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Using $^{137}$Cs technique to quantify soil erosion and deposition rates in an agricultural catchment in the black soil region, Northeast China

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**Abstract**

Soil erosion significantly affects the productive black soil region in Northeast China. Quantification of the soil erosion is necessary for designing efficient degradation control strategies. $^{137}$Cs measurements undertaken on 61 sampling points collected within a 28.5 ha agricultural catchment in the black soil region of Northeast China were used to establish the magnitude and spatial pattern of soil redistribution rates as well as sediment budget within the catchment. Estimated soil redistribution rates using the Mass Balance Model 2 (MBM2) ranged from ~56.8 to 171.4 t ha$^{-1}$ yr$^{-1}$ for the sampling points that were verified by means of both runoff plot data and pedological investigation. Erosion generally occurred behind the shelterbelts, especially in the ephemeral gully susceptible areas, while deposition mainly occurred along the shelterbelts and at the catchment outlet. In the study catchment, 69% of the eroded sediments came from the slopes and 31% the ephemeral gullies. Sediments deposited along the shelterbelts at a rate of ca. 78 t yr$^{-1}$ and ca. 33 t yr$^{-1}$ at the catchment outlet. The gross soil loss rate for the catchment was ~4.4 t ha$^{-1}$ yr$^{-1}$ with a sediment delivery ratio of 53%. The mean rate of ~14.3 t ha$^{-1}$ yr$^{-1}$ in the erosion areas was much higher than the tolerable value, suggesting that effective soil conservation measures are urgently required to reduce the severe black soil loss for sustainable management of the soil resource.

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**1. Introduction**

The black soil region in Northeast China has been cultivated as farmland, and is considered essential for Chinese crop production (Xu et al., 2010). Nevertheless, severe soil erosion has occurred since large-scale land reclamation in the 1950s, and the thickness of the A-horizon of the black soils has decreased from 60–70 cm in the 1950s to 20–30 cm at present (Fan et al., 2005; Zhang et al., 2007). In some places the loess parent material has been exposed, reducing soil productivity (Wang et al., 2009). The severe soil loss is also a threat to water quality in local streams and rivers (Yu et al., 2003). Understanding the spatial pattern of soil redistribution and the analysis of sediment budget are thus very important for designing soil and water conservation programs, targeting remediation measures and for evaluating the benefits of catchment management (Yang et al., 2006a).

Using classical erosion techniques such as erosion plots and predictive models for monitoring and assessing soil loss has many limitations: they are difficult to handle, time consuming, and expensive (Lafflen et al., 1991; Quine, 1999; Du and Walling, 2011). The use of $^{137}$Cs measurements has attracted increasing attention as an approach to quantitatively estimate soil redistribution over agricultural landscapes (Wakiyama et al., 2010). The artificial radionuclide $^{137}$Cs (half-life: 30.2 years) was introduced into the environment by the atmospheric testing of thermonuclear weapons, primarily during the period from 1954 to mid-1970s. After releasing into the stratosphere, the $^{137}$Cs was distributed globally and deposited as fallout, mainly in association with precipitation. Its use as a sediment tracer lies in its rapid and strong adsorption by fine particles (He and Walling, 1996) so that in most agricultural environments its subsequent redistribution is a direct reflection of the erosion, transport and deposition of soil particles. Estimates of soil loss and/or gain rates can be derived from $^{137}$Cs measurements by comparing the inventories measured at a specific point with the reference inventory. The $^{137}$Cs technique provides retrospective estimates of medium-term (ca. 50 years) erosion rates (Walling and He, 1999; Du and Walling, 2011), and the spatial pattern of erosion and deposition rates can be evaluated and analyzed based on a single visit. Using $^{137}$Cs technique for estimating soil erosion and deposition rates has been applied to a wide range of environments, and the basis of the technique is well established and documented (Ritchie et al., 1974; Elliot, et al., 1990; Nouira et al., 2003).

In recent years, the severe erosion of black soil in Northeast China has attracted increasing attention. Many studies have been conducted on environmental and anthropogenic impacts on soil erosion, and factors influencing erosion rates (Jing et al., 2003; Liu et al., 2005; Yang et al., 2006b), soil erosion types (Wang et al., 2010) and gully dynamics (Hu et al., 2007; Zhang et al., 2008; Wu et al., 2008) as well as the controlling strategies in the black soil region of Northeast China (Wang et al., 2003; Yang et al., 2005). However, limited...
scientific data on the rates of erosion and deposition associated with agricultural land use and landform positions were mainly focused at the slope scale (Fang et al., 2006a, 2006b; Wang et al., 2010).

