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Understanding erosion processes using rare earth element tracers in a preformed interrill-rill system

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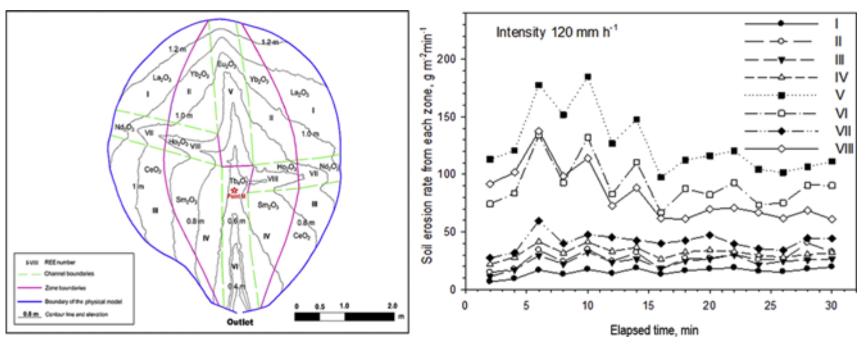
HIGHLIGHTS

- Rill erosion contributed most soil loss, ranging from 61 to 78%.
- Rill detachment limited rill erosion while transport limited interrill erosion.
- Interrill erosion was more sensitive to rainfall intensity than rill erosion.
- Rill erosion was controlled by discharge, slope, and rill development stage.
- Greatest sediment concentration occurred in the stage of fastest rill growth.

GRAPHICAL ABSTRACT



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ABSTRACT

Tracking sediment source and movement is essential to fully understanding soil erosion processes. The objectives of this study were to identify dominant erosion process and to characterize the effects of upslope interrill erosion on downslope interrill and rill erosion in a preformed interrill-rill system. A coarse textured soil with 2% clay and 20% silt was packed into a physical model of a scaled small watershed, which was divided into eight topographic units and was tagged with eight rare earth element (REE) oxides. Three 30-min rains were made at the sequential intensities of 60, 90, and 120 mm h^{-1}, and runoff and sediment were collected every 2 min at the outlet. REE concentration in sediment was measured and used to estimate source contributions after fine-enrichment correction. Results showed that interrill erosion rate and sediment concentration increased with downslope distance, indicating that sediment transport might have controlled interrill erosion rates. In contrast, rill erosion rate was limited by rill detachment and development process. Rill erosion contributed most soil loss; however, the proportion decreased from 78 to 61% as rainfall intensity increased and rill network matured over three rains. Interrill erosion was more sensitive than rill erosion to rainfall intensity increases. The former was mostly affected by rainfall intensity in this experimental setup, while the latter was controlled by flow discharge, gradient, and rill evolution stage. The greatest sediment concentration and delivery rate occurred in the stage of the fastest rill development. The increased sediment delivery from interrill areas appeared to suppress rill detachment by concentrated flow. This study enhanced our understanding of interrill and rill erosion processes and provided the scientific insights for improving soil erosion models.

1. Introduction

Data on sediment fluxes along an interrill slope or rill were few, and such data scarcity greatly hampered the development and validation of

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physically based soil erosion models (Kinnell, 2017; Zhang, 2017). Without spatially distributed erosion data, distributed erosion model cannot be rigorously calibrated and tested. Thus, the capability of predicting higher spatial resolution of soil losses by physically based models, compared with lumped empirical erosion models, would not be fully realized. Spatially distributed soil erosion data are also critical to thorough understanding of soil erosion processes, such as temporal and spatial dynamics of soil detachment and sediment transport. To fully understand the effects of interrill erosion on rill erosion or the effects of upslope interrill erosion on downslope interrill erosion as well as interrelationships among soil detachment, sediment transport, sediment deposition, and re-detachment at different slope distances, sediment tracking technique must be employed (Owens et al., 2016).

Various sediment tracers have been used to obtain spatially distributed soil erosion data at temporal scales varying from intra-storm to multi-years to multi-decades. At multi-decade scales, the atomic bomb fallout radionuclide ^{137}Cs and naturally occurring radionuclides ^{210}Pb and ^{234}Th were widely used to estimate spatial erosion patterns on a hillslope or small watersheds (Fukuyama and Takenaka, 2005; Zhang et al., 2015a, 2015b; Rubio-Delgado et al., 2017). At a single storm or multi-storm scales, naturally occurring radionuclides ^{7}Be (Liu et al., 2011) and deliberately introduced tracers such as radionuclides ^{56}Fe and ^{60}Co (Wooldridge, 1965; Toth and Alderfer, 1960), noble metals Au and Ag (Olmez et al., 1994), as well as exotic particles including colored particles (Young and Holt, 1968) and magnetic beads (Ventura et al., 2001) were used. The use of a single tracer as listed above is useful in estimating spatial soil erosion rates and patterns, but fails to provide information on sediment sources and fates as well as insights on soil erosion processes, which are essential for understanding erosion dynamics and sediment transport processes. In the past decades, the need of using multiple sediment tracers have become increasingly clear and the interest has grown markedly. Multiple tracers applied at different slope positions or landform units have been successfully tested and used to trace soil erosion and sediment transport dynamics at plot, hillslope, and small watershed scales as reviewed below.

