Combined influences of wheat-seedling cover and antecedent soil moisture on sheet erosion in small-flumes

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A B S T R A C T
Assessing and predicting soil erosion requires knowledge of the influences of antecedent soil moisture and vegetation cover as well as of their combined effects on soil erosion processes. Past research typically focused on either vegetation cover or antecedent soil moisture. Even though these parameters are likely related under field conditions, studies on their synchronous combined effect on soil erosion processes are scarce. We conducted laboratory experiments on soil erosion using simulated rainstorms (intensity 77 ± 4.5 mm h⁻¹; 60 min duration) on a light loamy soil under different levels of wheat-seedling cover and antecedent soil moisture that were both produced by different sprayed applications of water (30, 40, 50, 60 or 70 mm) during a 40- to 44-day growing period. The objective was to explore the effect of the combined effects of wheat-seedling cover and antecedent soil moisture on soil erosion. Wheat-seedling cover and antecedent soil moisture increased with applied water levels from 9.7% to 37.2% and from 8.4% to 12.2%, respectively. The shortest time to runoff was observed for intermediate values of cover and antecedent moisture (60-mm water level). Infiltration rates and total infiltration generally decreased with increases in water applications. Runoff rate and soil loss were not significantly different (P > 0.05) among the 40-, 50- and 60-mm water treatments, but abruptly increased under the 70-mm treatment. At the 70-mm level, the total runoff volume and total soil loss were, respectively, between 15% and 37% and between 15% and 45% higher than those at the other water levels were. Antecedent soil moisture was the predominant factor affecting infiltration, runoff and soil loss during the rainstorms. In this study, the effects of the relatively low wheat-seedling covers were obscured by those of the antecedent soil moisture at the small-flume scale. This suggests that the effects of vegetation cover and antecedent soil moisture on soil erosion should be considered together when assessing and predicting soil erosion.

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1. Introduction

Soil erosion is a widespread and major environmental threat to terrestrial ecosystems. Its severity varies over time and at different locations on the ground surface, depending on the combined actions of climate, surface runoff, soil composition, topography, vegetation cover, and soil management and conservation practices (Montenegro et al., 2013).

Rainfall is not only the primary cause of most soil erosion by water, it is also a crucial factor that affects certain secondary influencing factors related to erosion, in particular vegetation growth and soil water content (Hou et al., 1996; Asselman et al., 2003). The characteristics of a locality's vegetation, including vegetation type, net primary productivity, vegetation cover, biomass and root to shoot ratio, as well as its soil water content, are dependent on the amount and distribution of rainfall. In general, higher annual precipitation results in more abundant vegetation cover and higher soil water contents, whereas lower annual precipitation results in sparser vegetation cover and lower soil water contents.

The importance of vegetation in preventing soil erosion has long been recognized (Morgan, 2005). In general, vegetation mitigates soil erosion mainly by reducing the detachment forces of falling or flowing water and by consolidating the soil structure thereby increasing its resistance to erosion. Vegetation can reduce the forces of water by intercepting rainfall (Durán and Rodríguez, 2008), thereby reducing runoff (Ziegler and Giambelluca, 1998;
Wainwright et al., 2002; Rey, 2003; Puigdefabregas, 2005; Durán et al., 2006, 2008) and raindrop kinetic energy (Bochet et al., 1998; Durán et al., 2008), and by retarding overland flow (Styczen and Morgan, 1995). In addition, vegetation can increase soil resistance to erosion by increasing soil aggregate stability and cohesion, and by stabilizing the soil by the binding action of its roots (Gyssels et al., 2005; De Baets et al., 2007). The relationship between vegetation cover and soil loss and/or runoff has generally been described by a negative exponential function (Gyssels et al., 2005). However, some studies have also indicated that this function should be limited to a specific range of vegetation cover for soil erosion (De Ploey et al., 1976; Rogers and Schumm, 1991). Rogers and Schumm (1991) found that the relationship best describing the effect of vegetation cover on sediment yield is neither linear nor exponential when vegetation cover is less than 15%.

In addition, various vegetation morphologies have different effects on soil erosion (Van Dijk et al., 1996; Bochet et al., 2006). Van Dijk et al. (1996) showed that plant height and the completeness of the canopy cover were key features affecting sediment entrainment. Bochet et al. (2006) reported on the variation in the performance of different plant species in reducing runoff and soil loss, and explained that the different effects on erosion resulted from the species’ different morphologies and components. Therefore, vegetation can radically control soil and water losses.

