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Using ^{137}Cs technique to investigate the spatial distribution of erosion and deposition regimes for a small catchment in the black soil region, Northeast China

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ABSTRACT

Researches on the spatial distribution of erosion and deposition regimes are important to understand soil erosion mechanism and effectively implement soil and water conservation measures within watersheds. However, traditional monitoring techniques provide limited information for that at the catchment scale. Based on the ^{137}Cs tracer and GIS technology, this study clarified the spatial distribution of erosion and deposition regimes within a small catchment (Dongshan catchment), which has typical representativeness in the black soil region of Northeast China. The local ^{137}Cs reference inventory was 2378.4 Bq m^{-2}, and the summit of convex slope was preferably taken as the reference site when undisturbed sites were inexistence in the study area. Estimates of soil redistribution rates derived from ^{137}Cs measurement ranged from −35.89 to 53.63 t ha^{-1} yr^{-1}, with about 95.65% of the net soil loss coming from the slope surface. The average soil erosion intensity within the catchment was 4.54 t ha^{-1} yr^{-1} and it was 1.51 t ha^{-1} yr^{-1} in the gully area, but both were above the tolerance erosion rate in the black soil region of Northeast China. Further, gully head made the leading contribution to the gully erosion. When the geographical location shifted from the upstream to the middle-stream then to the down-stream of the catchment, the mainly erosion regimes changed from detachment-dominant to coexisting detachment and deposition dominant, and then deposition-dominant regime. Along the slope length, erosion rate increased from the summit to the shoulder and back slopes, and then decreased at the foot-slope, while at the toe of slope deposition occurred. However, erosion pattern along the slope was affected by the slope shape. For the convex slope, the most severe erosion location was the back of slope, while for the concave slope it was the shoulder of slope; erosion rate of the summit and foot slope for the convex slope was 0.5 and 1.97 times that of the concave slope.

1. Introduction

The vast black soil region of Northeast China is an important base for Chinese crop production (Xu et al., 2010), which provides one third to two fifth commodity grain for the native market. However, soil erosion becomes increasingly serious in this region. Approximately 38% of the land area is affected by soil erosion (Fang et al., 2006). The average soil thickness of the A horizon has decreased from 60–70 cm during its original cultivation period to 20–30 cm today, and the entire A horizon has been completely eroded away in some areas (Wang et al., 2009). This greatly reduces soil productivity and has threatened the security of Chinese food. Therefore, conservational measures are urgently needed to control soil erosion in order to maintain crop productivity in this region, while a better understanding of the spatial distribution of erosion and deposition regimes would be effective to design soil and water conservation measures and evaluate benefits of current catchment managements.

Classical erosion techniques such as erosion plots, surveying methods for monitoring soil erosion, and erosion models are effective to assess soil loss. However, these techniques possess a number of obvious limitations in perspective of time-consuming, the representativeness of obtained data, and the potential to provide long-term and spatial information of erosion rates. The ^{137}Cs technique overcomes these limitations, and using this method, only based on a single site visit, the spatial pattern of erosion and deposition rates can be evaluated and analyzed. Therefore, the successful application of the ^{137}Cs method to document rates of soil loss and sediment redistribution has been reported for a wide range of environments, such as humid continental region, Loess Plateau of China, and reservoir (McIntyre et al., 1987; Walling and Quine, 1990; Kachanoski, 1993; Basher et al., 1995; Garcia-Oliva et al., 1995; Pennock et al., 1995; Di Stefano et al., 1999;

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Bujana et al., 2003; Navas et al., 2005; Mabit and Bernard, 2007; Li et al., 2007, 2011; Schuller et al., 2007; Konz et al., 2009; Porto and Walling, 2012; Porto et al., 2012, 2014). However, previous general understanding of soil erosion redistribution in those environments cannot be applied to the black soil region of Northeast China due to its unique erosion environment (special topography and geomorphology characteristic).

In the black soil region of Northeast China, the slope length averagely ranges from 1000 m to 2000 m (Cui et al., 2007), and the slope gradient is mostly 1°–7°. Along the slope length, erosion and deposition dominant zones alternately occur with the position of slope, and the distribution pattern is very sensitive to slope shape (Fan et.al., 2004). This meant that slope shape was an important factor affecting soil erosion distribution pattern. However, the previous studies about soil erosion mechanism in this region mainly focused on the description of erosion intensity (Yan and Tang, 2005; Yang et al., 2003), and methods were limited to small-scale field monitoring and modeling (Wang et al., 2013; Wu et al., 2008). To date, only the two studies discussed the spatial distribution of erosion regimes for this region at a slope scale using the ^{137}Cs technology (Fang et al., 2006; Wang et al., 2010). Therefore, it urgently needs to quantify the spatial distribution of erosion and deposition regimes at a catchment scale.

The special erosion environment in the black soil region of Northeast China would induce the unique pattern of erosion redistribution. Therefore, a sample study was needed to explore the rates and patterns of soil redistribution within a typical small catchment located in this region. Based on the ^{137}Cs tracer and GIS technology, the field study and laboratory experiment were conducted to: 1) determine the ^{137}Cs reference inventory; 2) discuss the spatial distribution of erosion and deposition regimes both at the catchment and slope scale; and 3) analyze characteristic of the gully erosion in the catchment. The findings of this study will improve understanding of erosion and deposition regimes, and provide a scientific basis to implement effective soil and water conservation measures in this increasingly serious erosion region.

2. Materials and methods

2.1. The study area

Based on field investigation and positioning test according to 1:10,000 topographic map as well as soil type map, the Dongshan catchment (127°31′04″–127°34′02″E, 45°43′13″–45°46′37″N) with 2.34 km^2 in Hei Longjiang Province was selected as the study area, which was the typically serious soil erosion area in the Northeast China (Fig. 1). Rollied

