Variability of Beryllium-7 and Its Potential for Documenting Soil and Soil Organic Carbon Redistribution by Erosion

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Limited understanding of the redistribution of soil and soil organic C (SOC) within landscapes and their corresponding delivery ratios is available. To improve this assignment, the beryllium-7 ($^7$Be) technique and a simple conversion model were used to estimate soil and SOC redistribution rates on a sloping cropland plot (5 m wide and 15 m long with a slope of 10$^\circ$) in the hilly red soil region of southern China. Results showed that the soil erosion and deposition rates were relatively consistent with the magnitude of a rainfall event, and the estimated net soil and SOC losses were close to the measured values. These findings suggested the potential of $^7$Be measurements in quantifying soil and SOC redistribution patterns associated with short-term erosion from heavy rainfalls. The spatial redistribution patterns of soil and SOC presented alternating erosion–deposition patterns from the slope crest to the bottom. Heavy erosion occurred in the upper- and lower-middle regions of the slope. The estimated net soil and SOC loss were 1.14 kg m$^{-2}$ and 23.00 g m$^{-2}$ for tillage from spring to summer (S–S, March–July 2013), clearly exceeding the soil (0.017 kg m$^{-2}$) and SOC loss (0.43 g m$^{-2}$) observed for no tillage from summer to winter (S–W, July 2013–January 2014). The sediment delivery rates in the two periods were calculated to be 64.41 and 2.51%, respectively, and the SOC delivery rates were estimated to be 58.17 and 6.48%, respectively. Depending on the weather conditions, tillage can result in a substantial increase in soil and SOC loss under traditional land use.

Abbreviations: SOC, soil organic carbon; S–S, spring to summer; S–W, summer to winter.

Accelerated erosion by water and tillage can cause increased mobilization and redistribution of the surface soil and sediment-associated soil organic C (SOC) (Lal, 2003, 2005; Lal and Pimentel, 2008; Zhang et al., 2013b). Attention has been given to both the on-site and off-site impacts of soil erosion, and deep insights into the important role of soil erosion in the transfer of SOC in terrestrial land aquatic ecosystems have been obtained (Van Oost et al., 2007; Polyakov and Lal, 2008; Wang and Shi, 2015). These findings have heightened the need for a dependable quantitative method of evaluating soil erosional rates and patterns from agricultural land. Soil erosional rates, including gross and net erosional rates, provide evidence

Core Ideas

- The $^7$Be technique can quantify soil and SOC redistribution under short-term erosion.
- The heavy erosion happened in the upper-middle and down-middle location of the slope.
- Depending on the weather, plowing can result in a substantial increase in erosion.

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of soil degradation. In particular, net rates can determine the proportion of eroded sediments transferred toward a local water catchment instead of deposited close to the eroded area. The ratio of net to gross erosion in a specific areal unit is frequently obtained as its sediment delivery ratio (Butzen et al., 2014; García-Ruiz et al., 2015; Jha et al., 2015); this parameter offers a valuable measure of the efficiency of the transport processes operating within this unit. Soil organic C loss during erosion can also be estimated by the soil redistribution rate, which is obtained by multiplying the original SOC content by the SOC enrichment ratio (Starr et al., 2000; Polyakov and Lal, 2004; Martínez-Mena et al., 2008). Evidence indicating strong significant relationships between soil redistribution and SOC concentrations has been obtained, and these relationships have been observed to move along similar physical pathways in the agricultural landscape (Van Oost et al., 2005; Ritchie et al., 2007). Information on soil and SOC loss could be achieved using conventional field monitoring techniques (Rimal and Lal, 2009; Sasal et al., 2010; Ha et al., 2012). However, only a limited understanding of the redistribution of soil and SOC loss within landscapes and their corresponding delivery ratios is available. For example, field plots, (e.g., 1 by 1, 2 by 5, or 5 by 20 m), which are usually established to study soil erosion processes (Mutchler et al., 1994; Boix-Fayos et al., 2006; Ha et al., 2012), collect only information on the net erosion amount by measuring the sediment content in downsloping sand basins.

