Article Chinese Science Bulletin

Geography

June 2011 Vol.56 No.16: 1708–1713
doi: 10.1007/s11434-011-4477-0

Soil erosion rates and characteristics of typical alpine meadow using ^{137}Cs technique in Qinghai-Tibet Plateau

SHAO QuanQin[1], XIAO Tong[1,2], LIU JiYuan[1*] & QI YongQing[3]

[1] *Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China;*
[2] *Graduate University of Chinese Academy of Sciences, Beijing 100049, China;*
[3] *Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang 050021, China*

Received June 19, 2010; accepted November 5, 2010

Alpine meadow is the predominant ecosystem in Qinghai-Tibet Plateau. The firm turf of alpine meadow formed by sub-surface anfractuous roots can be effective in conserving water and soil. Alpine meadow is a primary contributor to the Chinese Water Tower. For quantitative assess anti-erosion ability of alpine meadow, this paper selected three typical meadow slopes with >60% vegetation coverage to evaluate soil erosion rates using ^{137}Cs. The results showed that (1) soil erosion intensity of typical alpine meadow was slight to light. Erosion rates were 464 t km^{-2} a^{-1} in Malong Village, 415 t km^{-2} a^{-1} in Yeniugou Town and 875 t km^{-2} a^{-1} in Zhenqin Town respectively; (2) soil erosion rates were correlated negatively with vegetation coverage, and the relationship was clearer at the slope scale than plot scale; (3) the relationship between soil erosion and vegetation coverage showed that vegetation coverage was a predominant factor in retaining soil and water on slopes. With complete turf and high vegetation coverage, alpine meadow was of great significance for soil conservation and prevention of soil erosion.

three Rivers headwater, soil erosion, alpine meadow, ^{137}Cs nuclide tracing

Citation: Shao Q Q, Xiao T, Liu J Y, et al. Soil erosion rates and characteristics of typical alpine meadow using ^{137}Cs technique in Qinghai-Tibet Plateau. Chinese Sci Bull, 2011, 56: 1708–1713, doi: 10.1007/s11434-011-4477-0

Cesium-137 (^{137}Cs) is a radioactive nuclide with a half-life of 30.17 a, which originated from atmospheric nuclear testing during the 20th century. ^{137}Cs, mainly settled to the ground with the rain, was absorbed strongly by soil particles and was hardly affected by absorption of vegetation and eluviation. The load of soil ^{137}Cs is associated only with radioactive decay and soil erosion [1–3]. ^{137}Cs is a good tracer of soil erosion, and a simple mathematical relationship can be established to calculate soil erosion or deposition rates by measuring the change and distribution of ^{137}Cs across vertical profiles and cross sections. Many researchers have made significant contributions using ^{137}Cs in different research areas since the 1970s. These included quantitative soil erosion research on the Loess Plateau [4], the spatial distribution of soil erosion and deposition and comparison of soil erosion intensity under different land uses [5,6], quantitative research on sloping farmland in important soil and water loss regions of the upper Yangtze River [7,8], characteristic of soil erosion and deposition in the black soil region [9], ^{137}Cs distribution in vertical profiles in the red soil region [10], and soil erosion research on different land use cover changes in the red soil hilly region [11]. Some nuclide tracer researches has been conducted on the Qinghai-Tibetan Plateau, but most were wind erosion studies focused on dunes, grasslands and other sandy landscapes[12–15]. Similar studies have been conducted on grassland transects across the Mongolian Plateau [16–18].

Water erosion research has not previously been addressed to any great extent in Dari County, Qinghai Province [19]. The hinterland of the Qinghai-Tibetan Plateau, which contains the headwaters of the Yangtze, Yellow and Lancang rivers, is the highest and largest plateau wetland

*Corresponding author (email: liujy@igsnrr.ac.cn)

ecosystem. Ecosystem types include rivers, lakes, marshes, jokuls and glaciers, what's more, the region also has one of the highest biodiversity hotspot in the world. Grassland is the main ecosystem in the region, covering 65.37% of total area [20]. Alpine meadow is the main grassland type accounting for 76% of total grassland. The firm turf formed by sub-surface anfractuous roots is effective in conserving water and soil, contributing to maintaining the "China Water Tower". Quantitative assessment soil erosion using ^{137}Cs in the typical alpine meadows is of great importance in revealing the mechanism of water and soil conservation in these areas.