Since the large-scale land reclamation, the black soil region in Northeast China has been affected by severe soil erosion although shelterbelts were there established ca. 40 years ago (Zhang et al., 2006b). The snow-melt runoffs in spring and storms in the rainy season usually induce the development of ephemeral gullies even in a small catchment (Hu et al., 2007; Zhang et al., 2007; Wu et al., 2008). It will be helpful to implement land use management for a small catchment through studying its soil redistribution pattern and sediment budget. However, limited quantitative data are available for assessing soil erosion characteristics of an agricultural catchment in the black soil region.

Therefore, a small catchment in the black soil region was selected for this study, in order to (i) evaluate the reliability of the $^{137}$Cs technique for the quantification of soil erosion; (ii) quantify the spatial pattern of soil redistribution by using $^{137}$Cs technique; and (iii) estimate sediment budgets at a medium (ca. 50-year) time period for the catchment.

2. Materials and methods

2.1. Study catchment

The study catchment is located at the Heshan Farm, Northwest Heilongjiang Province, China (125°11'E, 48°56'N; Fig. 1). The catchment has an area of 28.5 ha with an elevation of 320 to 360 m. The slopes of cultivated land for the catchment range from 0.4% to 8.4% with an average value of 4.2%. The region's climate is semihumid and continental with a long and cold winter. Mean January and July temperatures are $-20\degree C$ and 21 $\degree C$, respectively (Zhang et al., 2007). Precipitation is 534 mm with a 67% of annual rainfall from June to August (Wu et al., 2008).

The dominant soil association is classified as Udic Argiboroll in the USDA Taxonomy. The parent materials of the Phaeozem are Quaternary lacustrine and fluvial sand beds or loess sediments that lie below the Phaeozem (Sun and Liu, 2001). The main textural classes of the top soil are silt clay loam to clay loam (8–27% sand, 29–66% silt, and 26–40% clay) (Wu et al., 2008).

Most of the lands in Heshan Farm were historically covered by bush wood. However, intensive land reclamation was carried out in the black soil region with increasing people since the establishment of the People's Republic of China, and the newly cultivated land in Heilongjiang Province was up to 5.93 million ha by 1978 (Fan et al., 2005). Though historic records of the condition of the land in Heshan Farm are not extensive or specific, the reclamation history for the black soil region coupled with local people's interview survey informed us that the study catchment has been reclaimed for farmland since the 1950s and the general environmental conditions have not substantially changed over the last 50 years (Hu et al., 2007), which is the time range associated with the $^{137}$Cs measurements.

Soybean (Glycine max (L.) Merr.) is the major crop in the rotation with wheat (Triticum aestivum L.) and corn (Zea mays L.) for the study.

Fig. 1. Map showing the locations of the study catchment, sampling points, shelterbelts and ephemeral gullies. The sampling points along the transects A–H were indicated with a transect name and a number, and the ephemeral gullies (EGs) were named as EG1 to EG4.
catchment. A single tillage operation is used with a cultivator harrow to a depth of about 0.25 m after harvesting in autumn (late September) or before sowing (early May) in spring. From October to April, the crop-land is left fallow with no vegetation cover for cold weather. *Pinus* shelterbelts were established to protect crop against wind disaster. For the convenience of mechanical tillage, the tillage direction is usually parallel to the shelterbelt. The downslope cultivation easily accelerates soil erosion in the study catchment.

An ephemeral gully system was observed in the lower part of the study catchment (Fig. 1). In the black soil region, ephemeral gullies develop twice a year. The first takes place usually in late April, as a result of snowmelt runoffs, and the second occurs usually in late July resulting from rain storms (Zhang et al., 2007). The ephemeral gullies have been recognized as an important source of sediment eroded from croplands (Zhang et al., 2006a, 2007). The presence of the ephemeral gullies may contribute greatly to the sediment budget of the catchment.

