Effects of subsequent rainfall events with different intensities on runoff and erosion in a coarse soil

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A B S T R A C T

A deeper understanding of the hydrological response to subsequent rains would be useful in the prediction of runoff production for planning vegetation restoration and assessing flood risks. We used subsequent rains to study the role of rain intensity and antecedent soil moisture content (ASMC) on runoff and erosion for coarse soil of the semiarid Loess Plateau in China. The study used a rain simulator in a field planted with alfalfa (Medicago sativa), which is widely grown for animal feed to develop livestock operations, reduce soil erosion, and improve soil fertility/quality. A slope of 18% was selected because most of the land with slopes < 18% in the region is used for cropland. We tested three rain intensities (20, 40, and 60 mm h⁻¹), corresponding to low, moderate, and high intensities, respectively) with five successive rains (an initial and four subsequent rains) in triplicate. We quantified the changes of runoff depth (RD), sediment yield (SY), and sediment concentration (SC) over time and then analyzed the relationships between ASMC and runoff in 0–50 cm soil layers for all 45 simulated rains. Runoff commencement time (RCT) was shorter, the runoff coefficient (RC) was larger, and runoff was higher for the moderate and high intensities than the low intensity. Intermittency and the characteristics of the sequential rains also influenced these processes. A general linear model identified significant effects of rain sequence and intensity on RCT, RD, RC, SY, and SC (P < 0.01), but their interaction did not have a significant effect on RCT and SY. An exponential fit between ASMC and RC was best for the 0–10 cm and 10–20 cm layer (R² = 0.38, P < 0.000), and R² decreased from the 0–20 cm to the 30–40 cm layers. Soil moisture content (SMC) was an important factor controlling runoff, and the sequential rains led to high runoff and sediment transport, because runoff from storms on highly permeable soils is controlled by the saturation of the topsoil horizon and is more dependent on initial conditions.

1. Introduction

Heavy but brief local rainstorms, irrational land use, and the soft and loose soils of the Loess Plateau are responsible for runoff and soil erosion, especially where schemes of soil conservation have not been widely used (Shi and Shao, 2006; Fu et al., 2017). Recent studies, however, have challenged these conclusions. Both river discharge and sediment yield across the plateau have been reported to have decreased (linearly or exponentially) with increasing plant coverage (Arnau-Rosalén et al., 2008; Mohammad and Adam, 2010; Xin et al., 2011). Runoff and sediment yield tend to decrease (linearly or exponentially) with increasing plant coverage (Arnau-Rosalén et al., 2008; Mohammad and Adam, 2010; Xin et al., 2011). Vegetation coverage has increased substantially in most regions of the Loess Plateau in recent years when a series of measures of soil and water conservation, including terracing, forestation, grass restoration, and the conversion of sloping farmland to forest or grassland, under the national Grain for Green program were implemented (Wang et al., 2011; Liu et al., 2014). Vegetation restoration, though, can affect the soil water resources of the plateau (Chen et al., 2007). For example, long-term alfalfa production may severely deplete soil water and phosphate in 0–100 cm and even in 2–10 m profiles, which can lead to the desiccation of loessial soils (Fan et al., 2004, 2010). Feng et al. (2016) reported that the new plantings have increased both net primary productivity and evapotranspiration. The increase in evapotranspiration has also induced a

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significant \((P < 0.001)\) decrease in the ratio of runoff to annual precipitation across hydrological catchments. The conditions of soil moisture can affect the partitioning of rainwater into infiltration, consequently influencing runoff and soil erosion (Zonta et al., 2012). Liu et al. (2011) found that infiltration capacity was lower under higher ASMC. Water infiltration decreased in experimental plots with increasing antecedent SMC (ASMC) at a depth of 10 cm, which produced more runoff and sediments (Wei et al., 2007). The effects of SMC on runoff and soil erosion must therefore be considered, especially in semiarid environments where water resources are scarce. Many studies have thus investigated the interaction between SMC and soil erosion at different scales (Calvo-Cases et al., 2003; Khaledi Darvishan et al., 2011; Sachs and Sarah, 2017). Western and Grayson (1998) demonstrated that the surface runoff in a catchment was controlled by SMC, with a threshold of 41–46%, depending on the depth over which the SMC was averaged. Zhang et al. (2011) determined the effects of ASMC on runoff generation in a semiarid environment by process-based modeling and found an average change of 0.05 mm in runoff for each 1% change in SMC. Castillo et al. (2003) and Scherrer et al. (2007), however, reported that runoff response did not depend on ASMC when infiltration-excess overland flow was predominant. The effects of soil moisture on runoff formation are therefore still not clear, especially for coarse soil with a dry profile.