1 Study area

Plots are located in Maduo County of the source region of the Yellow River, in Chengduo County of the source region of the Yangtze River, and in Yushu County of the source region of the Lancang River. Average altitude is >4200 m above sea level. Vegetation type is typical alpine meadow associated with meadow soils. Climate type is typical continental, with alternating cold and hot seasons, clear wet and dry seasons, long sunlight hours and intense radiation. The annual average temperature and precipitation are –3.76°C, 316 mm in Maduo, –4.66°C, 508 mm in Chengduo, and 3.29°C, 479 mm in Yushu, respectively.

2 Data and methods

2.1 Sample collection and analysis

Soil samples were collected in July 2008 (Figure 1 and Table 1). The double slope line method, which two parallel transects were laid downslope with 15 to 30 m intervals, was used, and on each transect 7 to 9 sample points were plotted. Considering the distribution of ^{137}Cs was shallow in grassland soil, generally less than 15 cm [14,16–18], the sampling depth of 24 cm was identified. A 90 mm diameter auger was used to collect. ^{137}Cs samples were excavated using a 18 cm × 25 cm container to 24 cm depth, and were collected in 2 to 6 cm increments (0–2, 2–4, 4–6, 6–8, 8–12, 12–18, and 18–24 cm) in the middle of the slope line. Bulk density samples were collected by ring shear, with five replicates from each slope. Vegetation composition, coverage, height and biomass were assessed by quadrat survey.

Soil samples were air-dried, ground, and sieved to 2 mm to remove plant residue and gravel. Samples, at least 250 g, were weighed and sent to the Laboratory of Radiation and Environment in China University of Geosciences to measure ^{137}Cs activity. ^{137}Cs activity was determined by calculating the whole peak area of γ radial at 662 keV, detected by Ametek gamma spectrometers (HPGe, Despec). The relative detection efficiency was 30%. The energy resolution was 1.67 keV for ^{60}Co 1.33 MeV. The lowest limit of detection was 0.77 Bq kg^{-1}. The accumulative measurement time was between 11033 s and 38100 s for each sample, and was greater than 15000 s for samples with activity above zero. The standard error during the test was ±5% (at 95% confidence).

2.2 Calculation of soil erosion using ^{137}Cs

The specific activity of ^{137}Cs (Bq kg^{-1}) was measured. This can be converted to areal activity (Bq m^{-2}) by multiplying

