Rare earth elements tracing the soil erosion processes on slope surface under natural rainfall

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1. Introduction

 Soil erosion is composed of a complex processing including soil detachment by raindrop impact and surface flow, and soil particle transport by rain splash and surface flow during rainfall event (Ellison, 1944). Traditional soil erosion research methods, such as ground and stereo-photo-surveys, rainfall simulation, watersheds monitoring etc. can be used to study erosion intensity, causes, and effects. While these methods evaluate soil erosion as a temporally and spatially integrated quantity by comparing the eroded state after rainfall with the initial soil state or by collecting eroded and transported materials. Therefore, they are inadequate to investigate soil erosion physical processes. Also current studies cannot tell with accuracy the source of sediment in soil erosion processes, but the data of erosion process and sediment sources are extremely useful in developing erosion prediction models, understanding erosion processes and determining sediment sources.

A field experiment using rare earth elements (REEs) as tracers was conducted to investigate soil erosion processes on slope surfaces during rainfall events. A plot of 10 m × 2 m × 0.16 m with a gradient of 20° (36.4%) was established and the plot was divided into two layers and four segments. Various REE tracers were applied to the different layers and segments to determine sediment dynamics under natural rainfall. Results indicated that sheet erosion accounted for more than 90% of total erosion when the rainfall amount and density was not large enough to generate concentrated flows. Sediment source changed in different sections on the slope surface, and the primary sediment source area tended to move upslope as erosion progressed. In rill erosion, sediment discharge mainly originated from the toe-slope and moved upwards as erosion intensified. The results obtained from this study suggest that multi-REE tracer technique is valuable in understanding the erosion processes and determining sediment sources.

The best management practices to control soil erosion. While sheetwash can occur over much of the study area, the contribution of sheet erosion to water quality and the reduction in soil quality cannot be ignored (Whiting et al., 2001). In most physically-based erosion models, such as the WEPP (Flanagan and Nearing, 1995), upland erosion is conceptually divided into interrill/sheet and rill erosion. The physical significance of the difference on interrill and rill erosion is clear, but the physical significance of the erosion data used for evaluating the models is not clear because of difficulties experienced in separating the erosion amount from rill and interrill erosion with traditional measurement methods. Thus differentiation of rill and interrill erosion of a hillslope is of importance both scientifically and practically.

Recently, rare earth elements (REEs) as tracers have emerged to track soil mass movement for soil erosion. REEs or the lanthanides comprise a group of elements, periodic numbers 57 through 71, which have similar geochemical properties. Lanthanide's trivalent state and ionic radii ranging from 0.87 Å (Sc3+) to 1.16 Å (La3+), similar to that of Ca2+, allow them easy adsorption on to clays. The REEs have a great potential as a sediment tracer for their strong binding capability with soil, low natural backgrounds in soils, low mobility, safe in the environment, chemical stability, and the availability of a range of elements with similar properties. Researches have demonstrated that REE oxides could be evenly incorporated with soil aggregates and eroded at the same rate as soil mass without vertical movement in the soil profile (Zhang et al.,...
falls in April through October. Its annual average temperature is
with an annual average precipitation of 750 mm, of which 84.5%

1.94 km² is characterized by hilly land with an elevation range of
background concentration, such as Eu₂O₃, Yb₂O₃, had been placed
(Ran and Liu, 1999). Generally, the tracer with high price and low
method, the cost, and the extension prospect of the experiment
in the intensive soil erosion area, and the tracer with low price and
high background concentration, such as La₂O₃, CeO₂ had been placed
in the lower soil erosion area.

2.2. Experimental design

The REE tracing technique presented here has the ability to partition
rill and interrill erosions from the eroded materials of rainfall events, which supply insights into erosion processes, some-
thing that has not been possible with traditional erosion measure-
ment methods. The work is of scientific meaning to the soil erosion
science and practices. The experimental setup displayed here should be
useful to future study of erosion processes on slopeland.

An experimental plot (10 m × 2 m × 0.16 m) with a gradient of
20° (36.4%) was established on a north−west-facing slope of a hill
in the Wulongchi catchment. It was edged with bricks partially
driven into soil along its boundary, below which was a one cubic
meter tank used for runoff and sediment discharge measurement.
The plot was prepared on April 22, 2008 about one month before the
rainy season.