2.2. Soil sampling

From the catchment survey, the sampling strategy was based on a multiple-transect approach accompanied by the key points’ sampling method. Eight transects were selected representing the landscape characteristics from the upper plateau to the lowest position of the catchment. The sites that represented major landforms but were not on the transects were also sampled. A reference site for determining the $^{137}$Cs inventory was selected on an uncultivated second-growth *Quercus mongolica* forest land with a flat topography (Fig. 1). It was judged to have been unaffected by soil erosion or deposition since 1950, and it is located ca. 5 km away from the investigated catchment. The $^{137}$Cs soil samples were collected in late June, 2010, using a 5-cm-diameter hand operated core sampler. Soil cores were taken to a depth of 40 cm in the eroded cultivated land and 60–100 cm at the deposition sites to ensure that the core had penetrated to the full depth of the $^{137}$Cs profile. The distances between sampling points along the transects ranged from 50 to 100 m and between the other sampling points depended on the landform characteristics. The samples were sectioned with 3–5 cm intervals up to 30 cm to determine both the depth distribution and the $^{137}$Cs inventory for one of the reference sampling points.

2.3. Laboratory analysis

The bulk and sectioned soil core samples were air-dried, weighted, and passed through a 2-mm sieve for the measurements of $^{137}$Cs activity. The radioactivity of $^{137}$Cs in soil samples was measured by a hyper-pure coaxial Ge detector linked to a multichannel analyzer, detected at 662 keV peak with counting time over 80,000 s, providing a measurement precisions of ±5% for $^{137}$Cs at the 95% confidence level. The results were originally calculated on a unit mass basis (Bq kg$^{-1}$) and were then converted to an inventory value (Bq m$^{-2}$) using the total weight of the bulked core soil sample and the sampling area.

2.4. Estimation of soil redistribution rates using $^{137}$Cs radionuclide

A number of approaches have been proposed for deriving estimates of soil redistribution rates from $^{137}$Cs measurements in cultivated areas. Mass balance models have been frequently used to estimate $^{137}$Cs loss and gain for specified erosion and deposition rates and to establish calibration relationships. In this paper, the Mass Balance Model 2 (MBM2; Walling and He, 1999; Walling et al., 2002) was used to convert the areal activities of $^{137}$Cs into soil redistribution rates (t ha$^{-1}$ yr$^{-1}$).

For an eroding site, the change of the $^{137}$Cs total inventory with time can be represented as:

$$\frac{dA(t)}{dt} = (1-P)(t)(\lambda + P \frac{R}{d})A(t)$$

where $A(t)$ is the cumulative $^{137}$Cs activity per unit area (Bq m$^{-2}$); $R$ the erosion rate (kg m$^{-2}$ yr$^{-1}$); $t$ the time since the onset of radionuclide inputs; $d$ the cumulative mass depth representing the average plough depth (kg m$^{-2}$); $\lambda$ the decay constant for $^{137}$Cs (yr$^{-1}$); $I(t)$ annual deposition flux of $^{137}$Cs at time $t$ (Bq m$^{-2}$ yr$^{-1}$); $P$ the proportion of the freshly deposited $^{137}$Cs fallout removed by erosion before incorporation into the plough layer; and $I(t)$ the $^{137}$Cs concentration of deposited sediment.

$$R = \int_{t_0}^{t} \frac{A_{ex}}{C_0/C_1} e^{-\lambda(t-t_0)} dt$$

where $A_{ex}$ is the excess $^{137}$Cs inventory (Bq m$^{-2}$), defined as the measured total inventory $A(t)$ minus the local direct fallout input $A_{ref}$ and $C_0(t')$ (Bq kg$^{-1}$) the $^{137}$Cs concentration of deposited sediment.

2.5. Measurements of the ephemeral gullies

In August 2011, the ephemeral gullies of the catchment developed well, and the measurements of the ephemeral gullies were conducted using the method of Zhang et al. (2007). A portable hand-GPS devise (Magellan Explorist 500) was used in the field to determine the spatial distribution of the ephemeral gullies by linking the GPS positions. The developed ephemeral gullies were named FG1–FG4 (Fig. 1). At each of the positions along the ephemeral gullies, one channel width and three depths were measured. The length of each segment between two GPS points was measured using a 50-m-long surveyor’s tape. The eroded volume of each ephemeral gully was calculated using the cross-sectional dimensions and the distances between cross-sections. The soil losses from the ephemeral gullies were then calculated based on the volume estimations and topsoil bulk density of 1250 kg m$^{-3}$. The major geomorphic characteristics and the calculated soil losses from the ephemeral gullies are summarized in Table 1.

2.6. Calculating soil loss and/or gain for the catchment

ArcGIS 9.3 software was used with the location data of field measurements to create spatial distributions of $^{137}$Cs inventories (Bq m$^{-2}$) and the pattern of soil redistribution (t ha$^{-1}$ yr$^{-1}$) through the kriging interpolation method. The erosion and deposition areas of the catchment were extracted from the interpolated soil redistribution map. The mean rates of soil loss and/or gain in the erosion and deposition areas were obtained using ArcGIS software algorithms. The soil loss and sediment gain were calculated through multiplying the mean rates of erosion and deposition by corresponding soil redistribution areas. Soil gain per year along the shelterbelts as well as that at the catchment outlet was also obtained with the same method.