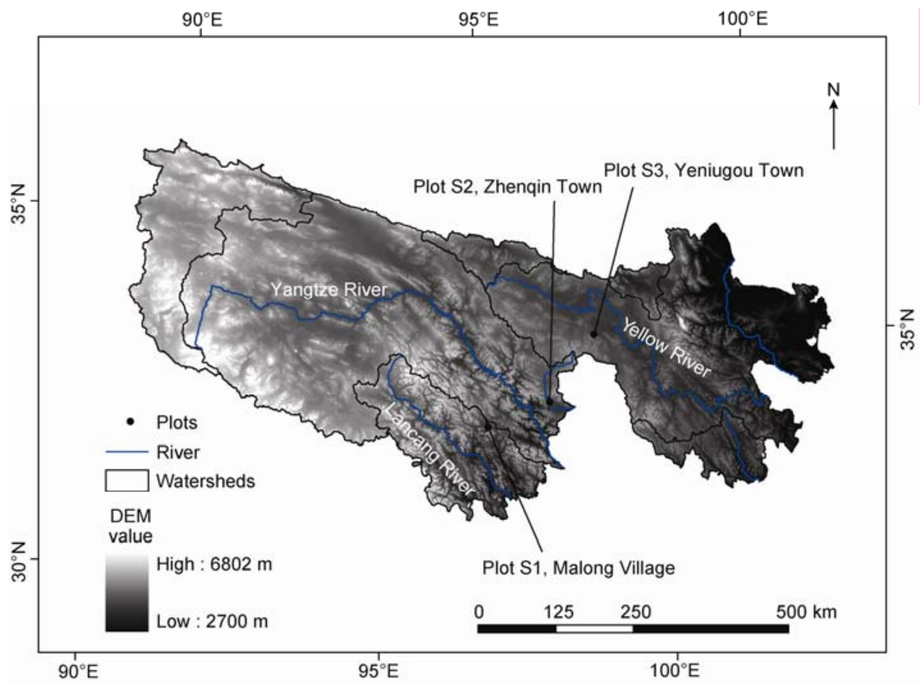

Figure 1 The terrain of study area and the locations of ^{137}Cs plots.

Table 1 Basic information on ^{137}Cs sampling plots

Symbols	Basin	Location	Altitude (m)	Soil types	Aspect/length of grade	Bulk density (g cm^{-3})	Vegetation cover (%)
S1	Lancang River	Yushu, Malong Village 32°58′25.3″N, 96°19′01.1″E	4384	alpine meadow soils	due south/ 800 m	0.95	83.88
S2	Yangtze River	Chengduo, Zhenqin Town 33°24′26.8″N, 97°20′25.4″E	4350	alpine meadow soils	due east/ 330 m	0.84	69.57
S3	Yellow River	Maduo, Yeniugou Town 34°27′51.98″N, 97°58′9.4″E	4430	alpine meadow soils	northwest/ 245 m	0.74	88.00

soil bulk density and plot depth. For each plot the areal activity of ^{137}Cs was the total activity from the soil surface to the depth, in which ^{137}Cs was not detected anymore. This can be calculated by [21]:

$$\mathrm{CPI} = 10^3 \sum_{i=1}^{n} C_i \cdot B_i \cdot D_i, \tag{1}$$

where CPI is a sample point's total ^{137}Cs (Bq m^{-2}), i is the sequence number of soil layer, n is the number of sample levels, C_i is the degree of ^{137}Cs activity in the i layer (Bq kg^{-1}), B_i is soil bulk density of the i layer (t m^{-3}), and D_i is the thickness of i layer.

Models, using ^{137}Cs activity to compute soil erosion, have been developed around the world, and the profile model was one classical model [22]. In this model, the distribution of ^{137}Cs in the soil profile was presumed to have an exponential distribution on undisturbed land, and a maximum ^{137}Cs deposition occurred in 1963.

Due to ^{137}Cs mobility, the classical model cannot describe exactly the distribution of ^{137}Cs profiles. Later, the ^{137}Cs distribution cannot be simulated by the profile model because of diffusion after the rainfall of ^{137}Cs. Based on the former work of Walling and He [23], Zhang et al. [24] developed an erosion appraisal model according to ^{137}Cs transmission diffusion process, further improved the precision of calculating erosion rates. This soil erosion model was:

$$K = 1 - \mathrm{e}^{-h_0 NH}, \tag{2}$$

where K, which can be calculated by $K = \frac{A_{\mathrm{rm}(T)} - A_{\mathrm{ref}(T)}}{A_{\mathrm{ref}(T)}} \times 100\%$, was the relative loss of ^{137}Cs in the soil profile, $A_{\mathrm{ref}(T)}$ was the inventory content of ^{137}Cs (mBq cm^{-2}), $A_{\mathrm{rm}(T)}$ was the profile content of ^{137}Cs in the sampled year (mBq cm^{-2}), H was the annual soil erosion depth (cm) since 1963, h_0 was the shape parameter of the ^{137}Cs profile, and N was the soil layers eroded since 1963.

2.3 ^{137}Cs inventory

The ^{137}Cs inventory, referring to the total ^{137}Cs in an uneroded soil profile since nuclide deposition [25], is an important basis for soil erosion calculation. Inventory samples were collected in three plots of typical alpine meadow, with flat terrain, no erosion and deposition. These plots had compact roots and high vegetation coverage from 90% to 100%. Each inventory sample consisted of one layered sample and four gross samples, and was collected using the same sampling methods as the slope samples.