The environmental radionuclides of $^{137}$Cs (half-life 30.1 yr) and unsupported $^{210}$Pb (half-life 22.3 yr) have been introduced to calculate soil erosional and depositional rates by soil erosion (Gaspar et al., 2013). The potential of using $^{137}$Cs and $^{210}$Pb to document medium- or long-term (i.e., approximately 45 yr for $^{137}$Cs and 100 yr for $^{210}$Pb) soil and SOC redistributions under various agroenvironmental and natural conditions has been successfully demonstrated in many regions (Collins et al., 2001; Li et al., 2003; Ritchie and McHenry, 1990; Wakiyama et al., 2010; Zhang et al., 2004; Fang et al., 2012; Zhang and Li, 2013). Reliable quantitative data on the patterns and rates of soil redistribution estimated by environmental radionuclides can provide a more comprehensive assessment of the magnitude of the problems and support the selection of effective soil conservation measures (Ritchie and McHenry, 1990; Zapata, 2003). However, neither of these radionuclides can be applied to study soil and SOC loss rates under individual rainfall events or short-term erosion characterized by the cultivated land (Mabit et al., 2008).

Beryllium-$^7$ (half-life 53.3 d) shows considerable potential in meeting this need because of its similar behavior but much shorter half-life compared with those of $^{137}$Cs and $^{210}$Pb (Mabit et al., 2008; Sepulveda et al., 2008; Schuller et al., 2010). The potential of using $^7$Be measurements to calculate soil erosion and sedimentation rates has been confirmed by numerous studies (Walling et al., 1999; Blake et al., 1999; Sepulveda et al., 2008; Shi et al., 2011a). Beryllium-$^7$ is a natural radionuclide formed by cosmic-ray spallation of $^N_2$ and $^O_2$ nuclei within the Earth’s atmosphere (Papastefanou and Ioannidou, 2004). Once produced, $^7$Be quickly combines with submicron-size aerosols and subsequently deposits on the Earth’s surface by wet and dry deposition (Feely et al., 1989). When $^7$Be comes in contact with soil, it is immediately and strongly fixed and retained predominantly in the upper 2 cm of the soil profile (Sepulveda et al., 2008; Schuller et al., 2010). Existing evidence reveals that the initial depth distribution of the $^7$Be inventory (Bq kg$^{-1}$) in undisturbed sites decreases exponentially with depth. In fact, most of the $^7$Be inventory has been found to concentrate within a millimeter of the surface soil (Wallbrink and Murray, 1996; Walling et al., 1999; Sepulveda et al., 2008; Schuller et al., 2010). The use of the $^7$Be technique to estimate soil redistribution is based on comparisons of the measured $^7$Be inventory (Bq m$^{-2}$) between sampling sites and a vicinal reference site with neither erosion nor deposition (Walling et al., 1999). Erosion occurs when the $^7$Be inventory decreases relative to the reference value, whereas deposition is distinguished by increased $^7$Be concentrations. The amount of soil lost and gained can be derived using the model developed by Walling et al. (1999). Given this premise, the $^7$Be method has been proven to be good for calculating the soil redistribution rate during an individual event or short-term soil erosion (Walling et al., 1999; Sepulveda et al., 2008).

In the red hilly region of southern China, the magnitude and pattern of soil erosion and SOC loss exhibit significant temporal and spatial variations because of seasonal changes in precipitation and tillage practices (Zhang et al., 2012; Nie et al., 2014). To clarify soil and SOC redistribution characteristics within the study area, the $^7$Be technique was applied to a field plot. This study had several objectives: (i) the soil redistribution rate was calculated by comparing the $^7$Be inventory in specific sampling points with that at the reference site; (ii) the potential of using $^7$Be measurements to document soil redistribution was then explored by comparing net soil loss values estimated using $^7$Be with those estimated by direct measurements of soil loss in short-term periods; and (iii) the redistribution rate of the sediment-associated SOC was estimated by coupling the soil loss calculated by the $^7$Be technique with the SOC computational method introduced by Starr et al. (2000) for short-term periods. The information obtained in this work will contribute to improving the current understanding of soil and SOC redistribution characteristics under short-term soil loss caused by water erosion and tillage practices and the soil and water conservation in the hilly red soil region of southern China.

MATERIALS AND METHODS

Study Site

The study site was located within a cultivated field at the soil and water conservation research station of Shaoyang (111°30’ E, 27°17’ N) in southwest-central Hunan Province, which belongs to the hilly red soil region of southern China, covering a total area of $2.18 \times 10^6$ km$^2$ (Zhao, 2002) (Fig. 1). The site, with elevations ranging from 231 to 276 m, is typical of hilly areas. The slope of the region is gentle at 10 to 15°. The width of this geographic area also makes it an important component of the

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The soil is a quaternary red clay Ultisol according to the US Soil Taxonomy (Soil Survey Staff, 1993) and is texturally classified as clay to loam (33% clay, 28% silt, and 39% sand within the upper 5 cm of the soil profile). Red soils are low in SOC (about 7%) and susceptible to erosion. The mean bulk density of the soil is 1.3 g cm$^{-3}$, and its pH is 5.5. The study area is characterized by a subtropical monsoon climate with a mean annual temperature of 17.1°C and mean annual precipitation of 1327.5 mm. High-intensity rainfalls are concentrated between the spring and autumn.