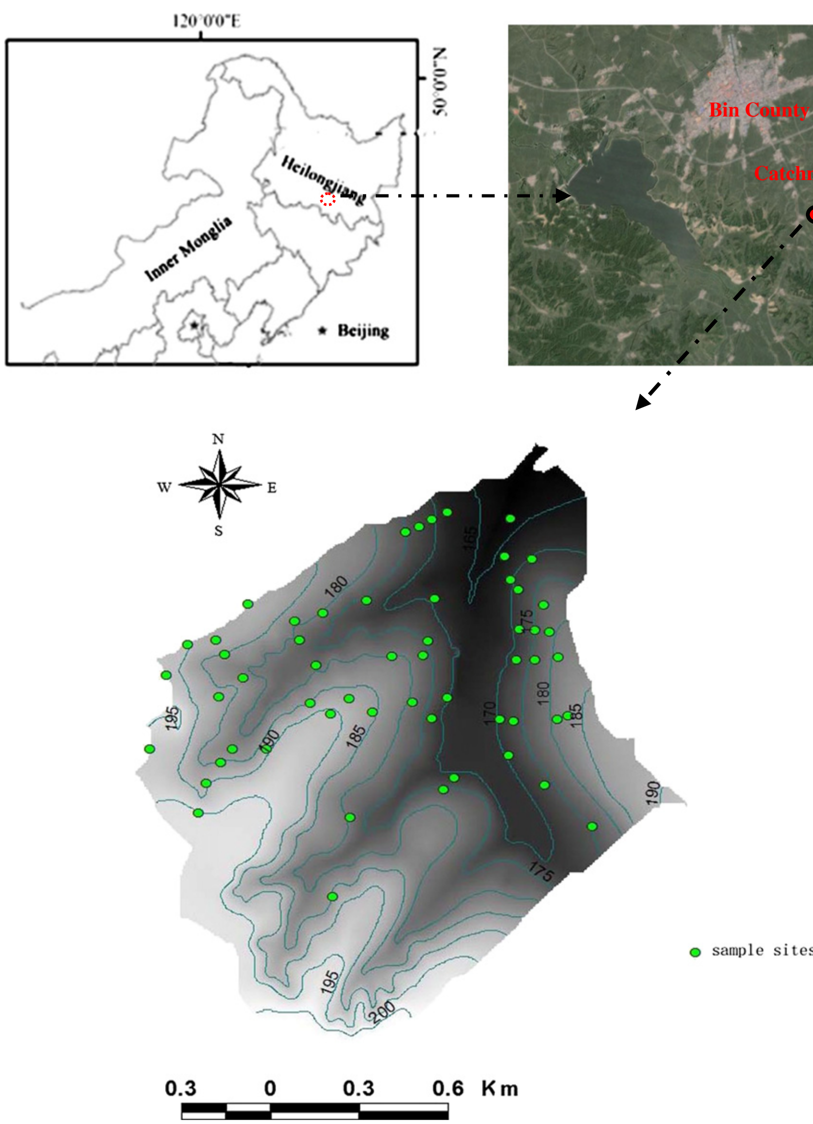

Fig. 1. The location of the study area.

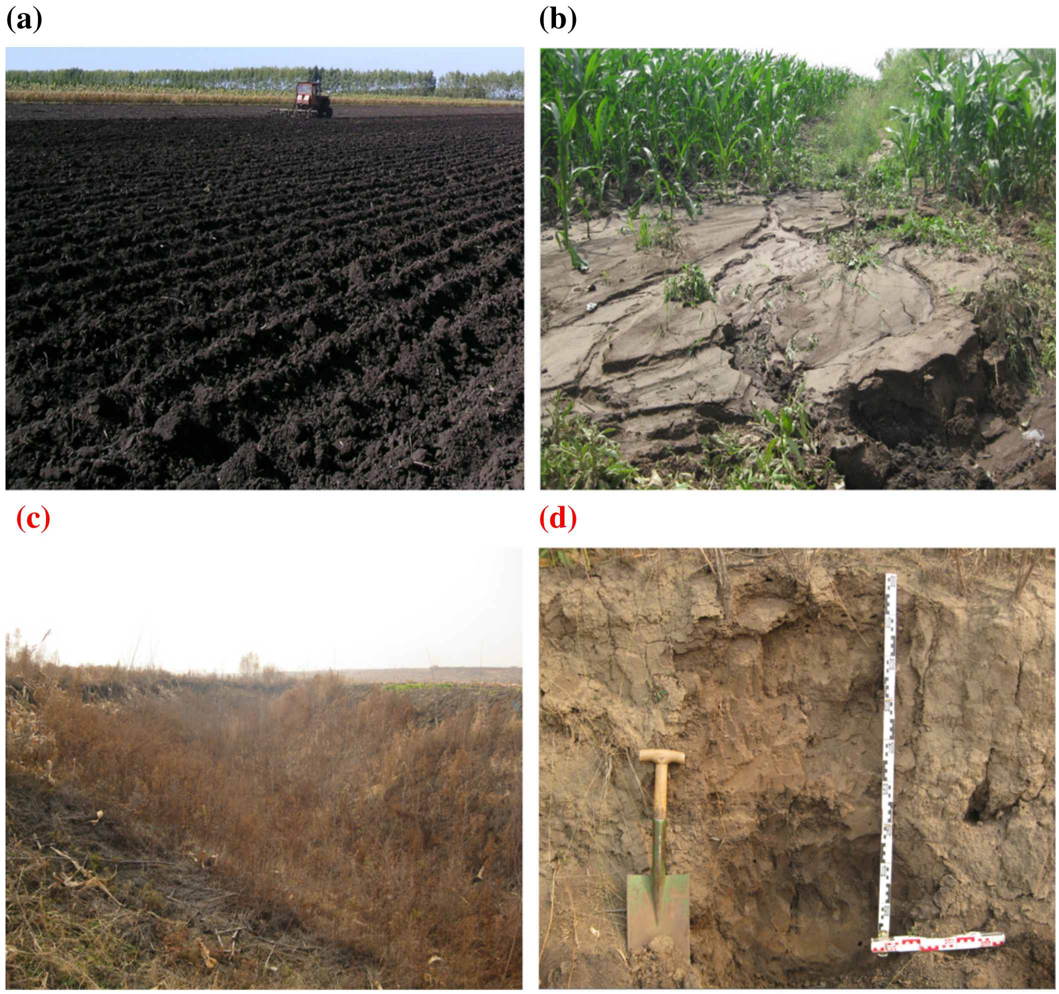

Fig. 2. A landscape of the study area (a: the view of the study area; b: erosion occurrence at the Maize land; c: the gully in the study area; d: depositional-prone area).

hilly is the main geomorphological characteristic. Slope gradient concentrates in 1°–7° with a few areas up to 10°. Slope length reaches hundreds of meters, the longest can reach thousands of meters (Fig. 2). The region is a semi-arid temperate zone with a continental monsoon climate, with the mean annual temperature of 3.9 °C. The minimum temperature is −29 °C in winter, and the depth of frozen soil even reaches 2.4 m. The mean annual precipitation is 548.5 mm, with 78.7% of the annual precipitation falling during the flood season from June to September. The black soil, classified as a Mollisol (USDA Taxonomy), is the main soil type in this region, occupying above 66.7% of the total area. The soil organic horizon mainly changes from 10 to 50 cm, and soil organic content is 1%–7%. About 90% soil was the cultivated land, among corn (maize) is the major crop grown.

2.2. Soil sampling

The field campaigns involved three sampling programs. Firstly, eight samples were collected to determine the local ^{137}Cs reference inventory from sites with the land use of graveyards or being wilderness nearby the study area. Secondly, at two typical sloping croplands, samples were collected from five representative slope locations, namely summit, shoulder-slope, back-slope, foot-slope, and toe-slope. In this sampling type, soil profiles were sampled into 5 cm increments to a depth of 50 cm. The totally obtained 100 samples were selected to determine the vertical distribution of ^{137}Cs content and soil bulk density. Thirdly, samples were collected along downslope transects, and some sampling points were selected on the main gully bed to be representative of this landform. Cores were collected to a depth of 30 cm using a soil auger (4 cm in inner diameter) in the whole catchment, and lastly 56 samples were taken to analyze the spatial distribution of ^{137}Cs concentration. For each sampling site of the third type, three soil samples were collected and mixed to produce a bulk sample for ^{137}Cs content analysis. Meanwhile, geographical coordinates of sampling locations were recorded using a Magellan GPS tracker, and slope gradient was measured.