The profile distributions of inventory ^{137}Cs presented exponential curves caused by diffusion processes [24,26]. The highest inventory ^{137}Cs activity was higher than the activity of slope samples (Figure 2).

To test the reliability of the inventory ^{137}Cs, we compared our results with the simulated inventory modeled by Walling and He [23]. The ^{137}Cs inventory in this study showed no big differences with results obtained by Yanping [12,13] and Zhang [14,15] on Gonghe Basin (Table 2), and was less than the inventory measured by Li [19] Dari County. The ^{137}Cs deposition model of Walling and He underestimated actual values because of the model assumptions [27]. Comparing measured values with the simulated data, measured inventory values were higher in Dari County [19], but our measured inventory values are similar to those in the other three sites.

3 Results and discussion

3.1 Soil erosion characteristics of typical alpine meadows in Qinghai-Tibet Plateau

The slope S1 was located in Malong village, where the soil type was alpine meadow soil. In this place, roots were distributed primarily at 0 to 15 cm depth, particularly at 0 to 10 cm. Soil depth ranged from 18 to 30 cm, and underlain by abundant clastic gravel slope wash. Vegetation coverage reached 84% and had a height of 2–5 cm. Vegetation types were mainly alpine meadow species such as *Kobresia humills*, *Kobresia humilis Serg.*, *Polygonum viviparum Linn.* and associated with *Saussurea pulchra Lipsch.*, *Gentiana straminea Maxim.*, *Potentilla nivea Linn.*, and *Scirpus distigmaticus (Kukenth.) Tang et Wang*.

Erosion rates on different parts of slopes differed (Table 3). On upper slopes where gradient was 10° (S1-01–S1-03), the farther away from the top of the slope, the erosion rate was higher. Almost no erosion occurred in the uppermost S1-01. Vegetation coverage in S1-03 was the lowest at 75%, and the largest erosion rate was 945 t km^{-2} a^{-1}. The mid-slope gradient was 5° (S1-04–S1-06). No significant differences in erosion intensity were observed, although erosion

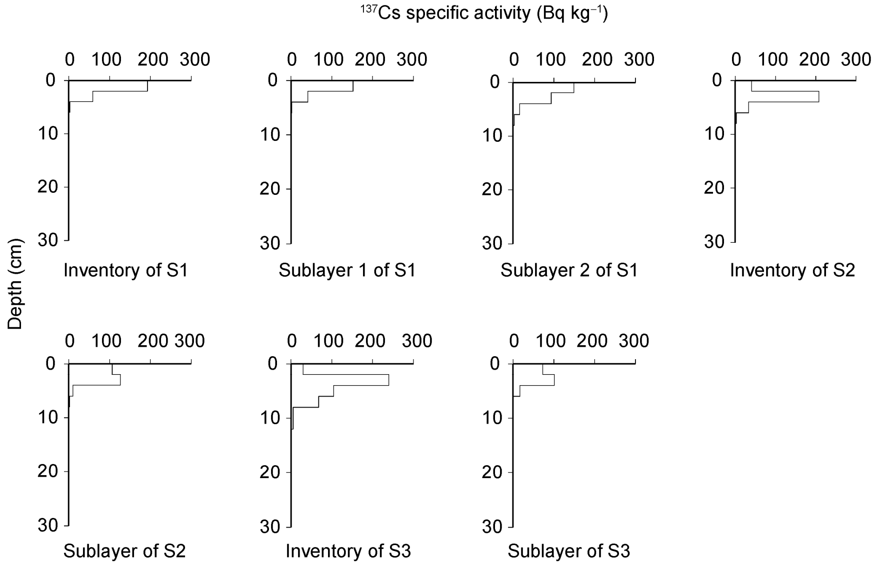

Figure 2 Profile distribution of ^{137}Cs on alpine meadow of Qinghai-Tibet Plateau.