**Rainfall Record and Soil Sampling Strategy**

**Rainfall Record**

Continuous rainfall records were obtained by using a digital rain gauge installed at the study site. Rainfall was recorded from January 2013 to January 2014 (Fig. 2). Soil redistribution was estimated for two extended periods. The first duration commenced on 8 Mar. 2013 and was terminated on 4 July 2013 (between spring and summer). The total rainfall of this period was 563 mm, including three heavy rainfall events (i.e., intensity >25 mm in 24 h) of 34.4, 45.8, and 53.7 mm, respectively, on 19 and 20 March and 28 June, respectively. After a prolonged rainy period, the field was sampled for $^7$Be measurement on 4 July. The second sampling was conducted on 2 Jan. 2014 after a period of 6 mo during which the total precipitation was merely 361 mm, including only one erosive rainfall event of 46.3 mm on 11 Nov. 2013.

**Soil Sampling Strategy**

The experiment was conducted at a 15- by 5-m (length by width) plot with a slope of 10°. The plot was established with its length parallel to the predominant direction of water flow. The soil was plowed in early March 2013 before maize ($Zea mays$ L.) was planted in May 2013. Thereafter, the soil was left undisturbed with no fertilizer application or weeding. The tillage depth was 30 cm. Upon intensive tillage, all of the $^7$Be was mixed within the plow layer, and the $^7$Be activity in the soil was diluted to levels below the detection limit before the heavy rainfall. A sand basin of 1-m$^3$ capacity was built at the bottom of the plot to collect eroded sediments for comparison between the simulated and measured values.
To document the distribution of the $^7$Be inventory and SOC concentration across the plot, the study plot was divided into a grid of 24 equivalent areas. Every soil sample was collected in the center of each area. A total of 24 soil samples was obtained. Each soil sample was collected from within an area of 15 by 30 cm to the 2-cm depth using a scraper. Each soil sample weighed 500 g and was subdivided into two portions. One portion was used for $^7$Be analysis, and the remainder was used to determine SOC concentrations. A total of 24 soil bulk density samples was collected at the corresponding sampling points to determine the $^7$Be inventory. The total sediment yield obtained for the entire study period was collected and weighed.

To determine the values of the reference $^7$Be areal inventory ($A_{\text{ref}}$) and the relaxation mass depth ($h_0$), an adjacent weed-less flat open area with no obvious signs of erosion or deposition was chosen as a reference site. Incremental samples of 3 mm were obtained using a scraper to the 2-cm depth in an area of 15 by 30 cm. Bulk samples were also collected.

**Laboratory Determinations**

All collected soil samples were air dried at room temperature and then crushed. Subsamples were sieved using a 0.25-mm mesh for SOC analysis. The SOC concentrations were determined using the dichromate oxidation method (Walkley and Black, 1934). Bulk samples were dried at 105°C for 48 h; stones and coarse roots in the samples were retained to determine their volume through water displacement in a measuring cylinder. The soil bulk density was calculated by dividing the oven-dried soil mass by the steel cylinder volume minus the stone and coarse root volumes (Carter, 1993).

Beryllium-7 measurement was performed at the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences. The relevant measurement processes have been presented by Shi et al. (2011b, 2012). The $^7$Be inventory of each sample was determined by $\gamma$-spectrometry using a GMX40P4 coaxial HPGe detector (Ortec) of 40% relative efficiency with a resolution of 2 keV at 1.33 MeV. The detector was calibrated using mixed sources in the same geometry. The validity for $^7$Be was calculated by interpolating the 477.6 keV $\gamma$-ray. Count times reached approximately 86,400 s with a detection limit of 5.7 Bq kg$^{-1}$ (better than ±10% at a 95% level of confidence). The $^7$Be activities were decay corrected to the day of sampling.

**Calculation of Soil and Soil Organic Carbon Erosion or Deposition**

A simple conversion model based on $^7$Be depth distribution was established to document the soil redistribution induced by high-intensity rainfall through comparison of the $^7$Be inventory of the study site with that of the reference site (Walleng et al., 1999; Blake et al., 1999). Sampling points with $^7$Be contents lower than that of the reference site were considered to feature erosion, and the sampling points with $^7$Be contents greater than the reference value were considered to feature deposition. The model, as presented by Sepulveda et al. (2008), is described below.