Rain frequency and the timespan between two rains are important factors for infiltration, runoff, and soil loss (Erpul and Çanga, 1999; Römkens et al., 2001). The characteristics of natural rains at a hillslope scale (total rainfall and rain intensity) and antecedent precipitation are the main variables affecting the runoff depth and coefficient (Li et al., 2011). Findell and Eltahir (1999) found a positive relation between subsequent rainfall and ASMC. SMC is an important factor affecting the loss of nitrogen in northeastern China, because erosion-induced pollution is dominant (Ouyang et al., 2017). Ran et al. (2012) analyzed a series of rains of different durations with no dry intervals, comprising an initial rain with initially dry soil and a multiple-peak intermittent rainfall pattern; the sediment concentration (SC) decreased over time as erodible particles were washed away, and the SC increased until stabilizing for low/moderate intensity rains because runoff was low and erosion was transport-limited. Sadeghi et al. (2016) reported significant effects \((P < 0.01)\) of a sequence of rains on runoff commencement time (RCT), runoff depth (RD), a runoff coefficient (RC, the runoff:precipitation ratio), and sediment yield (SY) and a non-significant effect \((P = 0.13)\) on SC when considering the durability of the effects of soil amendments during subsequent rains.

Climate change can have direct and indirect impacts on soil erosion, with many influencing factors. Higher rainfall, rain intensity, and frequency of extreme rains can directly increase soil erosion (Feng et al., 2015; Li and Fang, 2016; Anache et al., 2018). Rain characteristics become more variable and stochastic under climate change condition, which increases the uncertainties and risks of water erosion in China (Li et al., 2015; Feng et al., 2015; Zhang et al., 2018). Heavy or continuous rains with high rainfall may trigger surface runoff and induce major flood hazards (Dehotin et al., 2015; Ries et al., 2017). For example, two continuous rains in 2012 and 2017 on the Loess Plateau in China led to extreme soil erosion (Wang et al., 2016, 2017).

The characteristics of soil erosion and runoff after vegetation restoration should therefore be identified for heavy or continuous rains. We studied the effects of subsequent rains on hydrologic components to advance our understanding of the role of SMC in the reduction of water and soil erosion during vegetation restoration on the plateau. Other objectives were to assess the effects of ASMC on runoff and SY during five successive rains at three intensities and to determine the relationship between ASMC and RC to identify the threshold of notable runoff.

2. Materials and methods

2.1. Description of the study area

The study was carried out at the Shenmu Erosion and Environmental Station on the Loess Plateau in northern Shaanxi province, China (Fig. 1) in July and August 2015. The catchment has a size of 6.9 km², an elevation of 1094.0–1273.9 m a.s.l., and a mean slope of 27%. The average annual precipitation is about 437.4 mm. The minimum and maximum monthly temperatures average 3.1 and 13.8 °C, respectively. The watershed is characterized by a semiarid continental monsoon climate with precipitation mostly from June to September (Zhu and Shao, 2008; Fan et al., 2010), most of which falls during highly intense storms, so soil erosion predominately occurs in this period.

The study area was in a 900-m² alfalfa field with a mean slope of 10°. The alfalfa was planted a year before as part of the Grain for Green program. The main characteristics of the plant cover and soil are presented in Table 1.