Table 2 Comparison between measured and simulated inventory of ^{137}Cs in typical alpine meadows of Qinghai-Tibet Plateau*

Plots	Precipitation (mm)	Measured inventory (Bq m^{-2})	Simulated inventory (Bq m^{-2})	Source
S1	479	2130	1096	this work
S2	508	1969	1121	this work
S3	316	2538	938	this work
S4**	399	2139	1024	[12]
S5**	265	1888	879	[13]
S6**	370	1929	994	[14,15]
S7**	545	3462	1151	[19]

* Background values have been revised to 2008; ** S4, S5, S6, S7 are symbols of plots name from literature.

intensity increased slightly with distance from the top of the slope. The erosion rate ranged between 471 t km^{-2} a^{-1} and 651 t km^{-2} a^{-1}, lower than S1-03 because of lower gradient. The erosion rates of S1-07–S1-09 were slightly lower than the upper slope, and ranged between 491 t km^{-2} a^{-1} and 533 t km^{-2} a^{-1}. The average erosion rate of the whole slope was 464 t km^{-2} a^{-1}.

Turf on the Zhenqin slope was firm, relatively intact with a thick soil layer. Roots were distributed primarily between 0 to 15 cm. Average vegetation coverage was 70% and vegetation height was 1.5 to 2.5 cm. Vegetation was composed mainly of *Kobresia humills*, *Stipa purpurea Griseb.*, *Leontopodium nanum (Hook. f. et Thoms.) Hand.-Mazz.*, and associated with *Saussurea pulchra Lipsch.* and *Potentilla nivea Linn*.

The erosion intensity of Zhenqin ranged between 518 t km^{-2} a^{-1} and 1536 t km^{-2} a^{-1} (Table 3), and the average value was 875 t km^{-2} a^{-1}. The erosion rate at S2-03 with minimum vegetation coverage was the largest, up to 1536 t km^{-2} a^{-1}. The erosion intensities of the three plots with vegetation coverage more than 70% (S2-01, S2-05, and S2-06) had no obvious differences, with an average erosion intensity of 832 t km^{-2} a^{-1}. The average erosion intensity of two plots with vegetation coverage lower than 70% (S2-03 and S2-07) was 1174 t km^{-2} a^{-1}. The average erosion rate of slopes >5° (S2-02, S2-03, S2-04, and S2-05) was 890 t km^{-2} a^{-1}, and that of those <5° (S2-01, S2-06, S2-07) was 857 t km^{-2} a^{-1}.

The Yeniugou slope had intact turf, and the alpine meadow soil was 15 to 20 cm in thickness with a rich root system. Average vegetation coverage was 88%. Plants were 2 to 3 cm tall and composed mainly of *Kobresia humills*, *Kobresia humilis Serg.*, *Kobresia capillifolia (Decne.) C. B. Clarke*, and associated with *Saussurea pulchra Lipsch.*, *Potentilla fruticosa Linn.*, *Aster flaccidus Bge.*, *Pedicularis kansuensis Maxim.* and *Potentilla nivea Linn*.

A sediment accumulation zone occurred at the concave of mid-slope plot S3-04, with an accumulation rate reaching 729 t km^{-2} a^{-1}. The average erosion rate including S3-04, was 415 t km^{-2} a^{-1}, and was 606 t km^{-2} a^{-1} excluding S3-04. The former represented net soil loss intensity across the whole slope while the latter showed the influence of erosion on the Yeniugou slope. Excluding the accumulation plot, average erosion intensity of sites with vegetation coverage 90% (S3-01 and S3-02) was 368 t km^{-2} a^{-1}. In the sites where vegetation coverage was between 80%–90%, (S3-03, S3-06, S3-07) the erosion intensity was 429 t km^{-2} a^{-1}. The plot S3-05 with minimum vegetation coverage of 75% had the highest erosion intensity of 1614 t km^{-2} a^{-1}.