Antecedent soil moisture is an important variable affecting soil erosion processes and may be responsible for much of the variation in splash and water erosion rates (Truman and Bradford, 1990). Many previous studies have indicated that antecedent soil water content affected the partitioning of rainfall into infiltration and runoff (Le Bissontais and Singer, 1992; McDowell and Sharpley, 2002; Wei et al., 2007) and thereby influenced soil erosion (McDowell and Sharpley, 2002; Wei et al., 2007). However, the effects of antecedent soil water content on the infiltration process, runoff production and soil loss are still unclear, and opposing effects have been observed (Kemper and Rosenau, 1984; Luk, 1985; Bullock et al., 1988; Truman and Bradford, 1990; Reichert and Norton, 1994; Le Bissontais et al., 1995; Rejman et al., 2001; Lado and Ben-Hur, 2004; Bochet et al., 2006; Vermang et al., 2009; Defersha and Melesse, 2012). Bochet et al. (2006) found that antecedent soil water content strongly influenced runoff and soil loss rates; lower erosion rates occurred from soils when they were initially wetter. Conversely, Luk (1985) observed that soil losses from two silt loam soils increased by as much as five-fold as the antecedent soil water content ranged from close to the wilting point to saturation in interrill plots. Similarly, Le Bissontais et al. (1995) observed that total runoff and erosion were less from soils when they were air-dried than when they were moist because of a delay in seal formation and runoff initiation. Vermang et al. (2009) observed that no runoff or soil loss occurred in their study for the highest antecedent soil water content (15%), while the highest total runoff was observed for an intermediate antecedent soil water content (12%) and the highest soil loss was observed from the soil with the lowest antecedent soil water content (4%).

Rejman et al. (2001) found that soil losses from a Polish chernozem soil were mostly affected by the antecedent soil water content when caused by splashing, while surface micro-topography was the main factor when the losses were due to overland flow detachment and transportation. In addition, the effect of antecedent soil moisture on runoff and soil loss varied with soil type, slope and rainfall intensity (Mamedov et al., 2002; Defersha and Melesse, 2012). The opposing results reported by these previous studies can be attributed, to a certain extent, to the interactions between soil water content and other soil properties such as organic matter and clay contents, aggregate stability, and other factors such as the pre-wetting method and rate of wetting (Levy et al., 1997). Antecedent soil moisture should thus be considered as an influencing factor in at least some soil erosion prediction models (Vermang et al., 2009). Further research still needs to be carried out in order to better understand the relationship between soil loss and antecedent soil moisture.

In most cases, antecedent soil moisture and vegetation cover vary in different areas and at different times within the same region. Soil erosion always occurs on a sloping surface, which generally has differing levels of antecedent soil moisture and vegetation cover. Furthermore, vegetation cover and soil water contents are interlinked due to the water requirement for plant growth. As shown by the studies cited above, increasing vegetation cover typically reduces soil losses. In contrast, increasing antecedent soil moisture might have positive or negative effects on soil loss. It can be hypothesized that combined effects of various levels of vegetation cover and antecedent soil moisture on infiltration, runoff production and soil loss should exist and be dependent on each other. Furthermore, the combined contribution would differ from the independent, individual contributions of vegetation cover and antecedent soil moisture to the variations in infiltration, runoff production and soil loss. However, most previous studies have only investigated the relationships between soil erosion and vegetation cover or antecedent soil moisture as separate factors. Their synchronous effects on soil erosion have never been considered to the best of our knowledge.

Therefore, this study’s objective was to explore the synchronous combined effects of a series of vegetation covers and antecedent soil water contents produced by different levels of water application on infiltration, runoff and sheet erosion using small-flume laboratory rainfall simulation experiments. The results should enhance our understanding of the relationships among soil water content, vegetation and sheet erosion and thereby improve the assessment and prediction of soil erosion.

2. Materials and methods

2.1. Experimental design

This study consisted of two stages. The first stage was to produce the different degrees of wheat-seedling cover and antecedent soil water contents, and was a preparatory stage for the second stage, i.e., the rainfall simulation experiment that determined erosion. In the first stage, one vegetation cover species (wheat seedlings) was selected and sown in the small-flumes, which were irrigated by sprayed applications of water at five different levels (30, 40, 50, 60 and 70 mm) during this experimental stage; details are given in Section 2.1.2 below. Under the five different applied water levels, the canopies of the seedlings developed different degrees of cover, while concurrently inducing different antecedent soil moisture conditions prior to the rainfall simulation erosion study stage. Five water levels produced five combinations of cover and water content, and each of these combination tests was produced and investigated in three replications.