Sheet erosion occurs when soil particles are detached by rain-
drops and transported by shallow overland flow, whereas, rill
erosion is the detachment and transport of soil particles by con-
centrated flow. This detached soil is then transported and deliv-
ered as sediment downstream. Thus the experimental plot
was divided into two layers. The upper layer was 1.0 cm thick, and
soil loss from this layer was considered to be sheet erosion (Zhang
and Akiyoshi, 1998). The lower layer had a thickness of 15.0 cm,
which was used to determine rill erosion. Many tests have concluded that sediment discharge mainly occurred in the lower
segment of a slope (Tian and Liu, 1994; Liu et al., 2004; Xue et al.,
2004; Shen et al., 2007). Thus we divided the plot into four
segments (i.e., I, II, III, and IV), and the length of each segment was
1.0 m, 2.0 m, 3.0 m, and 4.0 m, respectively (Fig. 1).

The tracers were applied to the plot in a soil mixture, and the
applied and background REE oxide concentrations in this study were
presented in Table 1. To prepare the tracer mixture, soil collected
from the plot was air-dried in the field, passed through an 8-mm
mesh sieve, and thoroughly mixed with the tracers according to
the design concentrations (i.e., approximately 100 times that of
background concentrations). The referenced background concen-
trations of REEs in main types of soils in China have been reported by
Ran and Liu (1999). Before replacing the tagged soil in the plot, we
placed a compartment block (a thin iron sheet) between different
segments of the plot (the width of compartment block was the same
as that of the plot). The backfill depth was measured with ruler. The
soil tagged with REE oxides was then evenly spread onto the
different segments and layers of the plot according to the
Fig. 1, with care taken to prevent cross-contamination in neighboring layers. Each layer was filled according to its designed thicknesses (Fig. 1) and soil bulk density was kept at approximately 1.0 g/cm³. Afterwards,
the soil surfaces were evenly covered with cheesecloth and sprayed with water to near saturation point. In order to achieve normal soil conditions, the soil was then left to subside naturally for about one month. An automatic raingauge with 5 min time resolution was located at the study site. Runoff samples were collected with a 10-L bucket at 1-min time intervals during the rainfall events.

2.3. Laboratory procedures and neutron activation analysis

A total of 20 g of each treated sediment sample was sieved through 0.15-mm-mesh sieve and 50-mg subsamples were collected, weighed, and sealed in 1 cm × 1 cm aluminum foil bags. Sample irradiation for neutron activation analysis was conducted in a nuclear reactor at the Atomic Energy Institution of China. The integral flux of neutrons was $n × 10^{13}$/cm². The activated sample was then used to conduct $\gamma$ spectrometry analysis. To ensure analysis precision, international standard reference materials (GSR-1) were analyzed with each batch of samples. The precision of three replicates for each of the samples was better than 14.5% for all of the elements. The accuracy of determination was evaluated by comparing our values with the GSR standards (Liu et al., 2004).

2.4. Calculation of the erosion rate

Erosion rate (sheet erosion or rill erosion) ($R_j$) (g/(min m²)) from a section of the slope surface was computed from Eq. (1) (Xue et al., 2004):

$$R_j = \frac{M_j - B_i}{E_i - B_i} Q_i$$  

(1)

Where $j$ is the sampling time, $i$ is the tracer section, $M_j$ is the detected concentration (mg/kg) of REE at time $j$, $B_i$ is the background value (mg/kg) of REE, $E_i$ (mg/kg) is the concentration of REE applied to the soil, $Q_i$ is the erosion amount (g) at time $j$, $S_i$ is area of the tracer section.

The erosion rate $R_j$ (g/(min m²)) from either sheet erosion or rill erosion at time $j$ was calculated by Eq. (2):

$$R_j = \sum R_i$$  

(2)

The relative contribution $D_i$ (%) of the erosion rate to the total of REE i tracer section at time $j$ was calculated according to Eq. (3):

$$D_i = \frac{100R_i}{R_j}$$  

(3)

3. Results

3.1. Rainfall and erosive characteristics

Only three storms (on June 10, July 5 and July 15, 2008, respectively) produced sediment samples during the experimental period, and their characteristics were presented in Fig. 2. There was one obvious peak in the histograms and the maximum 30 min intensity fluctuated, reaching a peak at 10.8, 53.4 and 44.0 mm/h, respectively. Positive correlations between the sediment discharge, runoff rate and sediment concentration were significant except for the first rainfall event (Table 2). The correlation between the sediment discharge and rainfall intensity was also significant on July 5, 2008. Because the runoff duration time was too short, we could not analyze this relationship for the June 10 and July 15 events.

