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Runoff features of pasture and crop slopes at different rainfall intensities, antecedent moisture contents and gradients on the Chinese Loess Plateau: A solution of rainfall simulation experiments

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ABSTRACT

Pastures are important components of artificial vegetations for controlling soil erosion on the hilly region of Loess Plateau of China. However, runoff features of pastures and the differences with crops are not fully understood in this region. This study focused on two widely-planted pastures including ryegrass (*Lolium perenne* L) and alfalfa (*Medicago sativa* L) and one common crop spring wheat (*Triticum aestivum* L), and investigated their runoff features at soil boxes under different rainfall intensities, antecedent moisture contents and slope gradients through rainfall simulation experiments. And bare ground was set as control. The results indicated that the presence of vegetation delayed time to runoff and reduced runoff coefficient. The average values of time to runoff were ranked as: ryegrass > spring wheat > alfalfa > bare slope. Contrarily, the rank for slope runoff coefficient was: ryegrass < spring wheat < alfalfa < bare ground. Time to runoff and runoff coefficient showed significant ($P < 0.05$) correlations with rainfall intensity, antecedent moisture content, and slope gradient. Time to runoff showed a negative and exponential relationship with rainfall intensity and antecedent moisture content and a negative and linear relationship with gradient. Runoff coefficient indicated a positive and linear relationship with rainfall intensity and antecedent moisture content and a positive and power–function relationship with gradient. The results presented here could provide insights into understanding the effects of rainfall intensity, slope gradient, and antecedent moisture content on surface runoff for the Loess Plateau region.

1. Introduction

Both drought and soil erosion have adverse effects on economic and social development on the Loess Plateau of China (Wu et al., 2003). They are also the major driving forces leading to the fragility of natural ecosystems in this area. In this region, approximately 70% of annual precipitation falls between June and September, mainly in the form of heavy rainstorms. Thus surface runoff induced by heavy rainstorms is mainly responsible for soil erosion (Shi and Shao, 2000). It has been widely acknowledged that the dual goals of controlling soil erosion and easing drought can be achieved if surface runoff is regulated effectively (Wu et al., 2003; Zhao et al., 2009). Vegetation controls soil and water loss because the canopy, roots, and litter components enhance surface roughness and increase infiltration (Boer and Puigdefábregas, 2005; Gyssels et al., 2005). Accordingly, planting appropriate vegetation is an effective way to regulate runoff and reduce soil erosion on the Loess Plateau (Fraser et al., 1999; Lee and Shih, 2004).

Farming methods and land use types have a significant influence on runoff, affecting both time to runoff and runoff coefficient (Daverede et al., 2003; Dickie and Parsons, 2012; Siniscalco et al., 2011). For planted grasslands in the hilly region of the Loess Plateau, a power function relationship between time to runoff and rainfall intensity and a linear relationship between time to runoff and grass cover or soil moisture have been reported (Zhang and Liang, 1995). Fraser et al. (1999) and Williams et al. (2000) suggested that the runoff coefficient increases gradually with rainfall intensity. Pan et al. (2006) demonstrated that sediment concentration, average sediment rate, runoff and surface velocity were all reduced in the presence of vegetation compared to bare ground based on rainfall simulation experiments. Wei et al. (2007) found that shrubland had the most significant effect on reducing the runoff coefficient, followed by grassland, woodland, pastureland, and cropland. Li et al. (2007) studied the effect of vegetation spatial arrangement on water losses and its characteristics, and found that the grass coverage and slope gradient had significant influence on runoff resistance of hillslopes.

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Most studies mainly compared grassed with bare ground and there have been few studies focusing on the differences of runoff characteristics between pastures and crops on the Loess Plateau. In fact, the Loess Plateau is an important grain production region in western China and crops are widely planted. Moreover, hillslope runoff process is a complex and nonlinear hydrologic behavior, influenced by a number of factors including rainfall intensities, antecedent moisture contents and slope gradients and so forth. However, most of previous studies missed analyzing runoff characteristics of pastures under various physical conditions mentioned above. Time to runoff and the runoff coefficient are two important parameters to represent the characteristics of surface runoff (Cerdan et al., 2004; Chaplot and Bissonnais, 2003; Merz and Blölchl, 2009; Norbiato et al., 2009; Wainwright and Parsons, 2002). The main objective of this study was to characterize time to runoff and runoff coefficient of pasture and crop slopes at different rainfall intensities, antecedent moisture contents and gradients through rainfall simulation experiments. To this end, two widely cultivated pasture species, ryegrass and alfalfa, and a common crop, spring wheat, on the Loess Plateau were employed in this study.

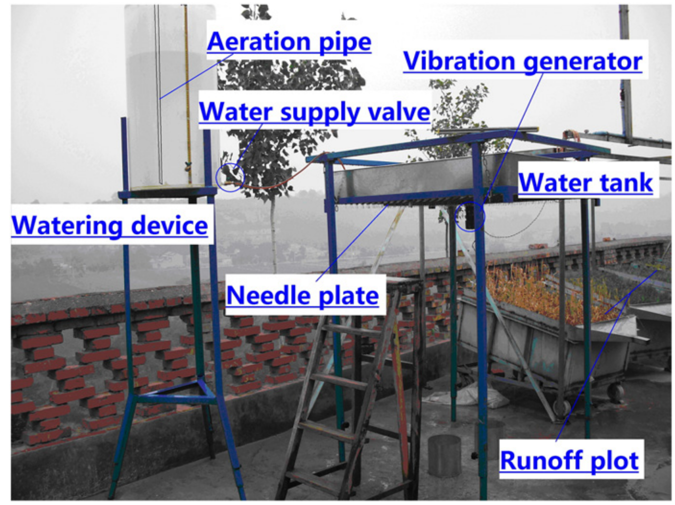

Fig. 1. The artificial rainfall simulator.