The reference $^7$Be mass activity distribution in the soil profile is expressed as

$$C(x) = C(0) \exp \left( -\frac{x}{h_0} \right)$$  \[1\]

where $C(x)$ is the $^7$Be inventory at mass depth $x$ (Bq kg$^{-1}$), $x$ is the mass depth of the soil measured from the surface (kg m$^{-2}$), $C(0)$ is the initial $^7$Be concentration in the surface soil (at $x = 0$), and $h_0$ is the relaxation mass depth (kg m$^{-2}$).

The reference $^7$Be areal inventory distribution in the soil profile is determined as

$$A(x) = \int_{x}^{\infty} C(x) \, dx = A_{\text{ref}} \exp \left( -\frac{x}{h_0} \right)$$  \[2\]

where $A(x)$ is the areal inventory below mass depth $x$ (Bq m$^{-2}$) and $A_{\text{ref}}$ is the initial $^7$Be areal concentration at the soil surface (at $x = 0$) (Bq m$^{-2}$):

$$A_{\text{ref}} = A(0) = \int_{0}^{\infty} C_s \, dx = b_h C_0$$  \[3\]

According to Eq. [2], the areal inventory below the relaxation mass depth is given by

$$A(b_h) = 0.368 A_{\text{ref}}$$  \[4\]

Therefore, 63.2% of the total areal inventory of $^7$Be will be found within the 0 to $h_0$ soil layer. Consequently, a greater $h_0$ would result in deeper penetration of the radionuclide into the soil.

The remaining $^7$Be areal inventory at the sampling point can be calculated as

$$A = A(R) = A_{\text{ref}} \exp \left( -\frac{R}{h_0} \right)$$  \[5\]

where $A$ is the $^7$Be areal inventory remaining at this eroded point (Bq m$^{-2}$) and $R$ is the soil erosion rate (a thin soil layer of mass depth removed by erosion) (kg m$^{-2}$).

The soil erosion rate at a sampling point was calculated as

$$R = b_h \ln \left( \frac{A_{\text{ref}}}{A} \right)$$  \[6\]

The soil deposition rate at a sampling point was estimated using

$$R' = \frac{A' - A_{\text{ref}}}{C_s}$$  \[7\]

where $R'$ is the soil deposition rate (a thin soil layer of mass depth accumulated) (kg m$^{-2}$), $C_s$ is the mean $^7$Be mass concentration of the deposited sediment (Bq kg$^{-1}$), and $A'$ is the measured $^7$Be areal inventory exceeding $A_{\text{ref}}$ (Bq m$^{-2}$).

The $^7$Be mass inventory of the sediment eroded from a point can be estimated as
where $S$ is the upslope contributing area (m$^2$) and $C_e$ is the $^7$Be mass inventory of the sediment eroded from a point (Bq kg$^{-1}$):

$$C_e = \int_S C_e RdS \int_S RdS$$

[8]

The SOC redistribution rate was calculated using (Starr et al., 2000)

$$SOC_{red} = soil_{red} CER$$

[10]

where SOC$_{red}$ is the amount of SOC lost or gained (g m$^{-2}$), soil$_{red}$ is the amount of soil lost or deposited (kg m$^{-2}$), C is the SOC content of the initial topsoil (g kg$^{-1}$), and ER is the SOC enrichment ratio, which was calculated as (Deumlich and Völker, 2003)

$$ER = 2.53d^{-0.21}$$

[11]

where $d$ is the total amount of soil eroded across the study area (t ha$^{-1}$).

**Geostatistical Analysis**

ArcGIS 10.0 was used to create soil (kg m$^{-2}$) and SOC (g m$^{-2}$) spatial redistribution maps. Erosion points were expressed with negative values and deposition points were expressed with positive values. Maps of the spatial distribution of the soil and SOC redistribution were produced using the ordinary kriging approach for data interpolation. Kriging is based on the assumption that the parameter interpolated can be regarded as a localized variable (Matheron, 1963). The method uses nearby points weighted by distance from the interpolate location and the degree of autocorrelation or spatial structure for those distances and calculates the optimum weights at each sampling distance. Erosion or deposition areas were obtained by calculating grid cell values using ArcGIS 10.0. Statistical analyses were conducted using SPSS 20.0 software.

**RESULTS**

**Relevant Parameters of Beryllium-7 Measurement Model**

The distribution of $^7$Be mass activity inventory varied with soil depth at the reference site (Fig. 3). As expected, the maximum $^7$Be concentration was detected in the surface soil layer, and subsequently, the inventory decreased swiftly and exponentially with increasing depth.