2.2. Experimental materials and design

The experiments were conducted in the field using a portable
dripper-type rain simulator (Bowyer-Bower and Burt, 1989; Battany and Grismer, 2000) that is relatively simple and inexpensive to build and can be fully operated by one person. The simulator consists of two units: a raindrop generator and a support frame. The support frame was 1.2 m wide, 2 m long, and 1.5 m high on flat ground. Two of the four legs could be extended to maintain a level raindrop generator on a slope. The raindrop generator was an open tank 1.5 m long and 1 m wide with >1100 hypodermic needles at the bottom and attached to the support frame with four chains. The needles were 23G and 21G with inner diameters of 0.34 and 0.51 mm, respectively, and the average spacing between the needles was 1.0 cm. Raindrop diameters ranged from 0.20 to 3.65 mm. The 23G needles were used to deliver an intensity of 20 mm h\(^{-1}\), but two constant water levels in the open tank were maintained to generate intensities of 40 and 60 mm h\(^{-1}\) using 21G needles. The average drop diameter produced for each of the 23G needles was around 2.5 mm (Naslas et al., 1994; Battany and Grismer, 2000) that is relatively simple and inexpensive to build and can be fully operated by one person. The simulator consists of two units: a raindrop generator and a support frame. The support frame was 1.2 m wide, 2 m long, and 1.5 m high on flat ground. Two of the four legs could be extended to maintain a level raindrop generator on a slope. The raindrop generator was an open tank 1.5 m long and 1 m wide with >1100 hypodermic needles at the bottom and attached to the support frame with four chains. The needles were 23G and 21G with inner diameters of 0.34 and 0.51 mm, respectively, and the average spacing between the needles was 1.0 cm. Raindrop diameters ranged from 0.20 to 3.65 mm. The 23G needles were used to deliver an intensity of 20 mm h\(^{-1}\), but two constant water levels in the open tank were maintained to generate intensities of 40 and 60 mm h\(^{-1}\) using 21G needles. The average drop diameter produced for each of the 23G needles was around 2.5 mm (Naslas et al., 1994; Battany and Grismer, 2000). The average drop diameter of erosive rainfall is 2.4 mm on the Loess Plateau (Jiang et al., 1983), so, the simulated raindrop is comparable to local rainfall. Raindrop size varied with rain intensity due to the different inner diameters of the needles and water pressures, but we did not account for the effect of raindrop size. Rain intensity was measured before a simulation by covering the plot with plastic film and collecting the water in two rain gauges for 3 min for each simulation. The average amounts of collected rainwater from 30 data points for the 20, 40, and 60 mm h\(^{-1}\) intensities were 19.9, 40.6, and 59.7 mm h\(^{-1}\), with standard deviations of 2.4, 3.2, and 4.5 mm h\(^{-1}\), respectively. Local well water was used for the simulated rains, which had an average pH of 7.6.

The experimental design included two factors: rain intensity and initial SMC. Three rain intensities of 20, 40, and 60 mm h\(^{-1}\) were simulated as dominant intensities with 7, 65, and 195 years return periods for the Shennu Erosion and Environmental Station (Fig. 1). Both water and wind erosion are severe in this region due to the erodible soil and the concentrated rainfall season: over 60% of the precipitation occurs between July and September, with over 50% occurring as high-intensity precipitation (Fan et al., 2010). The rain records from 2003 to 2017 indicated 194 events with precipitation >10 mm. The frequencies of the daily amount for rainfalls of >40 mm, >80 mm, and >120 mm were 14.9, 1.5, and 0.5%, respectively. Because of the 12 h intervals between two events, the 20 and 40 mm h\(^{-1}\) intensities could represent 40 and 80 mm per day and 60 mm h\(^{-1}\) rainfall could represent the extreme natural heavy rains (120 mm d\(^{-1}\)) in the region. We also assumed that the five rains would saturate the soil to a depth of 30 cm even at the 20 mm h\(^{-1}\) intensity. For two simulations during the daytime, we conducted one simulated rain in the morning and another in the middle of the afternoon, which provided an average return period of 12 h and various SMCs. The plot was protected from natural rain between simulated rains by a waterproof plastic cover. The spaces between the soil and the cover were kept open to allow ventilation, and the plastic cover was removed on sunny days to allow evapotranspiration. SMC would tend to increase because of the continuous rains, which provided a different ASMС for the next rain. Nine plots were separated into three groups, and each group of three plots was used to conduct five rains at the same intensity. Tin blocks (70 cm tall) surrounded each plot, and a PVC tube was installed at the lower edge as a runoff outlet. The simulated rains were maintained until runoff was collected for nearly 60 min. The simulated rains were then stopped, and the residual runoff and sediments were ignored due to the small size of the plot.