Table 1

<table>
<thead>
<tr>
<th>Site</th>
<th>Length (m)</th>
<th>Mean width (m)</th>
<th>Mean depth (m)</th>
<th>Volume (m$^3$)</th>
<th>Soil loss (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EG1</td>
<td>36</td>
<td>0.85</td>
<td>0.08</td>
<td>2.45</td>
<td>3060</td>
</tr>
<tr>
<td>EG2</td>
<td>53</td>
<td>0.93</td>
<td>0.10</td>
<td>4.93</td>
<td>6161</td>
</tr>
<tr>
<td>EG3</td>
<td>45</td>
<td>1.34</td>
<td>0.13</td>
<td>7.84</td>
<td>9799</td>
</tr>
<tr>
<td>EG4</td>
<td>103</td>
<td>1.47</td>
<td>0.09</td>
<td>13.63</td>
<td>17034</td>
</tr>
<tr>
<td>Total</td>
<td>237</td>
<td>1.23</td>
<td>0.10</td>
<td>28.85</td>
<td>36054</td>
</tr>
</tbody>
</table>

Note: Soil loss was estimated based on the volume estimations and a topsoil bulk density of 1250 kg m$^{-3}$. 
2.7. Topographical factors for the sampling points

Slope gradient and curvature at each sampling point were computed by ArcGIS 9.3 to study the impacts of topographical factors on soil redistribution rates. Slope gradient was described as a percentage. A positive curvature indicates an upwardly convex surface, while a negative curvature indicates a concave surface, and a value of zero indicates a flat surface.

3. Results

3.1. $^{137}$Cs inventory in the reference site

The $^{137}$Cs inventories for the five cores collected from the reference site are given in Table 2. The mean activity of $^{137}$Cs was 2506 Bq m$^{-2}$ with a standard deviation of 402 Bq m$^{-2}$. The $^{137}$Cs inventories were quite close except the R5 sampling point, which represented a percentage deviation of 31% higher than the mean reference value, whereas the reference value sampled at the R5 point was lower than all the other points with around 14.6% deviation from the mean. These variations result probably from the spatial variability of the radionuclide’s inventories due to soil heterogeneity, such as soil micro-topography, argillic level, vegetation density and biological activity as well as by splash or runoff phenomena. Such phenomena have also been observed in other regions (Owens and Walling, 1996; Nouira et al., 2003).

The depth distribution of $^{137}$Cs areal activity at the R5 point was used to validate the use of the mean value of these data as background value. The $^{137}$Cs areal activity profile showed a sharp decrease with increasing depth (Fig. 2), and could be fitted by an exponential function. The distribution was typical of an undisturbed site (Frissel and Pennders, 1983). Most of the $^{137}$Cs was contained within the top 15 cm soil layer, with 95% of the $^{137}$Cs accumulated in the upper 15 cm soil layer. In this study, the mean activity of $^{137}$Cs at the R5 point was 2506 Bq m$^{-2}$, which is quite close except the R4 sampling point, which represented a percentage deviation of 31% higher than the mean reference value, whereas the reference value sampled at the R4 point was lower than all the other points with around 14.6% deviation from the mean. These variations result probably from the spatial variability of the radionuclide’s inventories due to soil heterogeneity, such as soil micro-topography, argillic level, vegetation density and biological activity as well as by splash or runoff phenomena. Such phenomena have also been observed in other regions (Owens and Walling, 1996; Nouira et al., 2003).

The depth distribution of $^{137}$Cs for the R3 point is shown in Fig. 2. The established $^{137}$Cs reference value for the R3 point was lower than all the other points with around 14.6% deviation from the mean. These variations result probably from the spatial variability of the radionuclide’s inventories due to soil heterogeneity, such as soil micro-topography, argillic level, vegetation density and biological activity as well as by splash or runoff phenomena. Such phenomena have also been observed in other regions (Owens and Walling, 1996; Nouira et al., 2003).