The linear regression between the natural logarithm of the average $^7$Be areal activity inventory ($ln[A(x)]$) and the mass depth ($x$) showed significant correlations ($R = 0.92$ and 0.99 in July 2013 and January 2014, respectively) at the 99% level of confidence. The estimated values of the relaxation mass depth ($h_0$) and the reference areal activity inventory ($A_{ref}$) in July 2013 were 4.36 ± 0.17 kg m$^{-2}$ and 318 ± 18 Bq m$^{-2}$, respectively. These values in January 2014 were 4.11 ± 0.19 kg m$^{-2}$ and 215 ± 15 Bq m$^{-2}$, respectively. The estimated relaxation mass depth indicated that 63% of the $^7$Be areal activity concentrations were detected in the superficial topsoil above a mass depth of 4.36 and 4.11 kg m$^{-2}$ (≈4.63 and 2.67 mm, respectively) in July 2013 and January 2014, respectively.

By setting $h_0 = 4.36$ or 4.11 kg m$^{-2}$, $A_{ref} = 318$ or 215 Bq m$^{-2}$, and $C(0) = A_{ref}/h_0 = 72.94$ ± 52.31 Bq kg$^{-1}$ in July 2013 and January 2014, respectively, we thus expressed Eq. [1] and [3] as follows:

July 2013

$$C(x) = 72.94 \exp\left(-\frac{x}{4.36}\right)$$

[12]

$$A(x) = 318 \exp\left(-\frac{x}{4.36}\right)$$

[13]

January 2014

$$C(x) = 52.31 \exp\left(-\frac{x}{2.67}\right)$$

$$A(x) = 215 \exp\left(-\frac{x}{2.67}\right)$$

Fig. 3. The initial distribution of $^7$Be mass activity inventory at the reference site, including the reference $^7$Be areal inventory ($A_{ref}$) and the relaxation mass depth ($h_0$), in (a) July 2013 and (b) January 2014.
The $^7$Be activity is below the detection limit at mass depths of 11.11 and 9.11 kg m$^{-2}$ ($\approx 1.179$ and 5.92 mm, respectively) in July 2013 and January 2014, respectively. Hence, the calculated inventory below this depth should be deducted from the total concentration obtained from the regression. For instance:

**July 2013**

$$318 - \int_{x=11.11}^{\infty} 72.94 \exp\left(-\frac{x}{4.36}\right) dx = 293$$

**January 2014**

$$215 - \int_{x=9.11}^{\infty} 52.31 \exp\left(-\frac{x}{4.11}\right) dx = 192$$

The calculated values (293 and 192 Bq m$^{-2}$) are in very close agreement with the measured mean $^7$Be inventory values of $A_{\text{ref}}$ (293 ± 35 and 192 ± 23 Bq m$^{-2}$) obtained from the 2-cm-deep soil samples at the reference site in July 2013 and January 2014, respectively. Thus, the former could be applied to the estimate of the soil redistribution.

**Soil Redistribution Associated with Short-Term Rainfall**

The pattern and magnitude of soil redistribution were different according to slope locations, tillage practices, and seasons (Fig. 4). For spring to summer (S–S) under tillage, except for a small deposition at some sampled points, erosion occurred within 7 and 9 to 13 m away from the top of the plot, and a narrow deposition channel existed from the southwest corner to the northeast corner of the plot (Fig. 4a). Some estimates of the sampling points were higher or lower than expected from the general pattern. Nevertheless, the overall pattern of soil redistribution indicated that erosion was found principally in the upper- and lower-middle regions of the plot. By contrast, deposition was noted at the middle and bottom regions of the plot. For spring to winter (S–W) with no tillage, deposition occurred at the edge of the plot, whereas erosion was observed in the middle of the plot parallel to the flow. The heavy erosion points were located in the upper- and lower-middle regions of the plot. Differences existed in the magnitude of soil redistribution depending on the tillage practices and seasons during the two stages (Table 1). For S–S under tillage, approximately 57.44% of the sampled area experienced erosion, whereas de-

Fig. 4. Soil redistribution estimated by $^7$Be measurement in (a) spring to summer and (b) summer to winter.