The second stage was an erosion experiment and involved the application of simulated rainfall to induce soil erosion. Since the main purpose of the study was to observe the combined effects of vegetation cover and antecedent soil water content on erosion, other variables that would affect erosion were kept constant. Hence, erosion from only one soil type, one rainfall intensity (90 mm h⁻¹) and one slope gradient (15°) was considered.

2.1.1. Cultivating wheat

Wheat was selected as the experimental plant species because it is easily controlled during the experimental period and it is a typical crop widely grown on the Loess Plateau. Wheat seedlings
were grown in soil packed in the flumes used for the erosion experiment without fertilization.

The soil used in this study was a loessial soil, a light loamy, Calcaric Regosol (IUSS working group, WRB, 2006) that was collected from Ansai County, Shaanxi Province, China in May 2013. Loessial soils are typical of those found on the Loess Plateau. Disturbed soil was collected from the upper 0.25-m layer of a cultivated field, air-dried, crushed to pass through a 4-mm sieve, and thoroughly mixed. The soil particle size distribution, which was determined by laser diffraction using a Malvern Mastersizer 2000 (Malvern Instruments Ltd., England), comprised 12.8% clay (<0.002 mm), 48.5% silt (0.002–0.05 mm), and 38.7% sand (0.05–1 mm). The organic matter content was 0.53%, which was determined by multiplying the soil organic carbon content (0.31%), measured using the Walkley–Black acid digestion method, by a factor of 1.7 (Walkley and Black, 1934).

Square metal flumes (sides 40 cm in length and a depth of 60 cm) were used in the erosion experiment. A trough was placed at the lower edge of each flume to collect runoff and sediment samples. The air-dried, pre-sieved soil was manually packed into each flume to a depth of 50 cm. The soil was uniformly packed to reproduce a natural mean bulk density of 1.21 g cm$^{-3}$. This was achieved by tamping a given mass of soil into a 10-cm thick soil layer using a wooden board prior to adding the next layer. The surface of each layer was roughened with a small rake to reduce discontinuities at the layer interfaces.

Twelve evenly spaced pits were created in each soil-filled flume, and each pit was sown with three wheat seeds. The surface of the soil was smoothed after sowing.

2.1.2. Water control

The soil gravimetric water content was 7.9% when the wheat seeds were sown. The 15 flumes were divided into five groups. Each group of three flumes received a specific water amount (30, 40, 50, 60 or 70 mm) that was applied as a spray during the experimental period. Following wheat-seedling emergence, about 10 days after sowing, each water treatment was applied in six equal parts over the whole flume on six occasions during the experimental period. The wheat-seedling growth period was between 40 and 44 days for different water levels because each rainfall simulation had to be conducted on separate, consecutive days. The last application of sprayed water was carried out six days before the rainfall simulation experiment. The flumes were left outdoors, but were covered with a clear plastic sheet when it rained to prevent the addition of rainwater. However, water losses due to evapotranspiration were permitted to occur as part of the induced relationship between cover and soil moisture.

2.1.3. Wheat-seedling cover and antecedent soil moisture

Wheat-seedling covers and morphologies in the various flumes were different due to the different water levels. Wheat-seedling cover was determined by taking digital images before starting the simulated rainstorms. The cover was estimated by using ImageJ (1.43u) imaging processing software, as shown in Fig. 1 and detailed in Table 1. Leaf area was measured by hand using a ruler (Table 1). Antecedent soil water content was determined from the mass lost during oven-drying at 105 °C until constant mass of three small core samples of soil (10 cm depth) taken from each of the small-flumes immediately before starting the simulated rainstorms (Table 1).

2.1.4. Rainfall simulation

Five simulated rainstorms were applied on five consecutive days to the flumes with the wheat seedlings beginning 40 days after sowing using the Rainfall Installation in the Simulated Soil Erosion Experiment Hall of the State Key Laboratory of Soil Erosion