In the black soil region of Northeast China, use of $^{137}$Cs technique to examine soil erosion has been conducted and the values of reference inventories have also been reported in several studies. In Jilin Province, Yan and Tang (2004) and Fang et al. (2006a) reported the $^{137}$Cs reference inventories of 2464 Bq m$^{-2}$ in Jiutai County, and 2233 and 2376 Bq m$^{-2}$ in Dehui County. In Keshan County of Heilongjiang Province, a reference inventory of 2500 Bq m$^{-2}$ that was quite close to the averaged reference value in the present study was also reported by Wang et al. (2010). Generally, global $^{137}$Cs fallout deposition increases with increasing latitude in the Northern Hemisphere, though it is also a strong function of the annual precipitation (Zheng and Wang, 2002; Fang et al., 2006a). The reference inventories of $^{137}$Cs mentioned above are all located in the south of the study catchment. This means the $^{137}$Cs reference value should be larger than the reported values. In conjunction with the $^{137}$Cs profile distribution in Fig. 2, the established reference $^{137}$Cs inventory of 2506 Bq m$^{-2}$ is regarded as reliable.

3.2. Distribution of $^{137}$Cs inventories for the catchment

The $^{137}$Cs inventory values for the 61 bulk soil cores collected from the catchment varied greatly and ranged from 582 to 10,420 Bq m$^{-2}$, with a mean value of 2371 Bq m$^{-2}$. A majority (68.9%) of the soil samples had lower $^{137}$Cs inventory values than the established reference with a median of 1783 Bq m$^{-2}$ and a skewness of 3.3 (Table 3), implying that most of the catchment area could suffer from soil erosion. Correspondingly, 31.1% of the $^{137}$Cs inventories had higher values than the reference with a high standard value of 1086.2 Bq m$^{-2}$. The spatial pattern of $^{137}$Cs inventories indicates that the higher $^{137}$Cs inventories mainly appeared along the shelterbelts and at the catchment outlet. However, the lower $^{137}$Cs inventories were mainly located behind the shelterbelts, especially in the region where the ephemeral gullies occurred (Fig. 3).

3.3. Soil redistribution and sediment budget

The soil loss and/or gain rates within the study catchment were computed by using the MBM2 with site-specific parameters: $\gamma$ (proportion of the annual $^{137}$Cs fallout susceptible to erosion prior to incorporation into the soil profile by tillage) = 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 plough depth) = 312 kg m$^{-2}$ (multiplied by tillage depth of 0.25 m by soil bulk density of 1250 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) = $p^c$ (further particle size correction factor reflecting differences in grain size composition between mobilized and deposited sediments) = 1.0. The estimates of soil redistribution represent mean annual

| Table 2 Measurement inventories for $^{137}$Cs in the reference site (Bq m$^{-2}$). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Sampling points | R1  | R2  | R3  | R4  | R5  | Mean | Standard deviation |
| $^{137}$Cs activity | 2139 | 2388 | 2270 | 3281 | 2450 | 2506 | 402 |
| A.U. (activity uncertainty) | 3.22 | 7.14 | 4.70 | 8.84 | 6.69 | 6.69 | 6.69 |

Note: R1–R5 represent reference points and R5 is the sectioned reference sampling point.

| Table 3 $^{137}$Cs inventories for the sampling points. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Sampling points | Total samples | Inventories less than the reference | Inventories greater than the reference |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Minimum (Bq m$^{-2}$) | 582.0 | 582.0 | 2557 |
| Maximum (Bq m$^{-2}$) | 10,420.0 | 2435 | 10,420 |
| Mean (Bq m$^{-2}$) | 2371.1 | 1731.4 | 3785.8 |
| Standard deviation | 1437.5 | 494.9 | 1086.2 |
| Median (Bq m$^{-2}$) | 1783 | 1783 | 3220 |
| Skewness | 3.3 | -0.5 | 3.1 |
| Number of samples | 61 | 42 | 19 |
values for the past 50 years. The estimated soil redistribution rates for the 61 sampling points ranged from $-56.8 \text{ t ha}^{-1} \text{yr}^{-1}$ (maximum erosion) to $171.4 \text{ t ha}^{-1} \text{yr}^{-1}$ (minimum erosion), with an average of $-2.2 \text{ t ha}^{-1} \text{yr}^{-1}$ and a median of $-6.9 \text{ t ha}^{-1} \text{yr}^{-1}$ (Table 4). The mean rate for the sampling points that had experienced erosion was $-15.0 \text{ t ha}^{-1} \text{yr}^{-1}$, and $26.1 \text{ t ha}^{-1} \text{yr}^{-1}$ for those with deposition. The soil redistribution of the catchment had the same spatial pattern as that of the $^{137}$Cs inventories (Fig. 4). Except for topography, the erosion and deposition areas were also affected by the shelterbelts and ephemeral gullies in the study catchment. For the sampling points on the eight transects that run through the catchment, the soil erosion/gain rates varied from $-47.5$ to $171.4 \text{ t ha}^{-1} \text{yr}^{-1}$ (Fig. 5). Almost all the sampling points on transects A–D in Fig. 5 showed soil erosion, except for some depression sites and those located along the shelterbelts with soil gain rates of 8 to $16 \text{ t ha}^{-1} \text{yr}^{-1}$. However, in the ephemeral gully areas, all the sampling points presented soil loss with the largest erosion rate of $-47.5 \text{ t ha}^{-1} \text{yr}^{-1}$ (Fig. 5E–F). Sediment deposition generally occurred at the catchment outlet with soil gain rates of 32.63 to $171.41 \text{ t ha}^{-1} \text{yr}^{-1}$ (Fig. 5G–H).