2.3. ^{137}Cs content analysis

All of three type's samples were air-dried, weighed, crushed, and passed through a 2 mm mesh screen. A 400-g sub-sample of the <2 mm fraction of each sample was used to measure ^{137}Cs activity by low background gamma spectrometry, using a hyperpure coaxial germanium detector linked to a multi-channel digital analyzer system (EG&G, ORTEC) in the nuclear physics laboratory in the Institute of Soil and Water Conservation, Northwest A&F University, China. ^{137}Cs content was detected at peak resolutions (FWHM) of around 1.5 keV at 662 keV, with counting time over 80,000 s, which provided an analytical precision of ±5% for ^{137}Cs at the 95% confidence level. The originally measured ^{137}Cs content was calculated on a unit mass basis (Bq kg^{-1}), and was converted to an inventory value (Bq m^{-2}) using the sampling area and the weight of the bulked soil sample.

2.4. Estimation of erosion and deposition rates

One of the key problems using the ^{137}Cs technology was to establish the relationship between ^{137}Cs loss/gains or percentage residuals for each sampling site and the rate of soil redistribution. Mass balance models have been frequently used to establish calibration relationships. In this study, the Mass Balance Model 2 (MBM2) (Walling and He, 1999; Walling et al., 2002) was employed to convert ^{137}Cs activities into soil redistribution rates (t ha^{-1} yr^{-1}). In this model, if the total ^{137}Cs content of sampling site was less than the local reference inventory, the sampling site was regarded as the eroded site; contrarily, it was the depositional site.

For an eroded site, erosion rate can be calculated from the following equation:

$$\frac{dA(t)}{dt} = (1-\Gamma)I(t) - \left(\lambda + P\frac{R}{d}\right)A(t) \tag{1}$$

where R is the erosion rate (kg m^{-2} yr^{-1}); $A(t)$ is the cumulative ^{137}Cs activity per unit area (Bq m^{-2}); d is the cumulative mass depth representing the average plow depth (kg m^{-2}); λ is the decay constant for ^{137}Cs (yr^{-1}); $I(t)$ is the annual ^{137}Cs deposition flux (Bq m^{-2} yr^{-1}); Γ is the percentage of the freshly deposited ^{137}Cs fallout removed by erosion before being mixed into the plow layer; and P is the particle size correction factor.

For a depositional site, deposition rate can be expressed as:

$$R' = \frac{A_{ex}}{\int_{t_0}^{t} C_d(t')e^{-\lambda(t-t')}dt'} \tag{2}$$

where R' is the deposition rate (kg m^{-2} yr^{-1}); $C_d(t')$ is the ^{137}Cs concentration of deposited sediment (Bq kg^{-1}); A_{ex} is the excess ^{137}Cs inventory A_{ex} (Bq m^{-2}) (defined as the measured total inventory $A(t)$ less the local direct fallout input A_{ref}).

3. Results and discussions

3.1. Determining the ^{137}Cs reference inventory for the study area

The ^{137}Cs content values measured in the eight cores collected from undisturbed, uncultivated, and uneroded sites nearby the catchment averaged 2378.4 Bq m^{-2}, with a maximum value of 2769.65 Bq m^{-2}, a minimum value of 2149.93 Bq m^{-2}, and a standard deviation of 198.08 Bq m^{-2} (Table 1). The variance for ^{137}Cs reference inventory reached 8.3%. This was related to microscale variability, because ^{137}Cs content had a strong relationship with physico-chemical parameters of soil (McHenry and Jerry, 1977; Owens and Walling, 1996; Quang et al., 2004; Ritchie and McCarty, 2003), while soil physical and chemical characteristics even changed at the same catchment. Therefore, the small variation of ^{137}Cs reference value was reasonable.

To test the reliability of the observed ^{137}Cs reference value, we compared the value obtained from our measurements with that predicted by the model proposed by Walling and He (2001). In addition, results form previous studies carried out in the black soil region of Northeast China were also considered. It was found that the observed average value was very close to the calculated result of 2109 Bq m^{-2} according to the model of estimating bomb-derived ^{137}Cs reference inventories (Walling and He, 2001). In previous studies, the measured ^{137}Cs reference inventory was 2232.8 Bq m^{-2} at the area (44°43′N, 125°52′E) of 5 km southwest of Song Huajiang Town in Jilin Province (Fang et al., 2006) and 2506 Bq m^{-2} for Heshan Farm (48°56′N, 125°11′E) of Heilongjiang Province (Fang et al., 2012). Our study area of Dongshan catchment was in the middle of the above mentioned sites (Song Huajiang Town and Heshan Farm). In the Northern Hemisphere, the global ^{137}Cs fallout deposition increases with the increase of latitude (Qi et al., 2006). Therefore, the measured value of 2378.4 Bq m^{-2} determined as the local ^{137}Cs reference inventory was much scientific and reasonable.

3.2. The vertical distribution of ^{137}Cs concentration in the soil profiles

To better describe the distribution of ^{137}Cs content with soil depth, we chose two typical profile cores (eroded and deposition sites). Core A was an eroded location, because the total ^{137}Cs inventory of 1008.29 Bq m^{-2} in this core was substantially lower than the local reference inventory (Fig. 3). In this erosion site, the distribution depth of ^{137}Cs concentration extended 30 cm. Among, , ^{137}Cs content within 0-20 cm layer occupied 73.96% of the total content, and during this layer ^{137}Cs concentration varied from 128.39 to 189.45 Bq m^{-2}, with the coefficient of variation of 4.0%. This indicated that ^{137}Cs concentrations were relatively uniform within the top 20 cm. Furthermore, soil bulk density reached the greatest value of 1.43 g cm^{-3} at the depth of 20 cm, and it gradually decreased with the increase of soil depth when soil depth was above 20 cm. This illustrated that the plow depth was about 20 cm in this region, and ^{137}Cs concentrations distributed uniformly in the plow depth. This was consistent with previous findings (Fang et al., 2006; Yang et al., 2006). Therefore, 20 cm was regarded as the parameter of plow depth in the MBM 2 model in this study.

Core B was collected from the toe-slope of hillslope. In this core, the total ^{137}Cs inventory of 2468.91 Bq m^{-2} was substantially greater than the local reference inventory, indicating that the deposition of sediment containing ^{137}Cs which was eroded from upslope occurred at this location. The occurrence of deposition at this site is further confirmed by ^{137}Cs content distribution depth. The depth reached 35 cm, extending below that of the plow layer. Within 0–35 cm layer depth, ^{137}Cs concentration ranged from 287.98 to 439.58 Bq m^{-2}, and the content gradually decreased with the increase of soil depth. Further, 88.87% of ^{137}Cs content distributed within the top depth of 30 cm. This indicated that 30 cm as the sampling depth in the third sampling type was quite reasonable, according to the ^{137}Cs distribution depth of eroded and deposited cores. However, the coefficient of variation within the plow layer was 14.0% in this deposited core, which may be caused by the transport of deposited soil. This suggested that there was a wide range of difference in the vertical distribution pattern of ^{137}Cs content between eroded and deposited cores.

