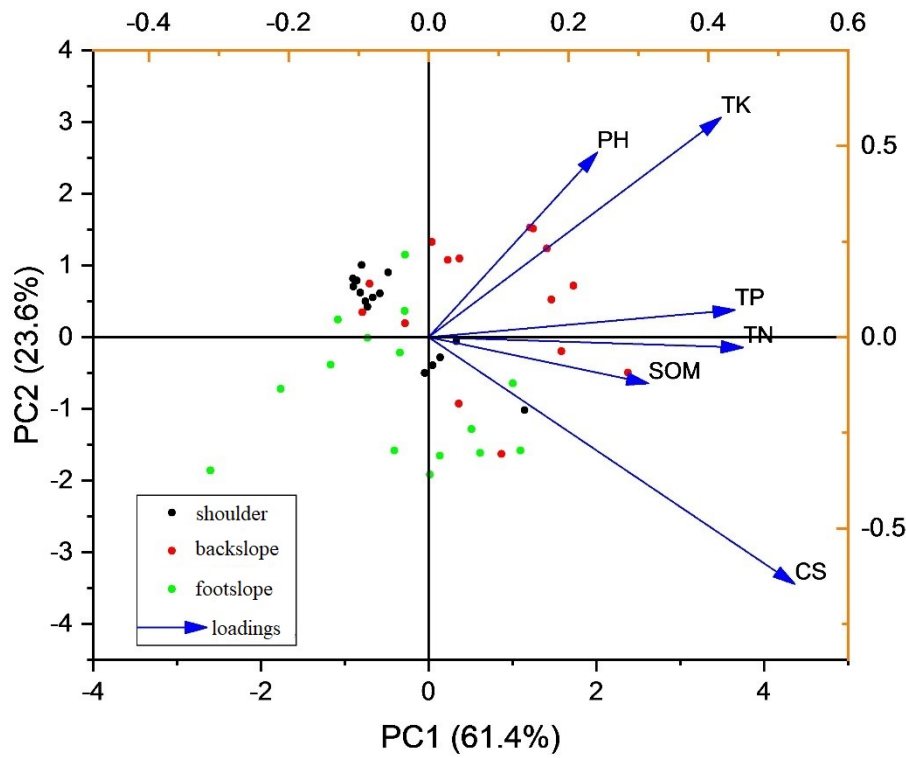


Figure 4: Eigenvectors from the principal component analysis (PCA) of the first two components.

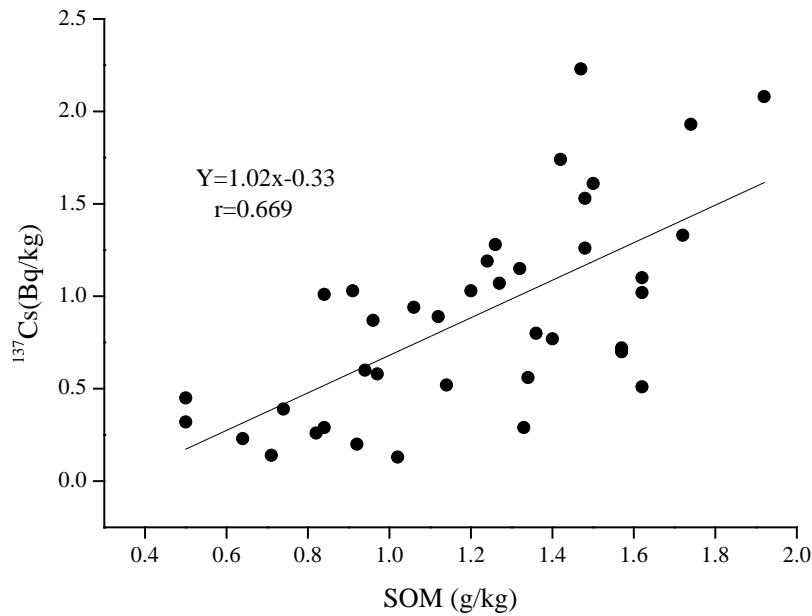


Figure 5: Linear correlation between ^{137}Cs and SOM (Soil Organic Matter) content.

230 3.5 Soil erosion modulus estimation

The reference soil value considered for this estimations were the bulk soil samples without distinguishing any layer. The average ^{137}Cs concentration in reference site was 6.28 Bq kg^{-1} . The surface area of each sample plot was 0.01 m^2 and the average weight for the fine particles was 1.5 kg. Using Eq. (2), we obtained 942 Bq m^{-2} as the reference ^{137}Cs inventory. The ^{137}Cs

inventory at different hillslope positions (shoulder, backslope, footslope) was lower than the reference plot inventory, possibly indicating that soil erosion happened in the disturbed hillslopes. Using the soil erosion rate Eq. (3) presented above, the calculated soil erosion rates in the shoulder, back- and footslope were 0.87 cm a^{-1} , 0.35 cm a^{-1} and 0.49 cm a^{-1} , respectively. Using the soil erosion modulus Eq. (6) and combining with the weight of different hillslope positions to calculate it, the average erosion modulus in the whole hillslope was $632 \text{ t km}^{-2}\text{a}^{-1}$.