### 2.3. Measurements of experimental components

Table 1 presents the main characteristics of the plant cover and soil properties in the experimental plots.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope (%)</td>
<td>18.0</td>
</tr>
<tr>
<td>Vegetation coverage (%)</td>
<td>40.0</td>
</tr>
<tr>
<td>Plant height (cm)</td>
<td>17.2</td>
</tr>
<tr>
<td>Dry biomass on the ground (g m(^{-2}))</td>
<td>96.11</td>
</tr>
<tr>
<td>Sand content (%)</td>
<td>64.29</td>
</tr>
<tr>
<td>Silt content (%)</td>
<td>23.40</td>
</tr>
<tr>
<td>Clay content (%)</td>
<td>12.31</td>
</tr>
<tr>
<td>Bulk density (g cm(^{-3}))</td>
<td>1.34</td>
</tr>
<tr>
<td>Total nitrogen content (g kg(^{-1}))</td>
<td>0.22</td>
</tr>
<tr>
<td>Total phosphorus content (g kg(^{-1}))</td>
<td>0.58</td>
</tr>
<tr>
<td>Organic matter content (g kg(^{-1}))</td>
<td>3.72</td>
</tr>
<tr>
<td>Field capacity (cm(^{3}) cm(^{-3}))</td>
<td>0.22</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity of bulk soil, K(_s) (mm h(^{-1}))</td>
<td>25.0</td>
</tr>
</tbody>
</table>

SMC in the 0–10, 10–20, 20–30, 30–40, and 40–50 cm soil layers was determined gravimetrically before and after a rain from samples collected using a soil auger with a 2 cm diameter. The results are presented as mass water content (%). All samples were collected near the center of the simulation plots, and all holes were carefully refilled. The rain intensity was calibrated before and after each simulated rain. Runoff and soil erosion samples were collected using several labeled plastic buckets at the outlet of each plot and measured for producing hydrographs at regular intervals for the various rain intensities. Samples were collected every minute for the first 10 min and then 10 times in the next 50 min for the 60 mm h\(^{-1}\) intensity. Runoff samples for the 20 and 40 mm h\(^{-1}\) intensities were collected every 2 min for the first 20 min and then 10 times in the next 50 min, because runoff was lower for the low and medium intensities than the high intensity. The samples were weighed, and the sediments were determined using settling, decantation, and air-drying methods (Khaledei Darvishan et al., 2015). The residual moisture in the air-dried sediments was negligible. The RDs were calculated by dividing the runoff volume by the plot area and the RCs were also determined by dividing the RD by total rainfall for each rain shower. All results are averages of three replicates.

### 2.4. Data analysis

An ANOVA was used to analyze the differences among group means, and the data were tested for normality. The RCT data were transformed to log-normal distributions because it was abnormal indicated by Shapiro-Wilk’s test. A general linear model (GLM) was used to statistically analyze the main and interactive effects of the variables (Sadeghi et al., 2016). Curve estimation was conducted to identify correlations between ASMС and RC, and between runoff and SY. All the data analysis was conducted by SPSS version 19 (SPSS Inc., Chicago, Illinois, USA).

### 3. Results

#### 3.1. Effects of subsequent rains on runoff and soil erosion

A total of 45 rains were simulated in nine plots, so five rains were simulated in each plot in three days. Rain intensity significantly affected the total sediment yields and runoffs of the five rains, but the differences between 40 and 60 mm h\(^{-1}\) were not significant. The differences between the SCs at the three rain intensities were also not significant (Fig. 2).

The main characteristics of RD, SY, and SC for each rain are presented in Table 2. SYs, RDs, and RCs were significantly affected by the subsequent rains, but SC was significantly affected only at the 20 and 40 mm h\(^{-1}\) rain intensities. Hydrographs and sediment graphs were analyzed to obtain the hydrological and erosion responses at the three rain intensities. The changes in runoff rate, SY, and SC over time for the subsequent rains are shown in Figs. 3–5.

RCT was often earlier and RD increased faster for subsequent rains than the initial rain, especially at a rain intensity of 60 mm h\(^{-1}\). Runoff
thereafter remained at a steady state due to the saturation of the topsoil. RD differed more between the initial rain and the 1st subsequent rain than between any two subsequent rains (Figs. 3-5). The low rain intensity (20 mm h\(^{-1}\)) produced a small amount of runoff (after reaching the outlet) during 60 min of rain, whereas RD reached 4.7 mm in the 1st subsequent rain. Subsequent rains at an intensity of 20 mm h\(^{-1}\) generated a lower runoff peak due to higher infiltration, and RD differed little between the four subsequent rains (4.7–7.7 mm) after the initial rain. RD increased considerably more at the moderate (40 mm h\(^{-1}\)) than the low (20 mm h\(^{-1}\)) intensity from the initial to the 4th subsequent rains and increased the most at the high intensity (60 mm h\(^{-1}\)).

These results demonstrated that RD increased with rain intensity under the same experimental conditions.