3.3. The spatial distribution of ^{137}Cs contents in the catchment

The ^{137}Cs inventories measured for the 56 sampling sites in the Dongshan catchment ranged from 683.29 to 3929.31 Bq m^{-2}

Table 1
Description of ^{137}Cs inventories for the sampling sites.

Description	Minimum	Maximum	Range	Mean	Standard deviation	Variance (%)	Number
	(Bq m^{-2})						
Reference sites	2149.93	2769.65	619.72	2378.4	198.08	8.3	8
Catchment sites	683.29	3929.31	3246.02	2201.00	357.24	16.0	56
Erosion sites	683.29	2367.63	1684.34	1872.40	417.90	22.0	37
Deposited sites	2404.17	3929.31	1525.14	3014.61	467.14	15.0	19

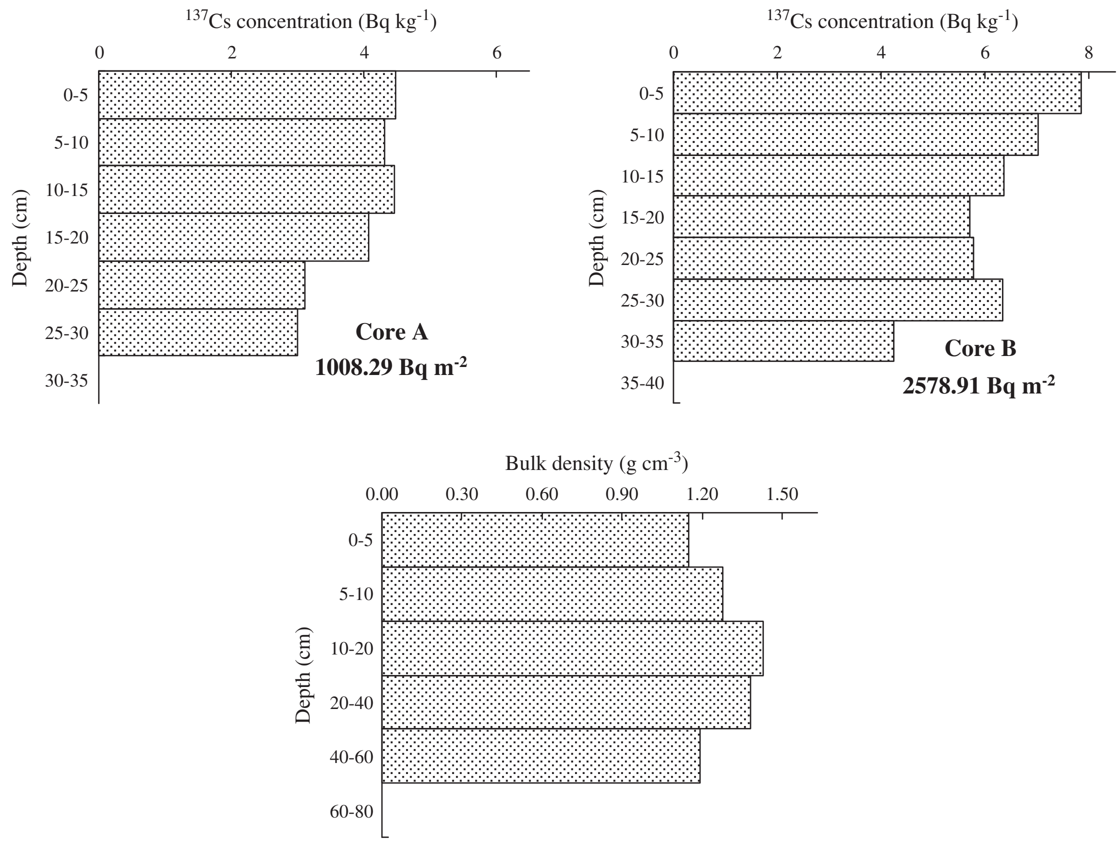

Fig. 3. The vertical distribution of ^{137}Cs concentration and soil bulk density for cultivated soil.

(Table 1). The average value reached 2201.00 Bq m^{-2} and it was lower than that of the local reference inventory (2378.4 Bq m^{-2}), indicating that erosion was the dominated regime in the study catchment. The variation of ^{137}Cs concentration was considerable, and the coefficients of variation reached 16.0%, emphasizing the importance of soil redistribution within the study catchment. Further, eroded and deposited degrees greatly varied along with the change of position. For 37 erosion sites, the coefficient of variation reached 22.0%; the average ^{137}Cs content was 1872.40 Bq m^{-2}, with a maximum value of 2367.63 Bq m^{-2} and a minimum value of 683.29 Bq m^{-2}. For 19 deposited sites, the variance reached 15.0%, and the average ^{137}Cs concentration was 3014.61 Bq m^{-2}, with the maximum and minimum values of 3929.31 and 2404.17 Bq m^{-2}, respectively.

The spatial distribution of ^{137}Cs inventories in the study catchment was derived using GIS and Kriging geostatistics (Fig. 4). Ordinary Kriging (spherical model) was the type of Kriging interpolation. It can be seen that ^{137}Cs inventories in the upstream of the catchment (I) were lower than the reference inventory, which demonstrated that erosion regime played a dominated role in the place. In the middle-stream of the catchment (II and III), ^{137}Cs inventories were either higher or lower than the reference inventory, indicating that erosion and deposition regimes appeared alternately. However, deposition regime took a leading position in the downstream of the catchment (IV), because ^{137}Cs inventories in this area were greater than the reference inventory. The redistribution of ^{137}Cs inventories within different areas suggested that the upper and middle-steams of the catchment should be emphasized on strengthening special management practices to reduce soil erosion.

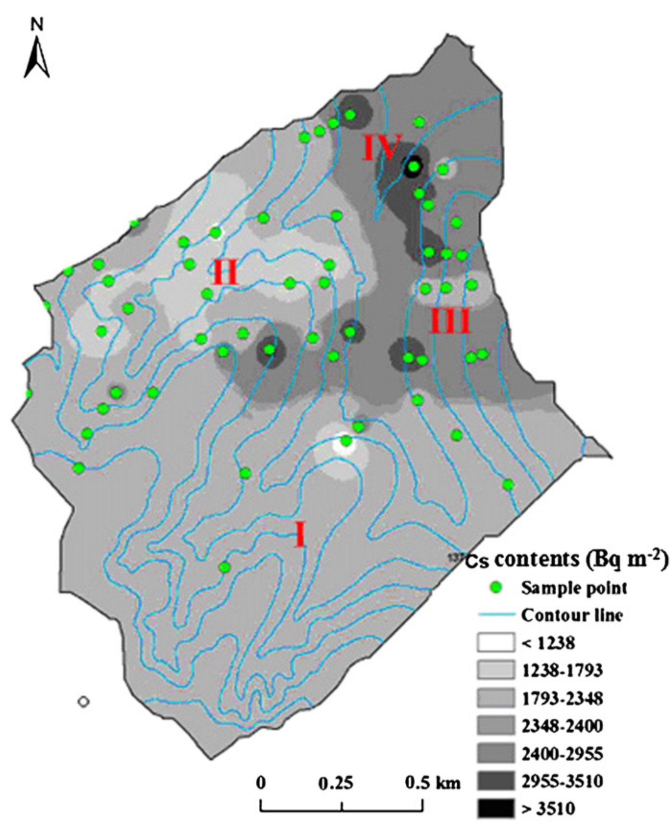

Fig. 4. The spatial distribution of ^{137}Cs inventories within the catchment.