3.2 Relationships between soil erosion and vegetation coverage on typical alpine meadow slopes

Differences in soil erosion intensity (Tables 1 and 4) can be interpreted by comparing the three study sites. Yeniugou, with the lowest precipitation and maximum vegetation coverage, had the lowest average erosion rate caused by the

Table 3 Soil erosion characteristics using ^{137}Cs technique in Qinghai-Tibet Plateau

Plots No.	The distance from top of slope (m)	Slope (°)	Vegetation cover (%)	^{137}Cs area activity (Bq m^{-2})	Erosion rate (t km^{-2} a^{-1})
S1-01	80	10	similar to S1-02*	2372.20±138.19	4
S1-02	180	10	85	2206.75±108.50	79
S1-03	280	10	75	1541.38±133.71	945
S1-04	380	5	90	1786.38±121.88	471
S1-05	480	5	85	1786.36±111.60	503
S1-06	580	5	85	1676.40±111.87	651
S1-07	680	5	80	1832.19±130.81	499
S1-08	780	3	85	1772.71±99.65	491
S1-09	830	3	similar to S1-08*	1953.29±135.25	533
S2-01	30	5	70	1477.85±125.69	836
S2-02	80	10	similar to S2-01*	1487.13±104.09	769
S2-03	130	8	62	1169.38±125.21	1536
S2-04	180	8	similar to S2-05*	1631.07±112.56	518
S2-05	230	8	70	1505.53±113.64	735
S2-06	280	5	75	1405.06±132.87	924
S2-07	330	3.5	65	1574.03±132.24	811
S3-01	20	10	similar to S3-02*	2417.30±144.52	374
S3-02	55	16	98	2449.78±149.62	362
S3-03	90	16	85	2431.94±201.80	327
S3-04	125	18	95	2814.22±159.41	–729
S3-05	160	12	similar to S3-06*	2057.84±146.67	1614
S3-06	195	6	80	2256.01±140.45	897
S3-07	245	2	85	2516.87±144.72	62

* No measured values.

concave terrain. Malong, with minimum gradient and medium vegetation coverage, the erosion rate was moderate. Zhenqin had the highest soil erosion rate which was caused by maximum precipitation and minimum vegetation coverage. Based on these analyses, it is concluded that precipitation, vegetation coverage and terrain had appreciable impact on soil erosion. On the slope scale, there was a negative correlation between soil erosion rate and vegetation coverage (Table 4). The higher the vegetation coverage, the smaller the average erosion rate (R^2 = 0.9863 where P<0.01).

We conducted correlation analysis among erosion rates, gradient and vegetation coverage. No specific correlation between soil erosion rates and gradient (excluding one accumulation point) existed at the plot scale. However, there was an obvious negative correlation between soil erosion rates and vegetation coverage (R^2 = 0.555 where P<0.01; Figure 3). This indicated that vegetation coverage had the most obvious impact on alpine meadow erosion intensity of all the factors influencing soil erosion. This can be explained by the characteristics of alpine meadow, in which aboveground biomass was relatively small but underground biomass was large. The high density of tough roots distributed in the sub-surface played an important role in preventing intensive soil erosion. Vegetation coverage determined growth status and in turn tightness of the root system, and high vegetation coverage tended to prevent erosion.

Table 4 Soil erosion modulus of typical alpine meadow in Qinghai-Tibet Plateau

Transect location	Erosion rate (t km^{-2} a^{-1})	Average gradient (°)	Average vegetation coverage (%)	Precipitation (mm)
S1	464	6.2	83.88	479
S2	875	6.8	69.57	508
S3	415	11.4	88.00	316

4 Conclusions

Based on the former discussion and analysis, we concluded that:

(1) The three typical alpine meadow slopes studied in this paper had intact turf and high vegetation coverage. The lowest measured soil erosion rates on the three slopes were 464 t km^{-2} a^{-1}, 875 t km^{-2} a^{-1} and 415 t km^{-2} a^{-1} in Malong Village, Yeniugou Town and Zhenqin Town, respectively. According to the current soil erosion classification [28], Malong and Yeniugou slopes were classified as experiencing a micro-degree of erosion, and Zhenqin had slight erosion.

