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Slope length effects on processes of total nitrogen loss under simulated rainfall

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ABSTRACT

Slope length effects on the processes of soil erosion have been the focus of research on hillslope hydrology and sediment transport. A field experiment was conducted to investigate the effects of slope lengths (1, 5, 10, 15 and 20 m) and rainfall intensities (75, 50 and 25 mm h^{-1}) on runoff, soil and total nitrogen (TN) losses under simulated rainfall conditions. Kastanozem was selected in the experiment. Generally, runoff rates and runoff-associated TN loss rates decreased with slope length, whereas sediment and sediment-associated TN losses increased with slope length under three rainfall intensities. The relationship between runoff and time could be described by the Horton infiltration model, with a correlation coefficient $R^2 > 0.85$. The function parameters of final infiltration rate (i_f) and coefficient (c) were closely related to slope length, suggesting that a model of runoff processes correlated to slope length was established. There was a significant positive power relationship between runoff and sediment yield rates ($p < 0.01$). Runoff-associated TN losses were mainly controlled by runoff rates, whereas sediment-associated TN losses were mainly controlled by sediment yield rates, and positive linear correlations best represented their relationships. Because sediment-associated TN losses dominated the total TN losses, sediment yield rates were positively correlated with the total TN losses. Increasing rainfall intensity generally increased runoff, sediment yield and TN loss rates, but changes in rainfall intensity did not influence their relationships. This study demonstrated that a model could be established to simulate the processes of TN loss for different slope lengths.

1. Introduction

Soil erosion induced by rainfall continues to be a global environmental problem (Pimentel et al., 1995; Montenegro et al., 2013). Many studies showed that nutrient loss due to rainfall was one of the major concerns involved in non-point source pollution and land degradation (Wei et al., 2007; Vadas et al., 2008; Wilson et al., 2008). Nitrogen is one of the key elements leading to water pollution and eutrophication. Research on the processes of nitrogen loss will contribute to the protection of ecosystems.

Scale effects on the processes of soil erosion have always been an active area of research but still remain a significant challenge (Moreno-de las Heras et al., 2010). Runoff depends on slope length. Many studies showed that the runoff per unit area decreased with increasing slope length, as a result of spatial variability of infiltration and reinfiltration along the slope. A clear reduction in runoff per unit slope length was found as slope length increased, and the reduction was closely related to the rainfall duration (Stomph et al., 2002). The median overland runoff decreased with increasing slope length, whereas the spatial variability of infiltration increased significantly with slope length (Ghahramani and Ishikawa, 2013). Soil erosion also depends on slope length. The study of Parsons et al. (2006) showed that sediment yield per unit area increased with increasing slope length when the slope length was less than 7 m and then decreased with increasing slope length. Wang et al. (2010) suggested that exponential equations could be used to describe the relationship between runoff and sediment losses. However, Kothyari et al. (2004) considered that a linear relationship was the best fit of the relationship between runoff and sediment.

Laboratory and field experiments were undertaken to investigate the impact of rainfall characteristics (Kleinman et al., 2006), soil type (Teixeira and Misra, 2005), and vegetation cover (Liu et al., 2012) on nutrient loss to runoff. The results indicated that nutrient losses were determined by runoff and sediment losses. However, research on slope length effects on nitrogen loss has been rarely reported.

One of the most important purposes of studying the influence of slope length effects on soil erosion was to determine potential scaling effects (Boix-Fayos et al., 2006). Most research has focused on slope length effects on runoff and sediment losses, but the influence of slope length on nitrogen loss requires further study. Soil erosion of catchments was often treated as a black box (Le Bissonnais et al., 1998). It

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is difficult to understand the mechanism of scaling effects on nitrogen loss due to the variable underlying surface and rainfall characteristics. Thus, it is important to determine the effects of slope length on soil erosion and nitrogen loss as a foundation of scale expansion.

The objective of this paper is to study the influence of slope length effects on runoff, sediment yield and nitrogen loss. The hypotheses tested in this study were as follows: (1) runoff rates decrease with increased slope length; (2) sediment and TN losses increase with increased slope length; and (3) a model could be established to simulate processes of runoff, sediment and TN losses under different slope lengths. Nitrogen loss is accompanied by runoff and sediment loss. In this paper, the influence of runoff on sediment and both runoff and sediment on nitrogen loss is discussed before the slope length effects on nitrogen loss are considered. Because rainfall intensity is one of the key factors that affects runoff, sediment yield and nitrogen loss, the influence of rainfall intensity on nitrogen loss is also discussed.

2. Materials and methods

2.1. Soil and slope preparation

The study site is located at HeLinGe'Er, Hohhot, Inner Mongolia, China (N40°12′, E111°41′). The study site has a semi-arid climate. Most of the precipitation occurs in June, July, August and September, with an annual precipitation of 417.5 mm and a maximum 24-hour precipitation of 99 mm. Soil samples were selected randomly in an "S" shape on the 20-m long slope for soil sampling and analysis. Five soil sampling points were selected, and one sample of approximately 500 g, which was taken at each point from a depth of 0 to 10 cm, was sealed in a plastic bag and then transported to the laboratory for chemical and physical analysis. Then, one cutting ring sample was collected at each point to determine the soil bulk density. Parts of the 500 g sample were sieved (2 mm) to remove roots and large stones. The particle-size distribution was determined by using the pipette method. The soil is classified as Kastanozem with a sandy (Table 1) texture (89.6% sand, 5.4% silt, 5.0% sand) and is susceptible to erosion. Soil bulk density was measured using the ring method. The soil pH was determined using a pH probe in a 1:2.5 soil:water suspension. Soil organic matter (OM) was determined by $K_2Cr_2O_7$ oxidation at 180 °C, and soil total nitrogen (TN) was measured by the semi-micro Kjeldahl method.