3.2. Erosion on slope surface

The storm on June 10, 2008 was the first rainfall event that resulted in runoff on the land surface. The sheet and rill erosion rates were 10.3 and 2.1 g/(min m²), respectively (Fig. 3A). The erosion primarily occurred in the downslope (i.e., segment I and II) (Fig. 4A). On July 5, 2008, the erosion rate was averaged 0.68 g/(min m²) in

<table>
<thead>
<tr>
<th>Date</th>
<th>Runoff rate vs. sediment discharge</th>
<th>Runoff rate vs. sediment concentration</th>
<th>Sediment discharge vs. sediment concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008.06.10</td>
<td>0.674**</td>
<td>-0.637</td>
<td>0.038</td>
</tr>
<tr>
<td>2008.07.05</td>
<td>0.966**</td>
<td>0.727**</td>
<td>0.762**</td>
</tr>
<tr>
<td>2008.07.15</td>
<td>0.992**</td>
<td>0.992**</td>
<td>0.970**</td>
</tr>
</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed).
the first half hour (Figs. 3B), and upslope ratios fluctuated at a low-level (Fig. 4B). Initially, the erosion ratio of segment I decreased and the other segments tended to increase in general. After time 0:37, all the segments remained generally constant, and the ratios were about 24%, 29%, 15% and 32%, respectively. Runoff coincided with the appearance of maximum rainfall intensity on July 15, 2008, and the erosion rate in all sections decreased with the extension of rainfall time (Fig. 3C). The ratio of relative erosion rate of each tracer section almost was equal and constant (Fig. 4C). The ratio of relative erosion rate of each tracer segment (i.e., I, II, III and IV) after three rainfall events and the basic rainfall information were presented in Table 3 and Fig. 5.

3.3. Sheet erosion and rill erosion

In the three captured rainfall events, sheet erosion was the major erosion type and accounted for more than 90% of total erosion (Fig. 6). On June 10, 2008, the rill erosion rate was relatively small (Fig. 3A (right), 0.0356 g/(min m²) at time 11:45), but it gradually increased during the raining process. In the following two rainfall events, the rill erosion rate changed with rainfall intensity, but the ratio of rill erosion to total erosion was always small (<1%). After the rains, the relative rill erosion rate in each tracer section (i.e., Nd section, Ce section and La section) was 1.775 g/(min m²), 0.295 g/(min m²), 0.131 g/(min m²) (June 10), and 3.067 g/(min m²), 1.648 g/(min m²), 0.526 g/(min m²) (July 5) and 3.013 g/(min m²), 3.728 g/(min m²), 1.542 g/(min m²) (July 15). Thus the ratio of relative rill erosion rate in each tracer section changed from 13.5 (Nd section): 2.3 (Ce section): 1.0 (La section) (June 10) to 5.8: 3.1: 1.0 (July 5), and then to 2.0: 2.4: 1.0 (July 15) (Fig. 7).

4. Discussion

The correlations among runoff rate, sediment discharge and sediment concentration (Table 2) under our experimental conditions illustrated that runoff was the principal factor influencing sediment discharge. In the rainfall event on July 5, 2008, correlation between the rainfall intensity and sediment discharge was strong and significant ($r = 0.803$, $p = 0.01$). It demonstrated that sediment discharge increases with an increase in rainfall intensity. With the increasing of rainfall intensity, the shear forces applied by the raindrops to the soil surface increased and then soil erosion tended to increase either by enhancing soil detachment or by the protection of the thin layer of material moving with the runoff flow (Kinnell, 1990; Fox and Bryan, 1999).

The ratio of relative erosion rate of each tracer section in the first rainfall event (on June 10) (Figs. 4A and 5) illustrated that sediment discharge on the slope surface mainly originated from the lower areas of the slope (Tian and Liu, 1994; Xue et al., 2004; Shen et al., 2007). Moreover, sheet erosion dominated in the first rainfall event (Fig. 6A). Based on the theory for Raindrop Induced Flow Transport (RIFT) (Kinnell, 1990, 1991), sheet erosion is associated with erosion by rain-impacted flows, and erosion by rain-impacted flows was size selective (Kinnell, 1990; Sander et al., 1996). Thus in rain-impacted flows, particles travel downslope from where they are detached (plucked from the cohesive soil surface) to the point where they are discharged at virtual velocities. Once sediment has become suspended in the overland flow, this sediment will begin to settle or deposit back on the soil surface. Not all the particles detached from the matrix are immediately lost beyond the downslope boundary of the plot surface when RIFT is active. Some of the particles will be deposited back on the soil surface. It takes some time for particles, particularly coarse ones, detached at the upslope end to be transported over the surface and discharged beyond the downstream end of the plot. Consequently, for the short duration of the rainfall-runoff event on June 10, 2008, sediment discharge mainly originated from the downslope area of the plot.