(2) Soil types of the three slopes were similar. Differences in soil erosion rate were influenced mostly by vegetation coverage at the slope scale. The higher the vegetation coverage, the smaller the average erosion rate. Soil erosion rates had no obvious correlation with gradient at the plot scale but they had a negative correlation with vegetation coverage.

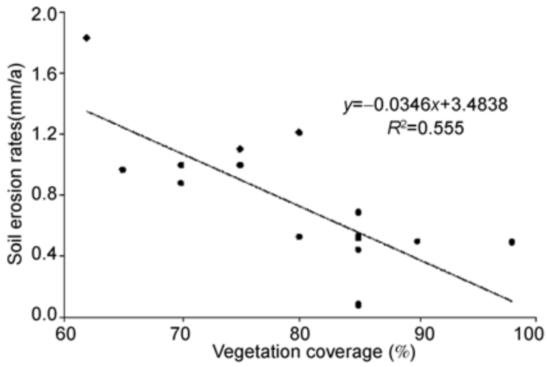

Figure 3 Relationship between soil erosion rates and vegetation coverage of typical alpine meadow in Qinghai-Tibet Plateau

(3) The three slopes are all alpine meadow, the most typical and widely distributed ecological system type in the headwaters of the Three Rivers. They are also the main provider of ecosystem services. The conservation of alpine meadow is important for sustainability of ecosystem in the Chinese Water Tower. Our results showed correlation between soil erosion and vegetation coverage demonstrates that native alpine meadow with intact turf and high vegetation coverage had an important ecological function in conserving soil and water. The prevention of alpine meadow ecosystem degradeation in this area is therefore of utmost importance method.

Professor Li Yingnian and his student Wang Jianlei at the Northwest Institute of Plateau Biology, Chinese Academy Sciences provided help during the field investigation and sampling. Associate Professor Zhong Huaping, Dr. Huanglin, doctoral candidates Zhao Zhiping and Bing Longfei of the Institute of Geographic Sciences and Natural Resources Research, CAS and Wang Deshan of the Youth Tourism Agency of Qinghai, all offered valuable suggestions. The authors also thank Professor Wang Nanping at the China University of Geosciences for her instruction and help in sample treatment and analysis. This work was supported by the National Basic Research Program of China (*2009CB421105*)*, Western Act Plan of the Chinese Academy of Sciences, and the National Technology Support Project* (*2006BAC08B00*)*.*