At the slope scale, ^{137}Cs inventories also presented the greatly spatial variability. At the summit of slope, the average ^{137}Cs inventory was very close to the reference inventory, indicating that erosion degree was very slight at this position. This provided a basis for taking the summit of slope as the ^{137}Cs reference site. At the middle of slope, ^{137}Cs inventories were lower than the reference inventory, indicating that soil erosion was relatively serious. However, ^{137}Cs inventories at toe-slope were higher than the reference inventory, because sedimentation occurred at this position. This better explained why in the Northeast China soil loss at the slope scale is large but sediment discharge of the rivers is relatively small compared to other regions (Cui et al., 2007). Additionally, at some sites ^{137}Cs inventories were higher or lower than expected from the general pattern. Especially at some gentle position (slope gradient lower than 2°), ^{137}Cs inventories were much less than the reference value. This was mainly related to micro-topography.

In this catchment, erosion was the dominated regime. This was closely related to management practices. Currently, downslope cultivation and longitudinal ridge tillage were the main tillage management in the catchment. In the future, contour ridge system can replace these practices, especially at the upper and middle-steams of the catchment. Further, increasing land cover at the slope is the better choice to control soil erosion, especially at the middle of slope, and protective measures such as shrub strips and hedgerow can be taken. Additionally, shelter forests should be strengthened at serious erosion area.

3.4. The spatial distribution of erosion and deposition rates in the catchment

The soil loss and/or deposition rates within the study catchment were computed by the MBM2. In this conversion model, the site-specific parameters were: γ (proportion of the annual ^{137}Cs input susceptible to removal by erosion) = 0.6, H (relaxation mass depth of the initial distribution of fallout ^{137}Cs in the soil profile) = 4 kg m^{-2}, d (cumulative mass depth representing the average plow depth) = 240 kg m^{-2} (multiplied by tillage depth of 0.20 m and soil bulk density of 1200 kg m^{-3}), and p (particle size correction factor defined as the ratio of ^{137}Cs of the mobilized sediment to that of the original soil) = p' (further particle size correction factor reflecting differences in grain size composition between mobilized and deposited sediments) = 1.0. According to the conversion model, the estimated soil redistribution rates for the 56 sampling points ranged from −51.07 t ha^{-1} yr^{-1} (maximum erosion rate) to 35.89 t ha^{-1} yr^{-1} (maximum deposition rate), with an average value of −0.76 t ha^{-1} yr^{-1} (Table 2). This further indicated that erosion was the dominated regime in the catchment. For the erosion area, the mean erosion rate was 10.32 t ha^{-1} yr^{-1}, with a maximum value of 51.07 t ha^{-1} yr^{-1}, and a minimum value of 0.16 t ha^{-1} yr^{-1}. For the deposition area, the mean deposition rate reached 13.62 t ha^{-1} yr^{-1}, with a maximum and a minimum value of 35.89 and 0.99 t ha^{-1} yr^{-1}, respectively. This indicated that both erosion and deposition degrees varied greatly with the change of position. Therefore, it was necessary to determine the spatial distribution of erosion and deposition regimes in the catchment.

The soil redistribution of the study catchment showed the same spatial pattern as that of ^{137}Cs inventories. In this catchment, the erosion-dominated area was 1.78 km^2 occupying 76.25% of the total area, and the average soil loss rate reached 8.24 t ha^{-1} yr^{-1} (Fig. 5). However, the deposition-dominated area only was 0.56 km^2, and the average deposition rate was 1.74 t ha^{-1} yr^{-1}. This further indicated that erosion regime played a dominated role in the catchment. Furthermore, soil erosion intensity was 3.52 times greater than the soil loss tolerance of 1.29 t ha^{-1} yr^{-1} in the black soil region of Northeast China (Xie et al., 2011). It suggested that if the current management practices remain, undeniably, the soil organic matter layer of black soil will become thinner and thinner and A-layer of Po PiHuang (Chinese term, meaning that soil organic horizon was mostly eroded and sub-layer with yellow color exposed at the surface) will be increasingly serious. Currently, the black soil depth decreased by 0.1–0.5 cm every year. If this erosion rate keeps on, the black soil will totally disappear in 40–100 year (Group of comprehensive investigation on soil erosion and ecological security in China, 2010). So, it is urgent to take soil conservation practices in this region.

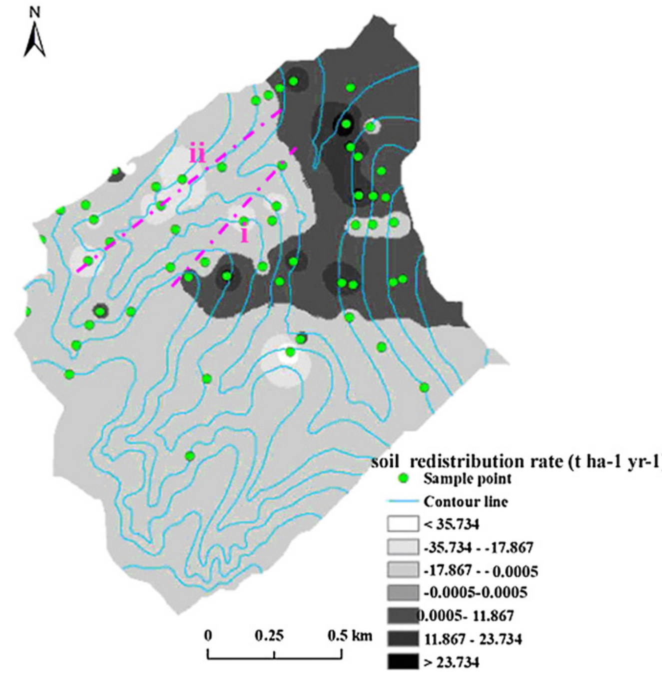

Fig. 5. The spatial distribution of erosion and deposition rates in the catchment.

To analyze the spatial redistribution of erosion rate at the slope scale, we chose two typical slope profiles: convex slope (i) and concave slope (ii). For the two slope profiles, erosion degree of the summit was the most slightly relative to the other sites of slope (Fig. 6), the middle of slope was the most serious position, and at the toe of slope deposition occurred. However, erosion degree and erosion distribution pattern were greatly different between them. For the convex slope, erosion rate of the summit was only 0.20 t ha^{-1} yr^{-1}, which was decreased by 98.33% relative to that for concave slope. This indicated that the summit of convex slope was more suitable taken as the ^{137}Cs reference site relative to the concave slope, when undisturbed area was inexistence nearby the study catchment. Furthermore, for the convex slope, the most serious erosion position was the back of slope (31.17 t ha^{-1} yr^{-1}), while it was the shoulder of slope (27.24 t ha^{-1} yr^{-1}) for the concave slope. The erosion rate of foot-slope for the convex slope was 1.97 times greater than that for the concave slope. What's more, with the increase of slope gradient, erosion rate increased for concave slope, while for convex slope, erosion rate gradually increased to the greatest value and then decreased. The comparison between concave and convex slopes suggested that slope shape was one of the important factors affecting erosion regime in the black soil region, and it should be considered when predicting erosion rates.