In the depression bottom, the ^{137}Cs distribution was much deeper than that of local ^{137}Cs reference depth and the plough layer. The ^{137}Cs inventory was much greater than the ^{137}Cs reference inventory. Based on the depression bottom's ^{137}Cs peak concentration (165 cm soil layer), the deposition depth since 1963 was 145 cm because the local plough layer is about 20 cm. From Eq. (4) and Eq. (5), we obtained that the average deposition rates since 1963 were 2.68 cm a^{-1} . Finally, the soil deposition modulus was $3216 \text{ t km}^{-2}\text{a}^{-1}$, calculated from Eq. (6).

4. Discussion

Choosing a reference plot was a critical step for assessing the soil erosion rates using ^{137}Cs fingerprinting technique. While some researchers doubted this method because of ^{137}Cs fallout heterogeneity (Parsons and Foster, 2011). It is well-known that ^{137}Cs fallout can be influenced by rainfall and latitude. In our research, the reference site is located only some kilometres away from our plot site and the rainfall and latitude in the reference site are consistent with the plot sites. By calculating, the reference inventory in our study site was 942 Bq m^{-2} , close to the values of previous studies under similar rainfall and latitude conditions. For example, Zhang et al. (2009) used 918 Bq m^{-2} as the ideal reference inventory plot in Dianchi watershed Yunnan province. Similarly, Xiong et al (2018) used 906 Bq m^{-2} as the reference inventory in Shilin county, Yunnan province. This period is rather known as the onset of ^{137}Cs fallout than a high fallout deposition year. We can advertise that a large uncertainty on the reference 1963 fallout peak position (somewhere between 150-200 cm soil depth) could be interpreted. Possibly, it can be due to soil particle's mixing if the land was cultivated or to a more complex deposition trend including a varying supply of ^{137}Cs -tagged soil particles. Accordingly, any deposition rate that can be derived using this soil depth may be questioned. Therefore, in the future, more soil samples or in situ measures must be performed to clarify this uncertainty.

While soil erosion is usually greatest in the shoulder, followed by the backslope and lowest in the footslope (Song et al., 2018), in our study, soil erosion was greater in either upper and lower hillslope parts than that in the middle one. A steeper gradient of the upper slope compared to the middle could be responsible for this finding. A previous study shows that the slope gradient is the key factor affecting soil erosion when the rainfall and vegetation coverage is remaining unchanged (Lu et al., 2016). On the other hand, other studies considered that steep bare soils subjected to high-intensity rainfall and soil surface features could be rapidly transformed from a loose seedbed to crusted surfaces with pronounced micro-relief, for example, in northern Laos (Ribolzi et al., 2011). In our research area, possibly, the geological or vegetation conditions can also affect in some different ways, therefore, they do not coincide with other published research. ". Possibly, the correlations observed in our study and

reduction of factors using the PCA may not be directly due to ^{137}Cs adsorption by soil organic matter but rather to the fact that soil micro-aggregates contain both organic matter and ^{137}Cs bound to fine clay minerals. On the long term a single process, i.e. erosion, would deplete topsoil horizons in both soil organic matter and particle's bound ^{137}Cs during soil aggregate breakdown. In backslope, chemical dissolution is strong, forming some relatively closed microtopography, such as lapies and solution pans.

270 Soil from the shoulder is easily deposited in these micro topographical forms (Zhang et al., 2009b). Another possible reason is that the coexistence between tillage and water erosion which could play a key role as the main cause of soil loss at the concave position (Lobb and Kachanoski, 1999), i.e. shoulder position (upper parts), while water erosion could lead to serious soil loss at lower hillslope position (these areas used to receive maximum runoff concentrations). However, other research carried out in steep and conventionally tilled managed fields also highlighted the importance of the soil management practices
275 conducted by handmade tillage or tractor passes redistributing soil sediments along the hillslope (Cerdá and Rodrigo Comino et al., 2020). This issue is closely related to the connectivity processes, which using this method could be uniquely estimated but not directly quantified (López-Vicente et al., 2015; Parsons et al., 2015; Smetanová et al., 2018). Therefore, in the future, using other techniques this factor should further be studied and its influence deciphered.

Following the trend in soil erosion observed in our results, ^{137}Cs concentration peaked in 5-10 cm soil depths in the shoulder
280 and footslope, but only in the first 5 cm soil depth of the backslope. These results implied that soil erosion is highly affecting the topsoil layers, which is a serious issue, specifically, in the shoulder and footslope. On the contrary, the microtopography that is formed in the backslope could capture the soil carried by the erosion from the upper part, which could be responsible for elevated ^{137}Cs concentration in the soil surface. However, this issue must be also studied in the future with much more detail.