1 Tamura T, Jacobs D G. Structural implications in cesium sorption. Health Phys, 1960, 6: 391–398
2 Rogowshi A S, Tamura T. Movement of ^{137}Cs by runoff, erosion and infiltration on the alluvial captina silt loam. Health Phys, 1965, 11: 1333–3340
3 Owens P N, Walling D E, He Q P. The behaviour of bomb-derived caesium-137 fallout in catchment soils. J Environ Radioactiv, 1996, 32: 169–191
4 Zhang X B, Li S L, Wang C H. The ^{137}Cs research of the source of soil and sands in small basin of loess plateau. Chinese Sci Bull, 1989, 34: 210–213
5 Yang M Y, Tian J L, Liu P L, et al. The soil erosion and distribution characteristic of sediment space in small basin using ^{137}Cs tracing method. Adv Nature Sci, 2001, 11: 71–75
6 Li R Y, Yang H, Zhao X G, et al. Application of ^{137}Cs technique to study of soil erosion on loess plateau region. Soils, 2004, 36: 96–98
7 Wen A B, Zhang X B, Wang Y K, et al. Study on soil erosion rates using ^{137}Cs technique in upper Yangtze river. J Soil Water Conserv, 2002, 16: 1–3
8 Wang Y K, Wen A B, Zhang X B. Study of soil erosion on cultivated slope land in severe soil loss regions of upper reaches of Yangtze River Basin using ^{137}Cs technique. J Soil Water Conserv, 2003, 17: 77–80
9 Fang H J, Yang X M, Zhang X P, et al. Study on soil erosion and deposition of black soils on a sloping cultivated land using ^{137}Cs tracer method. Acta Ecol Sin, 2005, 25: 1376–1382
10 Zhuang S Y, Wu C Y, Yang H. Distribution characteristics of ^{137}Cs in erosion sediment in red soil region. J Soil Water Conserv, 2002, 16: 65–67
11 Pu L J, Zhao Y Y, Jin P H, et al. Application of ^{137}Cs as tracing method to study soil erosion on sloping lands in the hilly red soil area— A case study in Fengcheng City, Jiangxi Province. Resour Environ Yangtze Basin, 2004, 13: 562–567
12 Yan P, Dong G R, Zhang X B, et al. Application of Caesim-137 technique on wind erosion in Gonghe basin, Qinghai Province (II)– ^{137}Cs reference inventory and ^{137}Cs model for wind erosion estimation. J Desert Res, 2003, 23: 391–397
13 Yan P, Dong G R, Zhang X B, et al. Preliminary results of the study on wind erosion in the Qinghai-Tibetan Plateau using ^{137}Cs technique. Chinese Sci Bull, 2000, 45: 1019–1024
14 Zhang C L, Zou X Y, Dong G R, et al. Characteristics of ^{137}Cs deposition in steppe area. Chinese Sci Bull, 2002, 47: 848–853
15 Zhang C L, Gong J R, Zou X Y, et al. Estimates of soil movement in a study area in Gonghe Basin, northeast of Qinghai-Tibet Plateau. J Arid Environ, 2003, 53: 285–295
16 Hu Y F, Liu J Y, Zhuang D F, et al. Distribution characteristics of ^{137}Cs in wind-eroded soil profile and its use in estimating wind erosion modulus. Chinese Sci Bull, 2005, 50: 1155–1159
17 Liu J Y, Qi Y Q, Shi H D, et al. Estimation of wind erosion rates by using ^{137}Cs tracing technique: A case study in Tariat-Xilin Gol transect, Mongolian Plateau. Chinese Sci Bull, 2008, 53: 751–758
18 Qi Y Q, Liu J Y, Shi H D, et al. Using ^{137}Cs tracing technique to estimate wind erosion rates in the typical steppe region, northern Mongolian Plateau. Chinese Sci Bull, 2008, 53: 1423–1430
19 Li Y S, Wang G X, Wang J D, et al. ^{137}Cs trace technique to study soil erosion at alpine meadow of Tibetan Plateau. J Mt Sci-engl, 2007, 25: 114–121
20 Xu X L, Liu J Y, Shao Q Q, et al. The dynamic changes of ecosystem spatial pattern and structure in the three river headwaters region in Qinghai Province during recent 30 years. Geogr Res, 2008, 27: 829–828
21 Walling D E, Quine T A. Use of Caesium-137 as a Tracer of Erosion and Sedimentation: Handbook for the Application of the Caesium-137 Technique (U. K. Overseas Development Administration Research Scheme R4579). Department of Geography, University of Exeter, Exeter, 1993. 15–34
22 Zhang X B, Li S L, Wang C H, et al. A study of sediment delivery from a small catchment in the loess plateau by the ^{137}Cs method. Chinese Sci Bull, 1990, 35: 37–42
23 Walling D E, He Q. Improved models for estimating soil erosion rates from cesium-137 measurements. J Environ Qual, 1999, 28: 611–622
24 Zhang X B, Long Y, He X B, et al. A simplified ^{137}Cs transport model for estimating erosion rates in undisturbed soil. J Environ Radioactiv, 2008, 99: 1242–1246
25 Zapata F. Handbook for the assessment of soil erosion and sedimentation using environmental radio nuclides. Dordrecht/Boston/London: Kluwer Academic Publishers, 2002. 219
26 Fu J X, Zhang X B, Qi Y Q, et al. Penetration process model for ^{137}Cs depth distribution in uncultivated soil without erosion. Nucl Tech, 2006, 29: 189–193
27 Qi Y Q, Zhang X B, He X B, et al.^{137}Cs reference inventories distribution pattern in China. Nucl Tech, 2006, 29: 42–50
28 Ministry of Water Resources of the People's Republic of China. SL190-96. Standards of Classification for Soil Erosion. Beijing: China Water Power Press, 1997