Geoderma 147 (2008) 8–15

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Estimation of the detachment rate in eroding rills in flume experiments using an REE tracing method

Qingwen Zhang [a,b], Tingwu Lei [a,c,*], Jun Zhao [a]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, CAS and MWR, Yangling, Shaanxi, 712100, PR China
[b] Institute of Environment and Sustainable Development in Agriculture. CAAS/Key Laboratory of Agro-Environment and Climate Change, Ministry of Agriculture, Beijing, 100081, PR China
[c] Laboratory of Modern Precision Agriculture Integration Research, College of Hydraulic and Civil Engineering, China Agricultural University, Beijing, 100083, PR China

ARTICLE INFO

Article history:
Received 7 September 2007
Received in revised form 23 June 2008
Accepted 14 July 2008
Available online 31 August 2008

Keywords:
Rill erosion
Net detachment rate
Rare earth element
Sediment loading flow
Flume experiments

ABSTRACT

Rill erosion can be a serious problem on cultivated slopes. Understanding the mechanisms of the detachment process in eroding rills is important in developing and improving process-based erosion prediction models. The detachment rate, defined as the sediment amount detached from a unit area in a unit time, is a crucial parameter in most physical erosion prediction models. Most current studies on rill detachment rates use spatially averaged soil erosion data, which provides little information about soil erosion dynamics due to the lack of spatially distributed, contemporaneous rill erosion data. The objective of this study was to estimate the net detachment rate in eroding rills using a rare earth element (REE) tracing method. Flume experiments were conducted with ten REE oxides (Ho_2O_3, Tb_4O_7, Eu_2O_3, Yb_2O_3, Dy_2O_3, Sm_2O_3, La_2O_3, Tm_2O_3, CeO_2, and Nd_2O_3) as tracers mixed with soil in different sections of five slopes (8.74%, 17.62%, 26.78%, 36.38%, and 46.6%) exposed to three water flow rates (2, 4, and 8 L min^{-1}). Regulated water flow was introduced to the upper end of flumes, 8 m long and 0.1 m wide, which were divided into 10 equal segments, each containing a different REE–soil mixture. The net detachment rate from each rill segment was calculated from the REE concentrations in the eroded and transported material. The detachment rates from different segments along the rills, at different slope gradients and flow rates, were compared with those estimated directly from previous studies, and were found to increase with increasing slope gradient and flow rate. Results also showed that the net rill detachment rates decreased linearly with an increase in sediment concentration, and decreased exponentially with an increase in rill length. The REE-derived detachment data and their relationship with sediment concentrations are consistent with the detachment function used in the WEPP model, and are helpful in understanding the processes of rill erosion. Using REEs to trace detachment rates in continuous rills is a valid and advantageous technique for estimating the spatial distribution of the rill detachment rates.

1. Introduction

Rill erosion is capable of detaching and transporting sediments from the soil mass, and can be a serious problem on cultivated slopes (Nearing et al., 1997; Zheng and Tang, 1997; Gyssels et al., 2002) and accounts for approximately 70% of the erosion from upland areas of the Loess Plateau in China (Zheng and Tang, 1997). Active erosion occurs as net soil detachment by water when the shear force, or stress, of rainfall or flowing water is greater than the critical shear strength of the soil surface. It is important to have a better understanding of the mechanisms of raindrop and water flow detachment in order to improve process-based erosion prediction models and developing conservation strategies (Nearing et al., 1997; Merten et al., 2001).