*Fig. 4. Soil redistribution estimated by $^7$Be measurement in (a) spring to summer and (b) summer to winter.*
position occurred in the remaining 42.56% of the area. The mean soil loss rate was 3.08 kg m\(^{-2}\) and the deposition rate was 1.48 kg m\(^{-2}\). The rainfall events brought about a net erosion of 1.14 kg m\(^{-2}\) characterized by sediment delivery of 64.41%. Compared with the measured soil loss of 1.52 kg m\(^{-2}\), the simulated value was approximately 25% lower. The area suffered lower intensity erosion in S–W under no tillage compared with that during S–S under tillage. Around 45.83% of the study plot was subjected to erosion, whereas deposition occurred in the remaining 54.17% of the plot. Both soil loss and deposition rates decreased relative to that in S–S under tillage. A soil loss rate of 1.45 kg m\(^{-2}\) was estimated for the erosion points, and the deposition rate was estimated to be 1.19 kg m\(^{-2}\). By combining these data, we obtained a net soil loss rate of 0.017 kg m\(^{-2}\), which was distinguished by a sediment delivery of 2.51%. This result was close to the measured soil loss amount of 0.018 kg m\(^{-2}\), which was 6% lower.

### Soil Organic Carbon Redistribution Based on Soil Erosion or Deposition

The pattern of the SOC displacement rate was similar to that of soil redistribution (Fig. 5). Soil organic C loss predominantly occurred in the upper- and lower-middle portions of the plot, whereas SOC increased in the middle and bottom plot regions in S–S under tillage (Fig. 5a). Soil organic C loss occurred in 57.44% of the study area, which concentrated within 6 and 9 to 13 m away from the top of the plot. By contrast, the remaining areas, mostly distributed within 6 to 9 and 13 to 15 m away from the top of the plot, were found to correspond to the SOC deposition area. Soil organic C redistribution presented a pattern of

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### Table 1. Soil redistribution by season documented for the study plot based on variability of \(^{7}\)Be inventory.

<table>
<thead>
<tr>
<th>Season†</th>
<th>Soil loss rate‡</th>
<th>Eroding fraction proportion</th>
<th>Soil deposition rate‡</th>
<th>Depositional fraction proportion</th>
<th>Total plot</th>
<th>Net erosion rate</th>
<th>Sediment delivery rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>S–S</td>
<td>3.08</td>
<td>57.44</td>
<td>1.48</td>
<td>42.56</td>
<td></td>
<td>1.14</td>
<td>64.41</td>
</tr>
<tr>
<td>S–W</td>
<td>1.45</td>
<td>45.83</td>
<td>1.19</td>
<td>54.17</td>
<td></td>
<td>0.017</td>
<td>2.51</td>
</tr>
</tbody>
</table>

† S–S, spring to summer; S–W, summer to winter.
‡ Soil loss and deposition rates are mean values.

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**Fig. 5.** Soil organic C (SOC) displacement rate under the influence of heavy rainfall events in (a) spring to summer and (b) summer to winter.
The seasonal and regional variability of $^7$Be inventories in the atmosphere (Kaste et al., 2002) make direct comparisons among reference inventory values from different locations very difficult. However, contrasting the given $^7$Be areal activities connected with the total rainfall during the research period can be attempted in regions of different latitudes. The information in Table 3 shows that $^7$Be reference inventory values are predominantly associated with latitude and precipitation. More release amounts of $^7$Be existed at high latitudes than low latitudes, whereas for the equivalent latitude, greater precipitation could cause greater deposition flux of the $^7$Be inventory. Matsi and Whiting (2012) also found a strong linear correlation between the annual delivery of $^7$Be and annual precipitation by summarizing preexisting studies. In this study, the $^7$Be reference inventory in the summer was higher than that in winter. This result could be attributed to the high concentration in the surface layer produced by strongly fluid air exchange between the stratosphere and troposphere from April to May and the abundant precipitation that falls in the summer.

Table 2. Soil organic C (SOC) redistribution estimated on the basis of soil loss rate derived by $^7$Be measurement by season.

<table>
<thead>
<tr>
<th>Season†</th>
<th>SOC loss rate‡</th>
<th>Eroding fraction proportion</th>
<th>SOC deposition rate§</th>
<th>Depositional fraction proportion</th>
<th>SOC net loss rate</th>
<th>SOC delivery rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>S–S</td>
<td>63.34</td>
<td>57.44</td>
<td>31.44</td>
<td>42.56%</td>
<td>0.43</td>
<td>6.48</td>
</tr>
<tr>
<td>S–W</td>
<td>14.43</td>
<td>45.83</td>
<td>11.42</td>
<td>54.17%</td>
<td>23.00</td>
<td>58.17</td>
</tr>
</tbody>
</table>

† S–S, spring to summer; S–W, summer to winter.
‡ Soil loss and deposition rates are mean values.