The reliability of ^{137}Cs technique to estimate erosion rates is very important. We compared erosion rates estimating from the ^{137}Cs measurements on the cores with data from soil erosion models and runoff plots which were established in a catchment 9 km away from the study catchment. Based on the Revised Universal Soil Loss Equation (RUSLE), the calculating average erosion rate was 1.0 mm yr^{-1} (Yang et al., 2003). This was very close to the measured erosion rate of 0.76 mm yr^{-1} in our study based on the ^{137}Cs-method. The observed mean erosion rates of the runoff plots during 2008–2009 ranged from 2.40 to 5.28 t ha^{-1} yr^{-1}, and the average soil erosion intensity within our study catchment was 4.54 t ha^{-1} yr^{-1}. The above comparisons indicated that erosion rates not only calculated by models but also measured from runoff plots were at the same order of magnitude with the results determined by ^{137}Cs method. This illustrated that soil redistribution rates from the ^{137}Cs measurements were reliable.

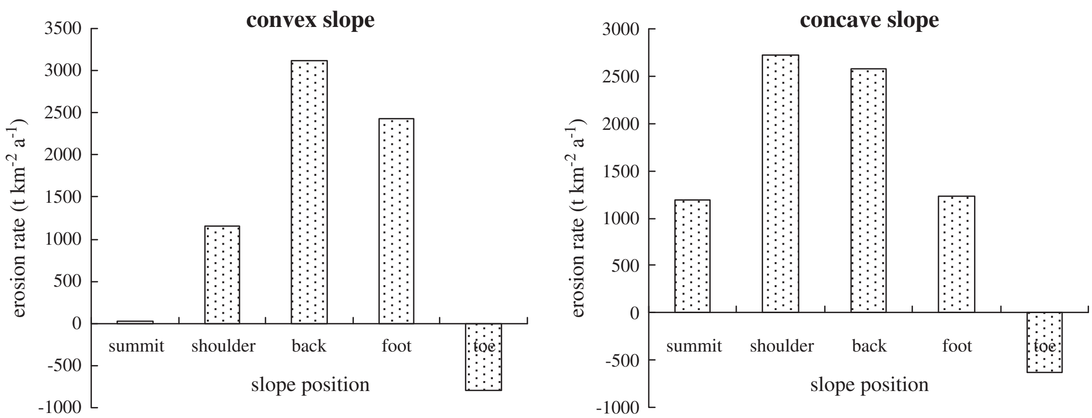

Fig. 6. The spatial distribution of erosion rate for the convex and concave slopes.

3.5. The spatial distribution of erosion pattern in gully

The black soil region of Northeast China has been undergoing severe soil erosion, while gully is one of its main components (Hu et al., 2007). The successful application of the ^{137}Cs method to investigate spatial distribution of gully erosion regimes has been reported (Ritchie et al., 1974; Yang et al., 2006). However, the very obvious freeze–thawing and snowmelt in spring would induce the unique characteristic for gully erosion in the black soil region. Based on ^{137}Cs concentration of soil samples on the main gully bed, the spatial distribution of gully erosion regimes in this study was obtained. However, some previous researchers used filed survey method to obtain gully erosion rates and took ^{137}Cs method to determine interill erosion rates (Fang et al., 2012; Porto et al., 2014) when determining the spatial distribution of erosion and deposition regimes within catchment. In the future, we would assess the rates of gully development using real-time kinematic GPS in the studied catchment and compare the observed results with that determined by ^{137}Cs method.

In this catchment, gully erosion was not serious as expected (Fig. 2). The amount of gully erosion only accounted for 4.35% of the total soil loss, although the gully (0.66 km^2) occupied 28.5% of the total area (Fig. 7). This further proved that sediment discharge in the rivers is relatively small in the black soil region of Northeast China, because a large portion of erosion resources from slope deposited at the toe of slope or on the gully bed. So, controlling slope erosion is more important. However, gully erosion is unignorable. This can be explained from two aspects. Firstly, the highest erosion rate of 51.39 t ha^{-1} yr^{-1} in the gully was very close to that (53.63 t ha^{-1} yr^{-1}) at the slope, although the greatest deposition rate of 35.89 t ha^{-1} yr^{-1} in the gully increased by 24.07% relative to that at the slope. Secondly, gully erosion intensity of 1.55 t ha^{-1} yr^{-1} increased by factors of 1.20 times, compared with the tolerance erosion rate for the black soil region of Northeast China (Xie et al., 2011). This meant that the total sediment production due to the gully erosion during the past 50 years was 94.47 m^3 yr^{-1}, which was obviously different from the surveyed values of previous studies. Wu et al. (2008) who assessed the rates of gully development and the resultant sediment production using real-time kinematic GPS from 2002 to 2005 in the black soil region of Northeast China, reported that the total sediment production due to gully erosion during the three years was between 257 and 1854 m^3 yr^{-1}. Hu et al. (2007) monitored the

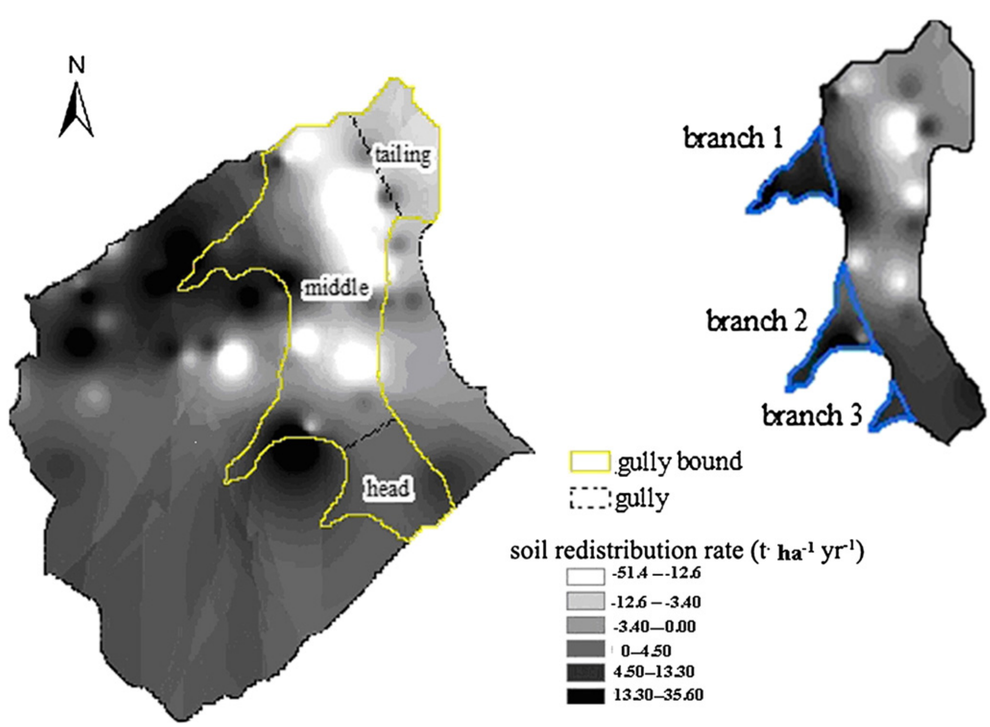

Fig. 7. The spatial distribution of soil redistribution rates in the gully.