2. Materials and methods

The experiments were conducted at the field monitoring station operated by Institute of Soil and Water Conservation, Chinese Academy Sciences, in Linghou, Wuquan Town, Yangling District, Shaanxi Province. Yangling (E107°59′–108°08′, N34°14′–34°20′) is located in the west of the Guanzhong plain in Shaanxi province. It lies north of the Wei River. The Yangling area slopes down from north to south and can be divided into five kinds of terrain: a slope in the north, with three terraces below, and the Wei River beach at the bottom in the south. The region can be described as warm temperate with a semi-humid monsoon climate. The average annual temperature is 12.9 °C. The maximum temperature is 42 °C and the minimum −19.4 °C. The frost-free period amounts to 221 d. The mean annual rainfall and the mean annual evaporation are 637.6 mm and 884.0 mm, respectively.

The test site lies on the upper part of the three terraces where the clay content of the soil is higher than in the Water Saving Exposition Garden on the lowest terrace; this soil is quite different from that (silt loam) in the hilly region of the Loess Plateau (target region), and the high clay content has an unfavorable effect on soil infiltration. To represent the soils of the target region as much as possible, we conducted tests and found that a soil texture similar to that of the target region can be created by combining soil from the first and third terraces at a ratio of 1:1. This was achieved by passing the soil from each location through a 10 mm sieve after drying (soil moisture content of 8%) before mixing to create the experimental medium. The relevant chemical and physical properties of this mixed soil are shown in Table 1.

We used an artificial rainfall device to simulate rainfall: Fig. 1. The device consists of Markov bottles to act as a reservoir, a rainfall generator to produce raindrops and a vibration device to simulate natural rain. The Markov bottles can supply water at a constant rate to the rain generators, thus ensuring evenly distributed artificial rain. The device was calibrated prior to the experiment so that it was possible to change the simulated rainfall intensity during the experiment by adjusting the relative water depth in the reservoir. The rainfall generator comprises about 650 hypodermic needles. To simulate low intensity rain ($\leq$1.0 mm min^{-1}) we used 7# needles and for heavier rain (>1.0 mm min^{-1}) we used 8# needles. The vibration device uses eccentric wheels driven by a motor to make the needles move in a reciprocating motion with a radius of less than 4 cm, thereby simulating rainfall quite effectively. A wind break around the rainfall device can be erected to prevent the drops from being blown away from the target area. The simulated rainfall intensity ranges from 0.3 mm min^{-1} to 3.0 mm min^{-1} and the rainfall height is 1.0–1.7 m. The maximum effective rainfall area is 1.0 m × 1.5 m and the coefficient of uniformity of rainfall is more than 80%. The raindrop diameter is 0.5–2 mm and its mean velocity is 4.78 m/s. The mean rainfall kinetic energy per unit time per unit area is 0.2193 J/m^2 s. Five rainfall intensity levels (0.5, 0.75, 1.0, 1.5, and 2.0 mm min^{-1}) were used in the experiment, based on field rainfall data collected over many years on the Loess Plateau.

The "plot" comprises a kind of mobile soil bin, the gradient of which can be adjusted (Fig. 1: runoff plot). Its size (length × width × height) is 1.2 m × 0.8 m × 0.45 m. A channel at the bottom discharges the muddy water representing the runoff. There are evenly distributed drainage holes at the bottom of the soil bins to allow infiltration to occur freely. A layer of gauze was placed in the base of the soil bin before it was filled with earth in order to facilitate even water infiltration. A total of four 10 cm deep layers were packed into the soil bins. These were then compacted uniformly, to achieve a soil bulk density between 1.35 and 1.40 g cm^{-3}. The surface of each layer was roughened before adding the next layer in order to reduce soil stratification which could affect infiltration. Four gradients (8.8%, 17.6%, 26.8% and 36.4%) were examined during the experiment.

We examined runoff over ryegrass and alfalfa, which were sown at the beginning of April 2009. Spring wheat was selected to represent a typical crop and this was sown in mid-march 2009; bare ground was also investigated as a control treatment. There were three replicates for each treatment. In all cases the seeds were sown by broadcasting. Ryegrass and alfalfa were mown three to five times during the experiment, as is the standard practice of local farmers. The experiment commenced in mid-May 2009, and, in total, 80 artificial rainfall simulation tests were performed. Time to runoff is an important parameter related

Table 1
Selected chemical and physical properties of the soil studied.

Particle diameter/mm			Soil texture	pH	Organic/g kg^{-1}	Total N/g kg^{-1}	Total P/g kg^{-1}	Total K/g kg^{-1}
<0.001	0.001–0.05	0.05–0.25						
0.31%	74.26%	13.27%	Silty loam	8.45	12.3	0.9	0.8	15.4