Spatial integration of the soil redistribution pattern shown in Fig. 4 indicates a net erosion rate of $236 \text{ t yr}^{-1}$ in the erosion area (i.e.,

**Table 4**

Soil loss and/or gain rates for the sampling points.

<table>
<thead>
<tr>
<th></th>
<th>Gross samples</th>
<th>Samples from areas of erosion</th>
<th>Samples from areas of deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum (t ha$^{-1}$ yr$^{-1}$)</td>
<td>$-56.8$</td>
<td>$-56.8$</td>
<td>0.9</td>
</tr>
<tr>
<td>Maximum (t ha$^{-1}$ yr$^{-1}$)</td>
<td>171.4</td>
<td>$-1$</td>
<td>171.4</td>
</tr>
<tr>
<td>Mean (t ha$^{-1}$ yr$^{-1}$)</td>
<td>$-2.2$</td>
<td>$-15.0$</td>
<td>26.1</td>
</tr>
<tr>
<td>Standard deviation (t ha$^{-1}$ yr$^{-1}$)</td>
<td>30.7</td>
<td>12.9</td>
<td>39.3</td>
</tr>
<tr>
<td>Median (t ha$^{-1}$ yr$^{-1}$)</td>
<td>$-6.9$</td>
<td>$-11.7$</td>
<td>13.2</td>
</tr>
<tr>
<td>Skewness</td>
<td>3.3</td>
<td>$-1.4$</td>
<td>3.2</td>
</tr>
<tr>
<td>Number of samples</td>
<td>61</td>
<td>42</td>
<td>19</td>
</tr>
</tbody>
</table>

Fig. 3. Spatial distribution of $^{137}$Cs inventories.

Fig. 4. Computed spatial patterns of soil redistribution rates.
14.5 t ha\(^{-1}\) yr\(^{-1}\)) and a net soil gain rate of 111 t yr\(^{-1}\) in the deposition area; hence a net soil loss of 125 t yr\(^{-1}\) for the study catchment (Table 5). Using these data, the sediment delivery ratio (SDR) for the catchment is calculated to be 53% (Table 5). This means that a large part of the eroded soil was re-deposited within the catchment.

### 3.4. Slope, curvature and soil redistribution

The computed slopes at the sampling points ranged from 0.5% to 8.4%, and the curvatures ranged from \(-0.5\) to \(0.5\) m\(^{-1}\). No significant correlations are found between soil erosion and slope gradient.
The 137Cs-method predicted a mean erosion rate of the same order of magnitude in the study catchment (Liu et al., 2008). The rates measured during the runoff plots were compared with data from the runoff plot measurements. The plots were established in a catchment ca. 8 km away from the study catchment. The estimated mean erosion rates of the runoff plots during 2003–2004 range from 8.1 to 28.2 t ha\(^{-1}\) yr\(^{-1}\) (Liu et al., 2008). The 137Cs-method predicted a mean erosion rate of the same order of magnitude (14.5 t ha\(^{-1}\) yr\(^{-1}\)). The measured sediment losses represent net export of soil only from the plots, because the plots are isolated from the surrounding areas. In addition, they are valid only for the measurement period although rainfall erosion capacity during 2003–2004 seems to be comparable to the mean rainfall erosion capacity in the study catchment (Liu et al., 2008).

4. Discussion

The reliability of 137Cs technique for estimating soil erosion is of great importance for soil loss control and land management. The rates of erosion estimated from the 137Cs measurements on the cores from the study catchment were compared with data from the runoff plot measurements. The plots were established in a catchment ca. 8 km away from the study catchment.