Table 2
Soil loss and deposition rates for sampling points.

	Gross samples	Samples from erosion area	Samples from deposition area
Maximum (t ha^{-1} yr^{-1})	35.89	−0.16	35.89
Minimum (t ha^{-1} yr^{-1})	−51.07	−51.07	0.99
Mean (t ha^{-1} yr^{-1})	−0.76	−10.32	13.62
Standard (t ha^{-1} yr^{-1})	16.38	11.52	11.01
Sample number	56	37	19

short-term gully retreat rate from 5 active gullies selected in the representative black soil area using differential global positioning system during April 2002 to June 2004, and found that the average volumetric retreat rate was 729.1 m^3 yr^{-1}. The difference between our result and previously observed value was mainly due to: (1) the difference of measured time length; and (2) in our study catchment, many willow trees were planted in the gully which weakened gully erosion in some extent.

For the gully erosion distribution pattern, the head area was the most serious erosion area (Fig. 7), compared with the middle and tailing areas. At the head area, no deposition occurred, and the average erosion rate was 6.29 t ha^{-1} yr^{-1}. At the gully middle and tailing areas, deposition regime predominated and the average deposition rates were 2.47 and 6.99 t ha^{-1} yr^{-1}, respectively. This suggested that controlling the development of gully head was the top priority to mitigate gully erosion (Hu et al., 2007; Oostwoud Wijdenes et al., 2000). However, the highest erosion rate (51.39 t ha^{-1} yr^{-1}) appeared at the middle area of gully, and at the gully head area it was 11.96 t ha^{-1} yr^{-1}. This meant that the gully in the study catchment was in the active stage and gully would greatly develop in the future. In the black soil region, the development of gully is mainly promoted by freeze–thaw cycles in spring and intense rain events in summer (Zhang et al., 2007) and affected by the typical agricultural operation of ridge tillage. Therefore, establishing check dam at the tailing of gully or retaining vegetation stubble (mulch) after harvesting may be effective measures to control gully erosion.

The gully included three branches (1, 2, and 3), and erosion was the dominated regime for each branch gully. The average erosion rate for branches 1, 2, and 3 was 12.81, 9.18, and 7.61 t ha^{-1} yr^{-1}, respectively, indicating that the gully in this catchment developed actively and branch 1 should be firstly taken key protection measures. Although the highest erosion rate (51.39 t ha^{-1} yr^{-1}) existed in branch 2, its deposition rate reached 5.77 t ha^{-1} yr^{-1}.

4. Conclusions

With the combined ^{137}Cs tracer and GIS technique, this study clarified the spatial distribution of soil redistribution regime at a catchment scale for the black soil region of Northeast China. The results showed that 76.25% of the agricultural fields in this catchment were affected by soil erosion, and the average annual erosion rate of 0.76 mm yr^{-1} was 3.52 times greater than the soil loss tolerance in the black soil region of Northeast China. Further, 95.65% of the total soil loss at the 50-year time-span came from slope, indicating that effective measures should be firstly taken on the slope. Upper and middle-steams of the catchment were the vital areas of erosion control in this catchment. Although the gully area occupied 28.5% of the catchment area, gully erosion only accounted for 4.35% of the total soil loss. This proved the fact that soil loss at the slope scale is large but sediment discharge of the rivers is relatively small. However, gully erosion intensity increased by factors of 1.20 times relative to the tolerance erosion rate for the black soil region, and gully head was the most serious erosion area with an average erosion rates of 6.29 t ha^{-1} yr^{-1}.

Slope erosion mainly controlled erosion intensity, but distribution pattern of erosion regime at the slope scale was affected by slope shape. For the concave slope, the shoulder of slope was the most serious erosion position, while it was the back of slope for the convex slope; erosion rates of the summit and foot slope for the convex slope were 0.5 and 1.97 times that of the concave slope, respectively. ^{137}Cs concentration of the summit for the convex slope was quite close to ^{137}Cs reference inventory, indicating that it can be taken as the reference site when undisturbed sites were inexistence in the study area.

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References

Basher, L.R., Matthews, K.M., Zhi, L., 1995. Surface erosion assessment in the South Canterbury downlands, New Zealand using Cs-137 distribution. Aust. J. Soil Res. 33, 787–803.
Bujana, A., Santanatogliab, O.J., Chagasb, C., Massobriob, M., Castiglionib, M., Yañeza, M., Ciallellac, H., Fernandezc, J., 2003. Soil erosion evaluation in a small basin through the use of ^{137}Cs technique. Soil Tillage Res. 69 (1–2), 127–137.
Comprehensive investigation on soil erosion and ecological security in China, Northeast group, 2010. The Control of Soil Erosion and Ecological Security in China, the Volume of Northeast Black Soil Region. Science Press, Beijing, pp. 52–55.
Cui, M., Cai, Q.G., Zhu, A.X., Fan, H.M., 2007. Soil erosion along a long slope in the gentle hilly areas of black soil region in Northeast China. J. Geogr. Sci. 17 (3), 375–383.
Di Stefano, C., Ferro, V., Porto, P., 1999. Linking sediment yield and caesium-137 spatial distribution at basin scale. J. Agric. Eng. Res. 74 (1), 41–62.
Fan, H.M., Cai, Q.G., Cui, M., 2004. Soil erosion developed with the vertical belts in the gentle hilly black soil regions in Northeast China. Trans. Chin. Soc. Agric. Eng. 21 (6), 8–11 (in Chinese with English Abstract).
Fang, H.J., Yang, X.M., Zhang, X.P., Liang, A.Zh., 2006. Using ^{137}Cs tracer technique to evaluate erosion and deposition of black soil in Northeast China. Pedosphere 16 (2), 201–209.
Fang, H.Y., Sun, L.Y., Qi, D.L., Cai, Q.G., 2012. Using ^{137}Cs technique to quantify soil erosion and deposition rates in an agricultural catchment in the black soil region, Northeast China. Geomorphology 169–170, 142–150.
Garcia-Oliva, F., Martinez Lugo, R., Maass, J.M., 1995. Long-term net soil erosion as determined by ^{137}Cs redistribution in an undisturbed and perturbed tropical deciduous forest ecosystem. Geoderma 68, 135–147.
Hu, G., Wu, Y.Q., Liu, B.Y., Yu, Z.T., You, Z.M., Zhang, Y.G., 2007. Short-term gully retreat rates over rolling hill areas in black soil of Northeast China. Catena 71, 321–329.
Kachanoski, R.G., 1993. Estimating soil loss from changes in soil cesium-137. Can. J. Soil Sci. 73, 515–526.
Konz, N., Schaub, M., Prasuhn, V., Bänninger, D., Alewell, C., 2009. Cesium-137-based erosion rate determination of a steep mountainous region. J. Plant Nutr. Soil Sci. 172, 615–622.
Li, S., Lobb, D.A., Lindstrom, M.J., Farenhorst, A., 2007. Tillage and water erosion on different landscapes in the northern North American Great Plains evaluated using ^{137}Cs technique and soil erosion models. Catena 70 (3), 493–505.
Li, S., Lobb, D.A., Kachanoski, R.G., McConkey, B.G., 2011. Comparing the use of the traditional and repeated-sampling-approach of the ^{137}Cs technique in soil erosion estimation. Geoderma 160 (3–4), 324–335.
Mabit, L., Bernard, C., 2007. Assessment of spatial distribution of fallout radionuclides through geostatistics concept. J. Environ. Radioact. 97, 206–219.
McHenry, J.R., Jerry, C.R., 1977. Physical and chemical parameters affecting transport of ^{137}Cs in arid watersheds. Water Resour. Res. 13 (6), 923–927.
McIntyre, S.C., Lance, J.C., Campbell, B.L., Miller, R.L., 1987. Using cesium-137 to estimate soil erosion on a clearcut hillside. J. Soil Water Conserv. 42 (2), 117–120.
Navas, A., Machín, J., Soto, J., 2005. Assessing soil erosion in a Pyrenean mountain catchment using GIS and fallout ^{137}Cs. Agric. Ecosyst. Environ. 105, 493–506.
Oostwoud Wijdenes, D.J., Poesen, J., Vandekerckhove, L., 2000. Spatial distribution of gully head activity and sediment supply along an ephemeral channel in a Mediterranean environment. Catena 39 (3), 147–167.
Owens, P.N., Walling, D.E., 1996. Spatial variability of caesium-137 inventories at reference sites: an example from two contrasting sites in England and Zimbabwe. Appl. Radiat. Isot. 47 (7), 699–707.