The flow detachment rate, defined as the sediment amount detached per unit area per unit time, is a crucial parameter in most physically based rill erosion models. Foster and Meyer (1972) suggested a set of erosion prediction equations, which were later adopted by Nearing et al. (1989) for use in the WEPP (Water Erosion Prediction Project) model, to describe soil detachment in rills. When concentrated flow is initiated with clean water, the sediment concentration in the flowing water increases along the rill as detachment proceeds, but as the sediment load in the flowing water increases, more energy is used for sediment transportation. Therefore, the detachment rate in the eroding rill decreases with increasing sediment load. In models such as WEPP, rill detachment is, conceptually, a function of the detachment capacity, sediment transport capacity and the existing sediment load described by the following equation (Nearing et al. 1989; Flanagan and Nearing, 1995):

$$D_r = K_r(\tau - \tau_c)\left(1 - \frac{qc}{T_c}\right) \quad (1)$$

* Corresponding author. China Agricultural University, Qinghua Donglu, Beijing, 100083, PR China. Tel.: +86 10 6273 6367.
E-mail address: ddragon@public3.bta.net.cn (T. Lei).

0016-7061/$ – see front matter
doi:10.1016/j.geoderma.2008.07.002

where, D_r (kg m^{-2} s^{-1}) is the contribution of rill detachment rate to rill sediment load, K_r (s^{-1}) is the erodibility of the soil, τ (kg m^{-2}) is the shear stress of the flowing water, τ_c (kg m^{-2}) is the critical shear strength of the soil; c (kg m^{-3}) is the sediment concentration, q (m^3 m^{-1} s^{-1}) is the flow rate per unit width, and T_c (kg s^{-1} m^{-1}) is the sediment transport capacity of the water flow. Although Eq. (1) is an essential component of WEPP for predicting sediment detachment rates, it needs to be verified experimentally.

Determination of soil detachment rates has long been a concern in soil erosion research (Sharma et al., 1995; Cochrane and Flanagan, 1996; Franti et al., 1999; Gimenez and Govers, 2002), especially in soil erosion prediction. A problem that may arise in evaluating flow detachment is that sediment load may, or may not, have an influence on the flow detachment rate as suggested by the following three cases:

a) An early conceptual model of the effects of sediment concentration in flowing water on erosion processes was proposed by Ellison and Ellison (1947). This model considers that clear water has a maximum transporting capacity, minimum detaching capacity, and causes very little erosion. Despite their original hypothesis, little work has been done to test the validity of the model, particularly as to how sediments transported in flowing water could affect erosion processes.
b) In contrast, Huang et al. (1996) believed that their experiments indicated that sediment detachment in rills appeared to be independent of sediment load.
c) A third possibility proposes that the potential detachment rate of flowing water could decrease to zero, as the sediment load approaches its transport capacity. Foster et al. (1977) supported this hypothesis by suggesting that the flow possesses finite energy, which may be expended either on soil detachment from the soil surface or on transporting the detached sediment particles. Merten et al. (2001) found that, in general, the detachment rate decreased with an increase in sediment load, but not in a way explained by the detachment-transport coupling theory. Zhang et al. (2005) found that net rill detachment rates tended to decrease linearly as sediment load increased while Lei et al. (2002) found that they were inversely proportional to the magnitude of the sediment load for a given time and slope gradient.

Due to the complexity and the stochastic nature of the processes, rill erosion is often easy to observe but hard to measure. The effect that sediment load may have on flow detachment can be validated only with spatially distributed sediment data. Currently, typical methods estimate 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. Many attempts (Zhang et al. 2003; Polyakov and Nearing, 2004; Polyakov et al., 2004; Lei et al., 2006) have been made to use tracers to obtain spatially distributed erosion data. The rare earth elements (REEs) may be suitable for sediment source studies. Forming the largest chemically coherent group in the periodic table, the Lanthanide elements, defined as REEs of atomic number 57 through 71 with similar chemical properties, are suitable for use in sediment source studies. Unlike atmospheric nuclear bomb-produced and naturally occurring radionuclides, the REE oxide powders can be controlled and deliberately introduced into a given environment in order to study soil erosion. The term rare earth elements derive from the initial view that they could only be isolated from very rare minerals. However, geological surveys have since shown that these elements are quite abundant in the Earth's crust. Recently developed procedures have made it possible to commercially separate and purify compounds of these chemically very similar elements and to make them available for a relatively inexpensive price. The availability of sensitive, rapid, and inexpensive analytical methods is other factors when selecting ideal tracers. Instrumental neutron activation analysis (INAA) has been widely used for REE measurement for many years. This method involves bombarding a sample with neutrons by placing it in a nuclear reactor. The neutrons interact with atoms in the sample to create new, radioactive isotopes. By measuring the gamma rays released when these isotopes decay it is possible to determine their presence and the relative concentrations of elements. The main advantages of INAA are the simplicity of sample preparation, freedom from matrix effects and unmatched long-term instrument stability (Lieser, 2001).