SY increased significantly from the initial to the 4th subsequent rain at the low and moderate intensities, whereas SY at the high intensity increased rapidly from the initial to the 2nd subsequent rain and then fluctuated (Fig. 4). SY during the initial and 1st and 2nd subsequent rains increased with rain intensity, though, some oscillations could be found in values obtained in study intervals. SY tended to fluctuate between the moderate and high intensities in the 3rd and 4th subsequent rains, although both SYs were larger than that at the low intensity, indicating that SY was limited by transport when the overland flow was small and by detachment when the flow was large.

SC was high during the initial rain at intensities of 40 and 60 mm h\(^{-1}\), when the available erodible particles were washed away (Fig. 5). SC then decreased quickly over time, because the soil was being eroded and sediment availability decreased, especially at 60 mm h\(^{-1}\). SC in the 3rd and 4th subsequent rains was higher at an intensity of 20 mm h\(^{-1}\) than at 40 and 60 mm h\(^{-1}\). The rain sequence could thus increase SC from the 1st to the 4th subsequent rain only at the low intensity. RD, SY, and SC differed distinctly between the three rain intensities with the subsequent rains.

The GLM analysis identified significant effects (\(P < 0.01\)) of rain sequence and intensity on RCT, RD, SC, and SY (Table 3). The interaction of rain intensity and sequence on RCT and SY was not significant, but the interaction of rain intensity and sequence on RD and SC was significant (\(P < 0.05\)).

3.2. Effects of ASMC on RC

The five rains occurred within three days during the decade of study, so SMC in the 0–10 cm layer increased considerably for the 1st subsequent rains at the three rain intensities, but SMC in the 10–20 cm layer improved significantly for the 1nd subsequent rains at 40 and 60 mm h\(^{-1}\). SMC in the 20–30 cm layer improved significantly for the
1st subsequent rains only at 60 mm h\(^{-1}\) (Fig. 6). SMC did not increase for the 3rd or 4th subsequent rains, indicating that it had increased to field capacity under the previous three rains.

ASMC was correlated with the rain sequence during the experiment and influenced the runoff. We analyzed the relationship between ASMC of the soil layers at 10-cm spacings (0–50 cm) and RC to investigate the importance of SMC on runoff generation. The correlation was a significant exponential function \(R^2 = 0.38, P < 0.000\) (Fig. 7) for the 0–10 cm layer and 10–20 cm layer. In contrast, the correlation between SMC and RC decreased when ASMC for the 20–30 cm layer was analyzed \(R^2 = 0.19, P < 0.005\), and the correlations were not significant for the 30–40 cm or 40–50 cm layers (data not shown). RC varied similarly when ASMC for the 0–20 cm layer ranged from 14 to 20%. RC was < 20% when ASMC was < 10%. These results further indicated that SMC as deep as 30 cm had a direct effect on runoff generation and that deeper soil (30 cm) could influence the distribution of soil water, which had an indirect effect on runoff response at short timescales. SMC for the 30–40 and 40–50 cm layers, though, did not significantly affect RC.

3.3. Effect of rain intensity on relationship between RD and SY

RD and SY varied with rain intensity (Table 2). RD and SY were generally highest at an intensity of 60 mm h\(^{-1}\), followed by 40 and 20 mm h\(^{-1}\). SY generally increased with RD, but some data points were scattered or outliers in present study (Fig. 8).

4. Discussion

4.1. Effects of the subsequent rains on runoff and soil erosion

The rain sequence (Table 2) significantly affected the time required to generate runoff at the three rain intensities. The rain sequence was negatively correlated with RCT (Table 2 and Fig. 3). Arnaez et al. (2007) and Sadeghi et al. (2016) reported similar findings. No runoff occurred in the initial rain for two of the replicates during a 70-min rain at an intensity of 20 mm h\(^{-1}\), perhaps due to two vital factors: raindrop impact and rain intensity. The infiltration rate has an increasing trend with rain intensity (Fig. 3), which has also been previously reported (Mertz et al., 2002; Stone et al., 2007). RD was higher in the 1st subsequent rain than the initial rain because infiltration decreased, and hydraulic conductivity would decrease with a decrease in surface roughness and an increase in soil sealing under wet conditions (Erpul and Çanga, 1999; Lei et al., 2006). Sadeghi et al. (2016) found that the RDs at all intervals were higher in the 1st subsequent rain than the initial rain because infiltration decreased, and hydraulic conductivity would decrease with a decrease in surface roughness and an increase in soil sealing under wet conditions (Erpul and Çanga, 1999; Lei et al., 2006). Sadeghi et al. (2016) found that the RDs at all intervals were higher in the 1st subsequent rain than the initial rain. Changes in the hydraulic properties of the soil could also account for the RDs for the 2nd, 3rd, and 4th subsequent rains. Our results generally indicated that rain sequence at the various intensities could efficiently increase the runoff. The increase in SY from the initial