Pennock, D.J., Lemmon, D.S., Jong, de, 1995. Cesium-137 measured erosion rates for five parent-material groups in southwestern Saskatchewan. Can. J. Soil Sci. 75, 205–210.

Porto, P., Walling, D.E., 2012. Validating the use of ^{137}Cs and $^{210}Pb_{ex}$ measurements to estimate rates of soil loss from cultivated land in southern Italy. J. Environ. Radioact. 106, 47–57.

Porto, P., Walling, D.E., Capra, A., 2014. Using ^{137}Cs and $^{210}Pb_{ex}$ measurements and conventional surveys to investigate the relative contributions of interrill/rill and gully erosion to soil loss from a small cultivated catchment in Sicily. Soil Tillage Res. 135, 18–27.

Qi, Y.Q., Zhang, X.B., He, X.B., Wen, A.B., Fu, J.X., 2006. ^{137}Cs reference inventories distribution pattern in China. Nucl. Tech. 29 (1), 42–50.

Quang, N.H., Long, N.Q., Lieu, D.B., Mai, T.T., Ha, N.T., Nhan, D.D., Hien, P.D., 2004. $^{239+240}Pu$, ^{90}Sr and ^{137}Cs inventories in surface soils of Vietnam. J. Environ. Radioact. 75, 329–337.

Ritchie, J.C., McCarty, G.W., 2003. ^{137}Cesium and soil carbon in a small agricultural watershed. Soil Tillage Res. 69, 45–51.

Ritchie, J.C., Spraberry, J.A., McHenry, J.R., 1974. Estimating soil erosion from the redistribution of fallout ^{137}Cs. Soil Sci. 38, 137–139.

Schuller, P., Walling, D.E., Sepúlveda, A., Castillo, A., Pino, I., 2007. Changes in soil erosion associated with the shift from conventional tillage to a no-tillage system, documented using ^{137}Cs measurements. Soil Tillage Res. 94, 183–192.

Walling, D.E., He, Q., 1999. Improved models for estimating soil erosion rates from caesium-137 measurements. J. Environ. Qual. 28, 611–622.

Walling, D.E., He, Q., 2001. Models for converting ^{137}Cs measurements to estimates of soil redistribution rates on cultivated and undisturbed soils (including software for model implementation) [R]. Report to IAEA. University of Exeter, UK.

Walling, D.E., Quine, T.A., 1990. Calibration of caesium-137 measurements to provide quantitative erosion rate data. Land Degrad. Rehabil. 2, 161–175.

Walling, D.E., He, Q., Appleby, P.C., 2002. Conversion models for use in soil-erosion, soil redistribution, and sedimentation investigations. In: Zapata, F. (Ed.), Handbook for the Assessment of Soil Erosion and Sedimentation Using Environmental Radioactivity. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 111–164.

Wang, Z.Q., Liu, B.Y., Wang, X.Y., Gao, X.F., Liu, G., 2009. Erosion effect on the productivity of black soil in Northeast China. Sci. China Ser. D Earth Sci. 52, 1005–1021.

Wang, Y., Yang, M.Y., Liu, P.L., 2010. The Wavelet Analysis on the Soil Erosion Intensity in the Black Soil Straight Cultivated Slope. J. Nucl. Agric. Sci. 24 (1), 98–103 (in Chinese with English Abstract).

Wang, B., Zheng, F.L., Römkens, M.J.M., 2013. Comparison of soil erodibility factors in USLE, RUSLE2, EPIC and Dg models based on a Chinese soil erodibility database. Acta Agric. Scand. Sect. B Soil Plant Sci 63 (1), 69–79.

Wu, Y.Q., Zheng, Q.H., Zhang, Y.G., Liu, B.Y., Cheng, H., Wang, Y.Z., 2008. Development of gullies and sediment production in the black soil region of northeastern China. Geomorphology 101, 683–691.

Xie, Y., Duan, X.W., Liu, B.Y., Liu, G., Feng, Y.J., Gao, X.F., 2011. Soil loss tolerance for black soil species in Northeast China. Acta Geograph. Sin. 66 (7), 940–952 (in Chinese with English Abstract).

Xu, X.Z., Xu, Y., Chen, S.C., Xu, S.G., Zhang, H.W., 2010. Soil loss and conservation in the black soil region of Northeast China: a retrospective study. Environ. Sci. Policy 13, 793–800.

Yan, B.X., Tang, J., 2005. Study on black soil erosion rate and the transformation of soil quality influenced by erosion. Geogr. Res. 24 (4), 499–506.

Yang, X.M., Zhang, X.P., Deng, W., Fang, H.J., 2003. Black soil degradation by rainfall erosion in Jilin, China. Land Degrad. Dev. 14, 409–420.

Yang, M.Y., Tian, J.L., Liu, P.L., 2006. Investigating the spatial distribution of soil erosion and deposition in a small catchment on the Loess Plateau of China, using ^{137}Cs. Soil Tillage Res. 87, 186–193.

Zhang, Y.G., Wu, Y.Q., Liu, B.Y., Zheng, Q.H., Yin, J.Y., 2007. Characteristics and factors controlling the development of ephemeral gullies in cultivated catchments of black soil region, Northeast China. Soil Tillage Res. 96, 28–41.