2.2. Rainfall simulation experiments

The 20 m long slope was divided into 15, 10, 5 and 1 m by PVC sheets, which were placed 30 cm deep in soil and 30 cm above the soil after the completion of simulated rainfall of longer slopes. Side-sprinkle simulators, which included 3 nozzles set every 5 m for each side, were used in the experiment. The spray angles of the nozzles ranged from 0 to 360 degrees. The spray angles of the middle nozzles were designed to be 180 degrees and 90 degrees for the nozzles of the four corners. Before each simulated rainfall experiment, plastic sheets were placed on the plot to prevent soil erosion, and rain gauges were placed at 1 m × 2.57 m, 1 m × 1.86 m, 1 m × 1.14 m, 1 m × 1 m and 1 m × 1 m with 40, 40, 40, 25 and 5 gauges for 20, 15, 10, 5 and 1 m long slopes, respectively. The weight of water in the rain gauges was measured to calculate the uniformity and rainfall intensity of every experiment after 10 min of simulated rainfall. The rainfall height was 3 m, with a uniformity of above 75%, which was appropriate for the rainfall simulation experiment. The measured median raindrop diameter was 1.4 mm, with a velocity of 5.2 m s^{-1} and a rainfall energy of 13.52 J mm^{-1} m^{-2}. Three rainfall intensities were designed for the experiment, including 75 mm h^{-1}, 50 mm h^{-1} and 25 mm h^{-1}, with frequencies of 0.97, 2.31 and 6.14 times per year, respectively. Rainfall intensities were adjusted by changing the aperture of the nozzle and water pressure. Pre-wet treatments were conducted 12 h before the simulated rainfall. Generally, the treatments were conducted at 6 PM to eliminate the influence of wind. The pre-wet treatments were exposed to rainfall at a constant intensity of 25 mm h^{-1} until runoff formed on the slope. Then, the simulated rainfall was conducted at 6 AM on the following day. Generally, the rainfall simulations were repeated one time per day after the determination of uniformity and rainfall intensity. The slope was leveled prior to the next simulated rainfall.

Rainfall simulation plots were 5 m wide for all of the treatments. All of the plots were established on slope gradients of 5 degrees. Slopes were bare before and during rainfall simulations. Grass was removed if found on the slope. During the simulated rainfall, runoff was first collected in the sampling gutter with a length of 5 m, width of 0.12 m and depth of 0.2 m, and then, a PVC pipe with a diameter of 0.075 m was used to transport runoff into the steel runoff tank (Fig. 1). The sampling gutter was made higher on both sides and lower in the middle. A small shovel was slid along the sampling gutter to guarantee that most of the runoff and sediment generated from the slope could reach the runoff tank during the simulated rainfall event.

The time at which runoff initially formed was recorded for each rainfall event. At the base of each slope, there was a steel runoff tank collecting runoff and sediment. Samples were collected at unequal intervals, namely, 0–1 min, 2–3 min, 5–6 min, 10–11 min, 20–21 min, and 30–31 min after the runoff initially formed. The mixture of runoff and sediment was first collected in a plastic bucket, and the runoff volume was measured following the simulated rainfall. Bucket samples were mixed, and a 500 mL subsample was then collected. A 300 mL subsample was collected from the bucket until the completion of the precipitation and then transferred into a plastic bottle. The plastic bottles were stored at 4 °C in a refrigerator for chemical analysis. The sediment in the bucket was air dried and sampled. Sediment in the 500 mL bottles was deposited, separated from the water, dried in an air-forced oven to a constant weight at 105 °C and weighed. In the laboratory, the concentration of TN (Potassium persulfate digestion — UV spectrophotometry) of runoff was measured, and the concentration of TN (Semi-micro Kjeldahl method) of sediment was also measured. Each treatment was conducted in triplicate.

2.3. Data analysis

To compare runoff, soil loss, runoff-associated TN loss and sediment-associated TN loss in each treatment, the runoff rate, sediment yield rate and TN loss rate were utilized. In this experiment, R_r is the runoff rate (mm min^{-1}), which was calculated using the following equation:

$$R_r = \frac{60Q}{1000BL} \tag{1}$$

where Q is the runoff (mL s^{-1}), B is the slope width (5 m for the experiment), and L is the slope length (m). S_r is the sediment yield rate

Table 1
Soil physical and chemical properties of five samples collected from study area (mean ± standard).

Soil type	Soil texture (%)			Soil bulk density (g cm^{-3})	pH	Organic matter (g kg^{-1})	TN (g kg^{-1})
	Sand/% (2.0–0.02 mm)	silt/% (0.02–0.002 mm)	clay/% (< 0.002 mm)				
Sandy	89.55 ± 0.39	5.43 ± 0.43	5.02 ± 0.27	1.52 ± 0.06	8.40 ± 0.16	2.81 ± 0.07	0.166 ± 0.02