The spatial distribution of sediment discharge is rarely considered in soil erosion studies, which directly affects the understanding...
of erosion mechanisms. In our experiment, the upward-moving
tendency of the main sediment discharge area was observed as
erosion intensified (Table 3, Fig. 5). The result was consistent with
previous studies (Zhang et al., 2003; Polyakov and Nearing, 2004;
Yang et al., 2008; Shi et al., 1997). It may indicate either that the
upper segment was predominated by detachment and lower
segment by transport (Zhang et al., 2003), or particles detached
upstream by raindrop impact form a layer of pre-detached particles

Table 3
The ratio of relative erosion rate of each tracer segment (i.e., I, II, III and IV) and basic
information of the three rainfall events.

<table>
<thead>
<tr>
<th>Rainfall date</th>
<th>Average rainfall intensity</th>
<th>Rainfall duration</th>
<th>Ratio of relative erosion rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008,06,10</td>
<td>7.1 mm/h</td>
<td>50 min</td>
<td>16.1:5.8:1.8:1.0</td>
</tr>
<tr>
<td>2008,07,05</td>
<td>25.2 mm/h</td>
<td>120 min</td>
<td>1.3:1.3:0.6:1.0</td>
</tr>
<tr>
<td>2008,07,15</td>
<td>18.0 mm/h</td>
<td>85 min</td>
<td>0.7:0.8:3.1:0:1.0</td>
</tr>
</tbody>
</table>

Fig. 5. The ratio of relative erosion rate of each tracer part (i.e. I, II, III and IV) after
three rainfall events.
above the soil matrix in the downstream areas of surfaces eroded by rain-impacted flows (Kinnell, 1991). The pre-detached particles thus provide a degree of protection to the soil matrix below them. The transport system explained by RIFT (Kinnell, 1990, 1991) leads to the storage of loose particles on the soil surface. If entrainment of the pre-detached material occurs at some later time, then an amount of pre-detached material will be rapidly flushed from the surface. Consequently, temporal variations in the amount of detached material stored on the eroding surface will have a considerable influence on the rate of soil loss during the following erosive events. Therefore, particles mobilized during one event that do not get discharged during that event may have been remobilized during subsequent events on the eroding surface and get discharged. This may have produced the tendency for the most sediment discharge area to move upward along the slope surface as erosion progressed.

Understanding of the relative contributions and its variability of sheet and rill erosion to the total soil loss associated with an individual event is important for developing effective soil erosion prediction models. The erosion processes of the three rainfall events indicated that under the conditions of limited individual rainfall events, with relatively weak rainfall intensity or short runoff duration (Fig. 2), sheet erosion was the main contributor to sediment loss (Fig. 6; Morgan, 1995). The change in the ratio of rill erosion rate about each tracer section (Fig. 7) demonstrated that rill erosion mainly originated from the bottom of the slope surface. This result is consistent with the results of previous studies (Xue et al., 2004; Shen et al., 2007), and the intensive rill erosion area mainly concentrated in the slope range from 0 to 3 m away from the toe of the slope, i.e., on the middle and bottom segments of the slope surface, and rill erosion tended to move upward along the slope surface, showing that the erosion type was on the stage of sheet erosion to the infancy of rill erosion. The transformation of sheet erosion to rill erosion was slow. Our results are supported by previous studies of Shen et al. (2007) and Song et al. (2003). All in all, the results obtained in this study demonstrated that the REE tracer method was helpful in increasing knowledge of intransient erosion processes and may provide a unique means to better understand erosion processes.

5. Conclusions

Our results demonstrated that eroded material mainly originated from the lower segment of the slope surface during the initial stage of erosion activity, and the main sediment discharge area migrated upslope as erosion intensified. The main erosion type is sheet erosion at the beginning of the rainfalls. Under limited individual rainfall events with gentle rainfall intensity or short-term runoff, sheet erosion was the main contributor to sediment loss. Rill erosion rate was small and mainly occurred at the bottom of the slope and then moved upwards gradually. The main sediment discharge in rill erosion occurred on the lower-middle segment of the slope surface. The transformation of erosion type was a slow progression from predominately sheet erosion to predominately rill erosion. Results obtained from the small amount of data that was collected from only one small plot and only three rainfall events. Thus they cannot be extrapolated to other conditions. But it is undeniable that the use of the multi-REE tracer technique provided a powerful and robust tool for quantifying the distribution of soil erosion, and it has great potential for further research on the mechanism and evolution pattern of soil erosion.

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