Discussion

Spatial Variability of Beryllium-7 Reference Inventory

As expected, the depth distribution of $^7$Be in the study region showed a smooth, exponential pattern, with the maximum concentration found at the top 3 to 5 mm of the soil (Fig. 2). These results are consistent with those obtained by Walling et al. (1999), Sepulveda et al. (2008), Schuller et al. (2010), and Iurian et al. (2013). Beryllium-7 is a product of high-energy spallation reactions of $N_2$ and $O_2$ in the upper atmosphere caused by cosmic rays. Once produced, $^7$Be is immediately attached in the upper few millimeters of soil. The highest mass activity of $^7$Be at the soil surface will decay below the minimum detectable activity after 5 mo time. Hence, measuring $^7$Be to document soil redistribution is limited to a short period and also to sheet erosion. Furthermore, this limitation results in the underestimation of soil erosion. Beryllium-7 could be detected in this study within the top layer of 11.11 and 9.11 kg m$^{-2}$ ($\sim$5.92 and 11.79 mm) during S–S and S–W, respectively. Many studies have recorded $^7$Be depth profiles in the upper 10 mm of soil (Blake et al., 1999; Walling et al., 1999; Sepulveda et al., 2008; Schuller et al., 2010). Sepulveda et al. (2008) pointed out that if $^7$Be can be discovered in the soil beyond the depth of 30 mm, bioturbation or cultivation will be the only interpretation.

Effects of Short-Term Water Erosion on Soil and Soil Organic Carbon Redistribution

Our results verify the potential of using $^7$Be techniques to document soil redistribution associated with short-term heavy rainfall events. First, the soil erosion and deposition rates were relatively consistent with the magnitude of the rainfall event, the condition of the field, and visual evidence of erosion. Second, the estimated net eroded soils during S–S and S–W were 25 and 6% lower than the measured values, respectively, which nearly agreed with $^7$Be measurements, with the result that the error rate was 14%, which is better than the error rate of 30% from the erosion pin by Shi et al. (2011b). Moreover, the $^7$Be techniques could be deemed a valuable supplement to $^{137}$Cs measurements for the study of soil erosion in the red hilly region of southern China. Ma et al. (2016) succeeded in using $^{137}$Cs measurement for estimating the averages of mid-term soil loss values from 0.16 ± 0.14 to 0.42 ± 0.13 kg m$^{-2}$ yr$^{-1}$ as reported for the previous 50 yr in this region. This result would then contribute to the understanding of long-term erosion. However, extreme rainfall events have increased in recent years because of weather changes (Martinez-Casanovas et al., 2002). Soil erosion has long existed with great differences; hence, short-term erosion will be of great importance in future studies. Beryllium-7, with its short half-life, could meet the requirement. The value of short-term net erosion from March 2013 to January 2014 in this research was recorded...
at 1.15 kg m$^{-2}$ yr$^{-1}$. Obviously, short-term soil erosion is higher than the average soil erosion for the past 50 yr. Beryllium-7 measurement can better respond to short-term erosion. In summary, erosion research can be accomplished by combining $^{137}$Cs and $^7$Be measurements. The simple conversion model of Walling et al. (1999) was selected in this study, and the results from this research showed its successful application. Data applied to the model are easy to obtain, and model calculations are simple. Hence, implementing the simple model is highly practical. Many researchers have used this model to estimate the redistribution rates of short-term erosion (Walling et al., 1999; Blake et al., 1999; Sepulveda et al., 2008; Shi et al., 2011b).

Magnitudes and patterns of soil redistribution are closely correlated with cultivation methods, slope locations, and precipitation. Tillage could disturb and loosen the soil, thereby enabling easy removal by runoff. In turn, the absence of tillage did not differently affect the soil, and therefore less relative influence would be exerted by water erosion. Previous evidence showed that tillage contributes to greater soil loss than the absence of tillage (Six et al., 1999; Basic et al., 2004). Data from field-simulated rainfall experiments in this area showed more soil loss generated under tillage than no tillage for high-intensity rainfalls (Ma et al., 2014). Obvious differences in soil redistribution rates among slope locations were noted. The spatial variation of the soil redistribution on the slope presented the pattern of alternate erosion and deposition, which agreed with the investigation undertaken by Shi et al. (2011b), who suggested that more sampling points experienced deposition in the middle and lower subfield of the plot than in the upper subfield. This can provide reference information on the slope length for soil and water conservation engineering.