Fig. 1. Soil surface photographs (left) of wheat-seedling cover in small-flumes and images (right) after analysis with ImageJ image processing software for applied water treatments of 30 mm (A), 40 mm (B), 50 mm (C), 60 mm (D), and 70 mm (E).
and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, CAS & MWR, Yangling. Simulated rainfall was produced from lateral jets at a height of 16 m above the ground. Raindrops (median diameter 2.2 mm), having followed a parabolic trajectory, fell vertically to the soil surface at close to the terminal velocity at a controllable intensity and a distribution uniformity of more than 85%. Tap water was used to simulate rainwater. The flumes with the three replicates of a given applied water level treatment were subjected to rainfall in the same simulation run. Three days before the rainstorm, the crust on the soil surface in the flume, caused by the sprayed water applications, was broken up and the soil surface was smoothed to minimize micro-topographic effects. The flumes were inclined on their frameworks to obtain a 15° slope gradient. The simulated rainstorms were applied for 60-min with an intended rainfall intensity of 90 mm h⁻¹, which was selected as being representative of the intense storms that occur on the Loess Plateau (Tang, 1990). Three rain gauges were used to measure the actual rainfall intensity during the simulated rainfall (Table 2). However, due to variability in the system controlling the rainfall intensity between experiments, the actual mean rainfall intensities determined from the total rainfall collected in storage rain gauges were all lower than the intended 90 mm h⁻¹; there was also some variation among the rainfall intensities recorded by the three rain gauges (Table 2). The mean rainfall intensity with the standard error was 77 ± 4.5 mm h⁻¹.

The runoff and sediments were collected continuously, from the time runoff commenced until the end of the rainstorm, in sampling containers that were changed at regular intervals of 3 min. The sampling containers with the runoff and sediment were weighed. After the sediment settled overnight, excess water was poured off and measured while the sediment was dried in an oven at 105 °C for 12 h. The excess water and evaporated water measurements were used to determine the mean runoff rate during each 3-min interval, while the mass of dried sediment was used to calculate the rate of soil loss from the flumes. In addition, each flume was weighed before and after each run to determine the total infiltration volume. There was no drainage.

2.2. Data analysis

The Fisher least significant difference (LSD) comparison test was used to identify statistical differences among treatments at \( \alpha = 0.05 \) using PASW Statistics version 18.0 (SPSS Inc., 2009).

### Table 1

<table>
<thead>
<tr>
<th>Water level (mm)</th>
<th>Antecedent soil moisture (%)</th>
<th>Seedling cover (%)</th>
<th>Shoot biomass (g)</th>
<th>Canopy height (cm)</th>
<th>Leaf area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>8.4 ± 0.4e</td>
<td>9.67 ± 1.8c</td>
<td>11.134 ± 0.846d</td>
<td>3.17 ± 0.26c</td>
<td>254.9 ± 36.9e</td>
</tr>
<tr>
<td>40</td>
<td>9.4 ± 0.3d</td>
<td>14.93 ± 0.85c</td>
<td>13.563 ± 1.269d</td>
<td>3.41 ± 0.34bc</td>
<td>424.2 ± 83.6d</td>
</tr>
<tr>
<td>50</td>
<td>10.3 ± 0.5c</td>
<td>23.80 ± 5.20b</td>
<td>34.803 ± 4.298c</td>
<td>3.72 ± 0.26ab</td>
<td>770.4 ± 113.0c</td>
</tr>
<tr>
<td>60</td>
<td>11.4 ± 0.2b</td>
<td>31.30 ± 4.95a</td>
<td>45.694 ± 5.843b</td>
<td>3.96 ± 0.15a</td>
<td>935.9 ± 17.8b</td>
</tr>
<tr>
<td>70</td>
<td>12.2 ± 0.3a</td>
<td>37.23 ± 3.60a</td>
<td>55.269 ± 8.226a</td>
<td>4.07 ± 0.10a</td>
<td>1172.9 ± 48.4a</td>
</tr>
</tbody>
</table>

Data is presented as the mean ± the standard deviation, with lowercase letters, which denote no significant difference between values within a given column when at least one letter is the same. Fisher’s LSD tested differences between means at \( P < 0.05 \).

### Table 2

<table>
<thead>
<tr>
<th>Water levels (mm)</th>
<th>Rainfall intensity (mm h⁻¹)</th>
<th>Time to runoff (min)</th>
<th>Total runoff (mm)</th>
<th>Total infiltration (mm)</th>
<th>Runoff coefficient</th>
<th>Soil loss (g m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>85 ± 1a</td>
<td>24.3 ± 0.3a</td>
<td>16.0 ± 1.1b</td>
<td>69.5 ± 1.2a</td>
<td>0.19 ± 0.01bc</td>
<td>63.7 ± 2.9c</td>
</tr>
<tr>
<td>40</td>
<td>78 ± 4b</td>
<td>19.3 ± 0.6b</td>
<td>13.4 ± 1.9c</td>
<td>63.0 ± 2.5b</td>
<td>0.17 ± 0.01c</td>
<td>74.9 ± 4.2b</td>
</tr>
<tr>
<td>50</td>
<td>75 ± 3b</td>
<td>18.4 ± 0.1b</td>
<td>14.3 ± 0.8bc</td>
<td>60.5 ± 3.5bc</td>
<td>0.19 ± 0.02bc</td>
<td>80.5 ± 5.3b</td>
</tr>
<tr>
<td>60</td>
<td>75 ± 5b</td>
<td>16.7 ± 0.4c</td>
<td>14.1 ± 1.3bc</td>
<td>58.1 ± 0.7bcd</td>
<td>0.19 ± 0.02bc</td>
<td>77.4 ± 2.9b</td>
</tr>
<tr>
<td>70</td>
<td>74 ± 4b</td>
<td>18.6 ± 0.9b</td>
<td>18.4 ± 0.5a</td>
<td>55.9 ± 3.4ed</td>
<td>0.25 ± 0.01a</td>
<td>92.9 ± 8.8a</td>
</tr>
</tbody>
</table>