![Fig. 4. Temporal variation of sediment for the five rains at intensities of 20 mm h\(^{-1}\) (a), 40 mm h\(^{-1}\) (b), and 60 mm h\(^{-1}\) (c).](image_url)

![Fig. 5. Temporal variation of sediment concentration for the five rains at intensities of 20 mm h\(^{-1}\) (a), 40 mm h\(^{-1}\) (b), and 60 mm h\(^{-1}\) (c).](image_url)
to the 4th subsequent rains was due to the decrease in hydraulic conductivity and the increase in runoff (Fig. 4) (Mutchler and Carter, 1983; Alberts et al., 1987; Yi and Fan, 2016). The hydrographs for the subsequent rains were characterized by higher constant runoff peaks, similar to those in other studies (Kleinman and Sharpley, 2003; Sadeghi et al., 2016). The increase in SY in the 1st, 2nd, and 4th subsequent rains was correlated with the decrease in hydraulic conductivity, which may also account for the high SC for the initial rain and following a decrease during the subsequent rains, because rain characteristics may have a dominant influence on runoff. The temporal variation of SY increased with rain intensity because of the detachment of soil particles by the higher raindrop force. The simulator delivers the same number of raindrops for the various rain intensities, but raindrop size and thus force increases with intensity (Yakubu et al., 2016).

Fig. 7. The relationships between the runoff coefficient and antecedent soil moisture content (ASMC, mass water content) in the three soil layers.

4.2. Effects of ASMC on runoff and soil erosion

The non-linear relationship between RC and ASMC indicated a soil moisture threshold above which a notable increase in runoff occurred. This threshold has been reported by many others (e.g. Ruggenthaler et al., 2015). Runoff formation during rain, however, was determined by several interacting factors, and SMC and its variability in space and time led to a high scattering level between RC and ASMC (Fig. 7). Yi and Fan (2016) reported that runoff and erosion in a field-monitoring study at the same site was significantly influenced by ASMC. The probability of generating runoff in cropland was as high as 85% when rainfall depth was > 10 mm and ASMC was > 0.12 cm$^3$ cm$^{-3}$ (Yi and Fan, 2016). Our ASMC threshold, however, was 0.17 cm$^3$ cm$^{-3}$ (13% by mass) (Fig. 7). Planting alfalfa has increased this threshold considerably by improving soil quality and reducing runoff (Fan et al., 2010).