Beryllium-7 measurement, combined with the calculation equation of SOC loss of Starr et al. (2000), was used to indirectly estimate the SOC redistribution rates. The SOC redistribution rates were calculated by the product of soil redistribution rates, original SOC content, and SOC enrichment ratio. Hence, SOC redistribution exhibited a similar pattern to that of soil redistribution. The SOC enrichment ratio, which was considered a constant, would increase the error between the simulated and measured values. However, the errors were not significant, and the calculation could be simplified. Field-simulated rainfall experiments in this region demonstrated that sediments are the main carriers of SOC loss (Nie et al., 2014). Thus, the SOC loss rate was subject to the initial SOC content as well as the soil loss amount.

The soil and SOC redistribution caused by soil erosion would result in soil degradation at erosion sites and an increase in soil quality at the depositional area (Lal, 2005). Soil organic C is a key factor determining soil quality, and SOC redistribution results in numerous ecological and environmental consequences (Lal et al., 2004). Such effects generate nonpoint-source pollution and lead to the emission of greenhouse gases (Lal et al., 2004). Soil organic C redistribution affects global C dynamics (Lal, 2003). Even so, the fate of eroded SOC is not clear and remains a controversial issue. Some researchers have argued that the eroded SOC transported to aquatic ecosystems is buried and sequestered (Harden et al., 2008), whereas soil scientists have believed that a fraction of SOC transported across the landscape is mineralized and released to the atmosphere (Lal and Pimentel, 2008). Quantitative estimation is needed to resolve the issue; thus, the application of $^7$Be measurement of soil and SOC redistribution is significant. The results can offer information for soil and water conservation in the hilly red soil region of southern China.

CONCLUSIONS

Beryllium-7 areal inventories were measured to calculate the erosion rates of soil and SOC in the hilly red soil region of southern China. The study results show that $^7$Be concentrations varied with the season and were strongly influenced by the precipitation regime. The soil erosion and deposition rates were relatively consistent with the magnitude of the rainfall event, the condition of the field, and visual evidence of erosion, and the net erosion sediment and SOC yields estimated by the model were close to the measured values. These findings clearly demonstrate the potential in using the $^7$Be technique to estimate soil and SOC redistribution on agricultural land associated with short-term erosion during heavy rainfall events. Information on short-term soil erosion obtained through $^7$Be measurements effectively supplements the data on mid-term soil erosion acquired through $^{137}$Cs measurements. Furthermore, the $^7$Be technique offers an obvious advantage in determination of the spatial distribution of erosion and deposition, except for information on gross and net soil and SOC losses from the overall plot, compared with the traditional monitoring methods (e.g., erosion plots). However, future work is required to explore the potential of $^7$Be measurements at larger scales of time and space.

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude</th>
<th>Sampling time</th>
<th>Precipitation during study</th>
<th>$^7$Be areal activity</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>San German, Valdivia, Chile</td>
<td>39°44′S</td>
<td>28 Apr.–25 June 2008</td>
<td>664</td>
<td>1071</td>
<td>Schuller et al. (2010)</td>
</tr>
<tr>
<td>San German, Valdivia, Chile</td>
<td>39°44′S</td>
<td>28 Apr.–24 Sept. 2008</td>
<td>2089</td>
<td>2678</td>
<td>Schuller et al. (2010)</td>
</tr>
<tr>
<td>Buenos Aires, Chile</td>
<td>38°37′S</td>
<td>3–29 May 2005</td>
<td>400</td>
<td>473</td>
<td>Sepulveda et al. (2008)</td>
</tr>
<tr>
<td>Ansai County, Shanxi Province, China</td>
<td>36°51′N</td>
<td>1 Apr.–20 Aug. 2011</td>
<td>290</td>
<td>540</td>
<td>Zhang et al. (2013a)</td>
</tr>
<tr>
<td>Shaoyang County, Hunan Province, China</td>
<td>27°3′N</td>
<td>8 Mar.–4 July 2013</td>
<td>563</td>
<td>298</td>
<td>this study</td>
</tr>
<tr>
<td>Shaoyang County, Hunan Province, China</td>
<td>27°3′N</td>
<td>5 July 2013–3 Jan. 2014</td>
<td>361</td>
<td>207</td>
<td>this study</td>
</tr>
</tbody>
</table>
The magnitude and patterns of soil and SOC transportation documented by \(^{7}\)Be measurements across the plot illustrate that tillage practices, slope locations, and precipitation exerted important roles in soil and SOC redistribution. The increases in soil and SOC erosion were caused by tillage, heavy rainfall, and, more particularly, the practice of leaving plowed fields exposed to summer rainfalls; soil and SOC losses decreased under no tillage. Heavy soil erosion principally occurred in the upper-middle position of the study plot, whereas deposition was noted at the bottom of the plot. Depending on the weather, tillage increases the soil and SOC erosional rates; the absence of tillage protects the soil from erosion.

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