Potential REE candidates for tracing soil erosion were demonstrated in laboratory flume experiments by Zhang et al. (2003), Polyakov and Nearing (2004), Polyakov et al. (2004) and Lei et al. (2006). Ideal REE tracers used for the study of soil erosion and sediment sources should have the following characteristics: 1) they should be capable of being strongly bound to soil particles or of being easily incorporated into aggregates; 2) they should not interfere with sediment detachment and transportation processes; 3) they should be easy, and inexpensive, to use and measure; 4) they should have low background concentrations in soils; 5) they should not be easily taken up by plants nor leached by water; and 6) they should be environmentally friendly (Riebe, 1995; Zhang et al., 2001). Furthermore, REE oxides are the most stable form of the various REE compounds, insoluble in water and basic solutions, and exist in powder form. Because of the properties described above, REEs have been employed in soil erosion research (Tian et al., 1992; Tian, 1997; Riebe, 1995; Plante et al., 1999; Zhang et al., 2001; Liu et al., 2004; Polyakov et al., 2004). Tian et al. (1992) tagged soils at various slope positions with different rare earth oxides by directly mixing the REE oxide powders with the soil materials in order to track sediment sources and movement. Zhang et al. (2001) reported that REE oxide powders, when directly mixed with a silt loam soil, were uniformly incorporated into soil aggregates of various sizes and were bound to the silt fraction. Polyakov et al. (2004) developed laboratory studies into a field study within a small watershed in Ohio, USA, and demonstrated the effectiveness of the tracers in field applications. Liu et al. (2004) used the stable REE tracers to estimate the distribution of soil erosion from specific areas for different rainfall events, while Lei et al. (2006) derived computational formulae for quantifying the distribution of amounts of eroded material along rills. These studies showed the feasibility of using REE oxides as tracers for soil erosion research and demonstrated that REEs were effective in identifying the relative contribution of sediment source areas despite sediment sorting during transportation.

The objectives of this study were: 1) to develop a method for estimating the soil detachment rates using REE tracers; 2) to assess the effect of sediment load on the rill detachment rates when influenced by slope gradient and flow rate; and 3) to evaluate the consistency between the REE-derived detachment rates and those obtained in previous studies that used an interrupted rill length runoff input method (Lei et al., 2002).

2. Materials and methods

Loessial soils are one of the most erodible soil types with a high susceptibility for detachment and transportation by rill flow. Rill erosion is a dominant process in the morphological development of the landscape of the Loess Plateau in China, and delivers great quantities of sediments to the river systems. In these silty, loess-derived soils, the REEs can bond effectively the greater part of the sediment (Zhang et al., 2001), which is important for effective sediment tracing. The soil used in the experiments was collected from the Ansai Agricultural Experiment Station on the Loess Plateau of China (109°20″ E, 36°50″ N). It was derived from loess parent materials, with a uniform soil texture profile (16% clay, 64% silt, and 20% sand), and classified as a Calciustept according to the U.S. taxonomic classification system (Soil Survey Staff, 1999). The soil contained 97.3 g kg^{-1} $CaCO_3$ and 4.01 g kg^{-1} organic matter, with a pH value of 8.5. The cation exchange capacity (CEC) of the loess soil was 7 meq per 100 g. The soil was prepared by air-drying before being passed through a 10-mm-mesh sieve.