Infiltration-excess overland flow is the predominant runoff availability (Chaplot and Bissonnais, 2003; Kleinman and Sharpley, 2003; Sadeghi et al., 2008). Ran et al. (2012) who also found that SC was higher for the initial than the subsequent rains, because more erodible particles were present. SC in our study was higher for the initial than the subsequent rains at an intensity of 60 mm h$^{-1}$. The higher RD and bigger raindrop splashes at the high rain intensity would increase SY and SC, in agreement with previous studies (Alberts et al., 1987; Erpul and Çangtaş, 1999).
mechanism on sloped farmland on the Loess Plateau. The land surface has wetting soil and a sparse cover (< 40%), so the thin topsoil layer is quickly saturated by raindrop force and subsequently sealed (Shen and Fan, 1984; Shi and Shao, 2000; Li et al., 2009). The ratio of rain intensity to soil hydraulic conductivity for such a mechanism determines the generation of overland flow (Castillo et al., 2003). A maximum of 80 mm of rainwater under the soil conditions in this study, however, could saturate the 0–20 cm soil layer if soil water storage is almost depleted by the alfalfa. Our soil should have 20 mm h⁻¹ infiltration at least, because no runoff was generated in two of the three replicates during the initial rain at the 20 mm h⁻¹ intensity. The generation of runoff after 5 min of the 2nd rain (12 h after initial rainfall) at the 20 mm h⁻¹ intensity supported the importance of saturated overland flow caused by the saturation of the topsoil layer during the long 40 mm rain in one day. RCT was 9.8, 8.5, and 5.3 min at the 20, 40, and 60 mm h⁻¹ intensities, respectively, in the initial rain, but RCT was markedly shortened by saturation of the topsoil to 2.6, 1.7, and 1.3 min at the 20, 40, and 60 mm h⁻¹ intensities, respectively, in the final rain, indicating that the saturation-excess overland flow was dominant when the topsoil was saturated by antecedent rain. Zhu (2006) reported that saturation-excess overland flow was not generated under a 500 mm rain in a forest, and infiltration-excess overland flow was not generated under a 120 mm h⁻¹ rain intensity on the southern Loess Plateau. Biddouc et al. (2017) also reported that runoff in grass-covered plots was mainly due to saturation of the uppermost soil. The mechanism of runoff formation has therefore changed due to the conversion of the land-use type from sloped cropland to forest under the Grain for Green program, as indicated by our study. A dry soil layer, even to a depth of 500 cm (Fan et al., 2016), can improve hydraulic conductivity and decrease raindrop force and sealing if dense plant cover contributes to soil infiltrability. SMC of layers as deep as 20–30 cm was still significantly exponentially correlated with RC, indicating that SMC for the deeper layers could affect runoff because of the high infiltration rate. Deep-rooting plants could thus be better able to reduce the proportion of saturation-excess overland flow for this kind of coarse soil, especially if subsequent rains are more frequent. Saturation-excess overland flow, however, occurred after the infiltration rate had exceeded the storage capacity, which may lead to debris flow and flood hazard. For example, a rainfall of 159–206.6 mm from a 12-hour rainstorm on 25 and 26 July 2017 on the northern Loess Plateau near our study site produced a maximum rain intensity of 52 mm h⁻¹ (Wang et al., 2017), which led to very serious floods and economic losses. Successive rains can increase SMC substantially, even when depleted by vegetation before a rain. Combining engineering measures in the Grain for Green program with vegetation restoration is therefore necessary. Vegetation can affect sediment yield at various scales (Zheng et al., 2008; Xia et al., 2017; Vaezi et al., 2017) and a linear or power function between sediment yield and runoff on the Loess Plateau (Zheng et al., 2008; Xia et al., 2017) was reported. Sediment yield was correlated with runoff as a power function in the small plot using a portable dripper-type rain simulator in present study. This result also indirectly indicated that rain-simulator experiments can be used to study runoff and erosion. Rainfall simulators, however, offer lower kinetic energies and coefficients of distribution uniformity than those of natural rainfall, although they are widely used for studies of soil erosion and infiltration (Bowyer-Bower and Burt, 1989; Clarke and Walsh, 2007; Schindler Wildhaber et al., 2012; Zhao et al., 2013a; Zhao et al., 2013b). Battany and Grimmer (2000) reported an average coefficient of distribution uniformity of 91.7%, and their system generated approximately 70% of the kinetic energy of natural rainfall at the 60 mm h⁻¹ intensity. These disadvantages may affect the results. Field experiments are therefore essential for understanding the process of soil erosion in natural alfalfa environments.

5. Conclusions
An initial rainfall event with three rainfall intensities of 20, 40, 60 mm h⁻¹ and followed by four consecutive rainfall events were conducted to investigate the hydrologic response of small plots in the present study. The soil and water loss from the alfalfa field under semiarid climatic conditions varied with rain intensity and subsequent rains. Runoff depth and sediment yield increased more at the high than the low and moderate intensities under the same plot conditions. Rain intensity significantly influenced the total sediment yields and runoffs of the five rains, but the differences between 40 and 60 mm h⁻¹ were not significant. The subsequent rains also had large effects on the hydrological characteristics, including runoff commencement time, runoff depth, sediment yield, and sediment concentration. A significant exponential function between sediment concentration and antecedent soil moisture content at 0–30 cm was observed and also a significant power function between runoff depth and sediment yield was found under different rain intensities on the small plot scale. The simulation of rain on sloped land, which is characterized by saturation-excess overland flow as the main mechanism generating runoff, may account for these findings. These results indicated that vegetation-restoration affected runoff formation on the Loess Plateau. Soil moisture content should be taken into consideration in soil-conservation efforts but also in runoff and erosion modeling. Engineering measures should thus be promoted in the Grain for Green program together with vegetation restoration to avoid flood hazards where sequential rains are becoming common.

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