The estimated mean erosion rates of the runoff plots during 2003–2004 range from 8.1 to 28.2 t ha\(^{-1}\) yr\(^{-1}\) (Liu et al., 2008). The 137Cs-method predicted a mean erosion rate of the same order of magnitude (14.5 t ha\(^{-1}\) yr\(^{-1}\)). The measured sediment losses represent net export of soil only from the plots, because the plots are isolated from the surrounding areas. In addition, they are valid only for the measurement period although rainfall erosion capacity during 2003–2004 seems to be comparable to the mean rainfall erosion capacity in the study catchment (Liu et al., 2008).

The soil redistribution rates from the 137Cs method represent time-integrated, medium-term averages for the last 50 years, and are less influenced by extreme events (Schuller et al., 2003). Therefore, they were compared with soil redistribution rates estimated from a pedological investigation by Cui (2007), which also reflected the cumulative effect of past processes. Both rates are at the same order of magnitude. Therefore, the soil redistribution rates from the 137Cs measurements seem to be reliable.

Soil redistribution rates greatly depend on the position of sampling points (Nearing et al., 2005). In Songhuajiang Town of the black soil region, Fang et al. (2006b) found that the topsoil of upper slope positions was eroded and produced soil was accumulated in lower slope positions. The same pattern was also found in Bajiamiao Village of Dehu City, Jilin Province (Yan and Tang, 2005). In contrast, the erosion areas in the studied catchment were mainly located 0 to 100 m away from the shelterbelts, especially where ephemeral gullies occur. A large portion of eroded soils were deposited along the shelterbelts and at the catchment outlet (Figs. 4 and 5). The spatial pattern of soil redistribution led to a lower SDR value (Table 5). By contrast, in the Lucky Hills catchment of the Walnut Gulch Experimental Catchment (WGEW), southeast Arizona, SDR estimated from 137Cs data was 89% (Nearing et al., 2005). Annual rainfall in the WGEW is around 300 mm, which is less than that in our catchment, whereas slopes are much steeper in the WGEW, which may explain the higher SDR value.

Topographic factors such as slope gradient and curvature are usually regarded as main factors controlling soil redistribution (e.g., Sadiki et al., 2007; Porto et al., 2011). However, our study, as well as Fulajat (2003), Bujan et al. (2003) and Afshar et al. (2010) for Slovakia, Argentina and Iran suggested weak relations of soil redistribution rates with slope gradient and curvature. In our study area, soil redistribution may be more influenced by slope length (Cui et al., 2007) as well as disturbance by the shelterbelts and ephemeral gullies (Figs. 4 and 5). Although the on-site impacts of slope gradient and curvature may be limited, the off-site impacts linked to sediment transfer may still be important, as suggested from the SDR values for our study catchment and the WGEW. Moreover, gentle and long slopes characterize the study catchment, and a large upslope drainage area is usually required for ephemeral gully development in the black soil region.

The shelterbelts in the study catchment that split the long slopes into smaller ones were established in the 1970s (Zhu, 1985). When soil erosion occurs, the sediment eroded from upslope is intercepted by the shelterbelts, and some sediment also accumulates behind the shelterbelts due to reducing soil erosion capacity when runoff passes across the shelterbelts (Fig. 4; Cui et al., 2007). For the upper shelterbelt, the deposition areas in front of and behind the shelterbelt were 4.3 and 1.0 ha, with deposition rates of 6.8 and 4.7 t ha\(^{-1}\) yr\(^{-1}\), respectively. For the lower shelterbelt, the deposition areas in front of and behind the shelterbelt were 3.6 and 2.5 ha, with deposition rates of 7.6 and 8.1 t ha\(^{-1}\) yr\(^{-1}\), respectively. Annually, ca. 34 and 44 t yr\(^{-1}\) sediments were deposited along the upper and lower shelterbelts, respectively (Table 6).

The gullies developed in spring due to snowmelt runoff are eliminated by tillage activity when seeds are sowed, and reoccur at the same locations in the following rainy season (Casali et al., 2006; Meng and Li, 2009). Although we did not measure soil losses from the ephemeral gullies in spring, they can be very similar to those in the rainy season because of similar gully sizes (Zhang et al., 2007). Therefore, annual soil loss from the ephemeral gullies was around 72 t yr\(^{-1}\) (Table 1), with a gross erosion rate of 2.5 t ha\(^{-1}\) yr\(^{-1}\) (i.e., 0.25 kg m\(^{-2}\) yr\(^{-1}\)) for the whole catchment. The estimated erosion rate is comparable to those reported for other gully areas: 0.045 to 0.47 kg m\(^{-2}\) yr\(^{-1}\) for 19

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**Table 5**

Gross sediment budgets using the interpolated soil redistribution map.