Rare earth elements, which are the Lanthanide series with 14 elements possessing similar chemical and physical properties, have been successfully tested and used as multiple tracers to track sediment movement and deposition, especially sediment sources, sinks, and fates, at various spatial and temporal scales (Zhang et al., 2001, 2005; Kimoto et al., 2006; Liu et al., 2016a; Xiao et al., 2017b). Those studies have shed light on sediment transport modes and mechanisms, effects of sediment load on soil detachment, and relationships among sediment transport, deposition, and re-detachment were gained using the REE oxide tracer technique. Zhang et al. (2003, 2017b) studied interrill erosion processes with five different REE oxides. Their results showed that sediment transport on interrill areas limited interrill erosion rates. The upper slope section was dominated by soil erosion with raindrop-driven creeping being the dominant transport mode, while the lower slope section was dominated by sediment transport due to upslope sediment influx, with flow-driven rolling being the prevalent mode of transport. Moreover, strong positive correlation was found between steady state sediment discharge rates from each segment to the outlet and amounts of sediment deposited downslope from each corresponding segment. Such positive correlation indicated that soil detachment, sediment transport, deposition, and re-detachment occurred simultaneously in the interrill erosion systems. The coexistence of sediment transport and deposition demonstrated that sediment was transported as bedload in the form of rolling or creeping on interrill erosion areas.

One major concern of using REE oxide tracers is the selective binding of tracers to finer soil particles and the selective erosion for finer particles, especially for poorly aggregated soils on interrill erosion areas. Kimoto et al. (2006) and Liu et al. (2016b) investigated the binding ability of REE oxides to different soil particle classes in two coarse-textured soils, and reported that REE oxides were preferably bound with fine particles especially clay and silt fractions. Owing to the selective binding, the selective erosion would lead to large soil erosion estimation errors (Polyakov and Nearing, 2004; Stevens and Quinton, 2008). To minimize soil erosion estimation errors, Kimoto et al. (2006) suggested that REE tracking technique should be applied in a piecewise manner to individual particle size groups in situations where severe selective erosion existed, and mathematically demonstrated that use of four particle size groups would reduce potential error to 4% in a coarse-textured soil. Liu et al. (2016b) analyzed REE concentrations in nine particle size groups in a laboratory rainfall simulation study using a coarse-textured soil, and showed that soil estimation errors were considerably reduced if REE measurement in multiple size classes were used for correction. However, the drawback of the multi-size approach was the increased time, cost, and complexity of the REE analysis (Guzman et al., 2013). Zhang et al. (2017a) developed a simple enrichment correction factor that took preferred erosion of fine particles into consideration reduced soil erosion estimation error to $<4\%$ without the need of measuring REE for different size classes.

The newly developed simple correction factor was used to improve soil erosion estimates from each REE-tagged topographic unit. The corrected erosion estimates were then used to study soil erosion processes in an interrill-rill erosion system. The objectives of this study were to identify the dominant erosion process (detachment vs. transport) in an interrill-rill erosion system, and to characterize the effect of upslope interrill erosion on downslope interrill as well as further down on rill erosion in a miniature watershed or plot with a preformed rill system.

2. Material and methods

2.1. Soil and particle size analysis

The soil was a coarse-textured purple soil, which was classified as an entisol according to the soil taxonomy of the U.S. Department of Agriculture. The soil was derived from sandy shale under sub-tropical humid climate and contained approximately 2% clay, 20% silt, and 1% organic matter. The soil sample was taken from an upper 20-cm surface layer in a cultivated field (31°14′ N, 110°42′ E).

The size distributions of the parent soil and the sediment samples were measured using laser diffraction (Mastersizer 2000, Malvern Instruments, Malvern, UK). For primary particle size distribution of the soil, soil samples were pretreated with hydrogen peroxide to remove organic matter and were chemically dispersed using sodium hexametaphosphate prior to analysis. For sediment size distribution, sediment samples were wet sieved and then measured using laser diffraction without any pretreatment.

2.2. Rare earth element oxide powders

Eight REE oxide powders (i.e., La_2O_3, CeO_2, Nd_2O_3, Sm_2O_3, Eu_2O_3, Tb_4O_7, Ho_2O_3 and Yb_2O_3) were used in the study. Table 1 shows the selected physical and chemical properties of the selected REE oxides. Each tracer was uniformly mixed with a small amount of soil sample initially, and then more blank soils were introduced and well mixed. This step was repeated several times in a dilution fashion to obtain the predetermined REE concentrations of Table 1 (Liu et al., 2016b). The tagged soils were packed at different topographic units in a physical model of a small watershed (Fig. 1).

2.3. Plot setup

The plot was bordered with a concrete brick wall, and was filled with sand in the bottom to facilitate drainage. The model watershed or plot was divided into eight different topographic units (Fig. 1), each being labeled with a tracer. The eight units were upstream upper slope (I), upstream lower slope (II), downstream upper slope (III), downstream lower slope (IV), upper main channel (V), lower main channel (VI),