285 Our research also showed the ^{137}Cs concentration of different soil depth was significantly correlated with SOM. These results are consistent with previous studies conducted different environmental conditions (Parsons and Foster, 2011). This connection has a significant impact on the pathways of ^{137}Cs movement in the near-surface environment (Agapkina et al., 1995). In soil profiles, the concentration of ^{137}Cs shows a discontinuous trace distribution in different depths. On one hand, it can be hypothesized that there would be the possibility to observe soil creeping in soil and rock interfaces attending the parent material
290 composition, in this case, carbonate rocks. On the other hand, ^{137}Cs is mainly adsorbed by the fine soil particles and soil organic matter. The fine soil particles are easy to be mobilized to the deep soil layers under the action of gravity and leaching of rainwater.

The soil erosion modulus averaged $632 \text{ t}/(\text{km}^2 \cdot \text{a})$, which was much higher than the karst peak-cluster area in Longhe village Guangxi Province. On the one hand, some treatments and preventions of soil erosion have made great progress and the soil
295 erosion modulus decreased about 500 t km^{-2} from 2003 to 2015 (Luo et al., 2018). On the other hand, the soil in peak-cluster was thinner and some areas have no soils, just remaining bedrocks owing to previous soil erosion epochs. To understand the extent of soil erosion in our study site, we used the standard procedures established by Cao et al (2008) who considered the

carbonate rock soil formation rate by analyzing the factors influencing soil formation. Cao et al (2008) used soil formation rates as soil loss tolerance and redefined the classification standard of the intensity of soil and water losses in the karst area into the following categories: very slight, slight, medium, serious and very serious (<30 , $30-100$, $100-200$, $200-500$, $500-1000$ and $>1000 \text{ t km}^{-2} \text{ a}^{-1}$, respectively). Based on the above-mentioned classification, our research site was seriously eroded, which would require corrective measures to reduce soil erosion.

In our research site, the area of the whole hillslope and depression bottom is 1.91 km^2 and 0.067 km^2 , respectively. Considering the different soil erosion rate and weight of area at different hillslope positions, the annual soil loss was about 1207 t. According to the sediment rates and depression bottom areas, the annual soil sediment reached only 213 t. In the same closed catchment, the loss soil is much more than the sediment soil. This indicated that a part of the soil loss from the hillslope could be got into the subterranean stream from the sinkhole of northeast depression. From the erosion and sediment difference, we obtained that the sediment delivery ratio in our study site was about 0.82. This result is greater than the empirical value of reasonable sediment delivery ratio (0.7), which was obtained by Zhang et al (2010) using DEPOSITS model. Ward et al. (1981) proposed DEPOSITS model for estimating sediment delivery ratio in small impoundments based on plug flow theory. The DEPOSITS model assumes that the sediment delivery ratio is in proportion to runoff retention time. In karst area, depression can be considered as temporary impoundment because the area is easily flooded (Wang et al., 2004). At the same time, the plug flow theory only considers flooded conditions. Nowadays, in our study site, there are many rainfall events which do not lead to flooding. Therefore, calculating the sediment delivery ratio that considers local conditions could be more reliable than the generic empirical value.

The research depression is the typical geomorphic unit of karst garbin basin. There are a great number of depressions in the karst garbin basin which are the major soil erosion area. When the soil erosion happens in the studied hillslope after a rainfall event, the soil loss is divided into two parts according to the sediment delivery ratio. 18% of soil loss is deposited in the depression bottom, and 82% flowed into the subterranean stream system. The sediments which flowed into the subterranean stream is also divided into two parts. One part is deposited in the subterranean conduit; another is discharged from the subterranean stream outlet. The ratio of sediment in subterranean is the challenging and meaning research of the next step.

Because soil erosion mainly happens on hillslopes which remain cultivated, biological measures such as afforestation using deep-rooted species should be the prioritized. To encourage the shift in crop selection, high-value perennial crops such as honeysuckle can be promoted. The use of plough should be avoided to further reduce soil erosion. Finally, growing plant fence or sediment storage dam can be built in front of the sinkhole because most of the lost soil flow into the sinkhole of depression bottom.

5. Conclusions

The ^{137}Cs are mainly distributed in the topsoil between 0 and 10 cm owing to the ^{137}Cs adsorbed in the soil fine particles and soil organic matter. For this study case, the soil erosion rate is 0.87 cm a^{-1} , 0.35 cm a^{-1} , 0.49 cm a^{-1} in the shoulder, back- and

330 footslope, respectively. Possibly, the main driving factors were the micro topographical changes, the strong slope gradients
and tillage. Based on the sedimentation rates of the depression bottom (2.68 cm a^{-1}), sediment delivery ratio (0.82) and the
average soil erosion modulus at each hillslope position ($632 \text{ t km}^{-2} \text{ a}^{-1}$), soil erosion intensity can be considered according to
the karst soil erosion gradation criterion. To reduce soil erosion in this region, we suggest some control measures that are
feasible and can be implemented, even by farmers.

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