<table>
<thead>
<tr>
<th>Locations</th>
<th>Soil redistribution (t ha(^{-1}) yr(^{-1}))</th>
<th>Soil loss (t yr(^{-1}))</th>
<th>Sediment delivery ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erosion area</td>
<td>-14.5</td>
<td>236.4</td>
<td>-</td>
</tr>
<tr>
<td>Deposition area</td>
<td>9.1</td>
<td>1110</td>
<td>-</td>
</tr>
<tr>
<td>All</td>
<td>-4.4</td>
<td>125.4</td>
<td>53</td>
</tr>
</tbody>
</table>

\((r^2 = 0.05, p = 0.07)\) and between soil erosion and curvature \((r^2 = 0.01, p = 0.50; \text{Fig. 6})\), suggesting that the impacts of slope gradient and curvature on soil redistribution rates were very limited.

**Fig. 6.** Relationships of soil loss/gain rates with (A) slope gradient and (B) slope curvature.
2005), the obtained mean erosion rate in the whole erosion area.

In the northern part of the study area, i.e., the Loess Plateau (Fang et al., 2008) and other regions (e.g., Nearing et al., 2000), the SDR catchment and an ephemeral gully had a mean erosion rate of 33 t yr^{-1} (14% of the total deposition) and 44 t yr^{-1} (19%), respectively. A sedimentation deposition rate at the catchment outlet was 33 t yr^{-1} (14%). Hence, a net soil loss from the catchment was ca. 125 t yr^{-1} (Fig. 7).

Although most eroded soil was deposited within the studied catchment and SDR was significantly lower than in the Loess Plateau (Fang et al., 2008) and other regions (e.g., Nearing et al., 2000), the obtained mean erosion rate in the whole erosion area (15.0 t ha^{-1} yr^{-1}) was much higher than the tolerable value (5.5 t ha^{-1} yr^{-1}; Fan et al., 2006). The black soil on the slopes in the catchment was shallow (usually 20–30 cm depth), and once topsoil was eroded below a certain thickness, it becomes unsuitable for agriculture and hard to be recovered. Therefore, effective soil conservation measures are required to reduce soil loss for sustainable land use.

5. Conclusions

The $^{137}$Cs technique was used to assess soil erosion and deposition characteristics for a 28.5 ha catchment in the typical black soil region of Northeast China. The soil redistribution rates were estimated by using the MBM2 for the 61 sampling points, and were verified by means of both runoff plot data and pedological investigation.

Based on the $^{137}$Cs data and the resultant estimates of soil loss/gain rates, the spatial distributions of $^{137}$Cs inventories and soil redistribution were mapped using the kriging interpolation. The gross soil loss for the whole catchment was $-4.4$ t ha^{-1} yr^{-1}. The soil redistribution was highly influenced by the shelterbelts and the development of the ephemeral gullies, whereas the impacts of slope gradient and curvature were insignificant at the 0.05 level. Soil erosion mainly occurred behind the shelterbelts and in areas with ephemeral gullies, while deposition occurred along the shelterbelts and at the catchment outlet. The soil losses from the slopes and the ephemeral gullies were 164 t yr^{-1} (69% of the total soil loss) and 72 t yr^{-1} (31%), respectively, and sediment gains along the shelterbelts and at the catchment outlet were 78 and 33 t yr^{-1}. Although only 53% of the eroded soil can be exported out of the catchment at the 50-year time-span, the net soil erosion of 14.5 t ha^{-1} yr^{-1} in the erosional areas was much higher than the tolerable value. Effective soil conservation measures are required to reduce the severe soil erosion and realize a sustainable land-use management.

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**Table 6**

<table>
<thead>
<tr>
<th>Area and sediment gain along the shelterbelts based on the interpolated soil redistribution map.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper shelterbelt</td>
</tr>
<tr>
<td>In front of shelterbelt</td>
</tr>
<tr>
<td>Area (ha)</td>
</tr>
<tr>
<td>4.3</td>
</tr>
</tbody>
</table>

**Fig. 7.** Sediment budget including the main erosion and deposition processes based on values in Tables 1, 5 and 6. The soil loss from the slopes is estimated from the total soil loss in the catchment and the soil loss from the ephemeral gullies.
References


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