Data is presented as the mean ± the standard deviation, with lowercase letters, which denote no significant difference between values within a given column when at least one letter is the same. Fisher’s LSD tested differences between means at \( P < 0.05 \).

### 3. Results and discussion

#### 3.1. Wheat-seedling cover and antecedent soil moisture

Sprayed water levels had a significant effect on both wheat-seedling cover and antecedent soil moisture (Table 1). Wheat-seedling covers increased obviously with the increase in the applied water amount from 9.7% ± 1.8% (mean ± standard deviation) to 37.2% ± 3.6%, although the differences were not significant (\( P > 0.05 \)) between the water levels of 30 and 40 mm or between 60 and 70 mm. The other wheat characteristic parameters, including biomass, canopy height and leaf area, measured for the whole flume also increased with the increase in applied water level. With increasing applied water amount, the antecedent soil water content increased significantly from 8.4% ± 0.4% to 12.2% ± 0.3% and was significantly different among the applied water amounts (\( P < 0.05 \)).

#### 3.2. Time to runoff

The times to runoff commencement exhibited significant differences among the different water treatments (\( P < 0.05 \)), with the exception of those between the 40- and 50-mm water treatments (Table 2). As water levels increased from 30 to 60 mm, the time to runoff was reduced. In contrast, when the water levels increased from 60 to 70 mm, the time to runoff increased. The shortest and longest times to runoff occurred for the 60 and 30 mm water levels, respectively.

Vegetation cover and antecedent soil moisture are considered as main factors that can affect time to runoff, but with opposing effects. In general, time to runoff should increase as vegetation cover increases (Zhang and Liang, 1995; Li et al., 2005; Yang et al., 2013), but should decrease as antecedent soil moisture increases (Lado et al., 2004; Liu et al., 2011). In our study, the different applied water levels induced combined effects of wheat-seedling cover and antecedent soil moisture that consistently reduced the time to runoff as the applied water increased from 30 to 60 mm. However, the time to runoff was increased as the applied water increased from 60 to 70 mm. Hence, there was a complex variation of the time to runoff when considering the combined rather than the separate effects of the parameters.

A binomial expression, with a determination coefficient of 0.95, related time to runoff to the applied water level, which had
influenced both the wheat-seedling cover and the antecedent soil moisture (Fig. 2). Both the antecedent soil water content and the wheat-seedling cover were lowest at the 30 mm water level. The combined effect of the antecedent soil water content and the wheat-seedling cover resulted in the time to runoff being significantly greater \( (P < 0.05) \) than those of the other water levels. This increase in the time to runoff occurred even though the rainfall intensity applied to the 30-mm water level treatment was significantly higher than that for any other water treatment and would, thus, have been expected to reduce the time to runoff (Table 2). Since lower vegetation cover and higher rainfall should both result in shorter times to runoff, this clearly indicated that the antecedent soil moisture exerted the predominant effect on the time to runoff in our study. Furthermore, since increasing the applied water level from 30 to 60 mm increased both the antecedent soil water content and the wheat-seedling cover, the observed reduction in the time to runoff suggested that the role cover played was weaker and was obscured by the effect of the antecedent soil moisture (Fig. 2). However, the times to runoff increased with the further increase in the applied water level from 60 to 70 mm. This suggests that the consistent increases in the wheat-seedling cover gradually strengthened its role relative to that of the antecedent soil moisture at this level of water application. Thus, it became the predominant factor controlling the time to runoff. The combination of the effects of wheat-seedling cover and antecedent soil moisture resulted in the shortest time to runoff occurring for the 60-mm water treatment. These results indicated that time to runoff was determined by the combined effects of wheat-seedling cover and antecedent soil moisture and that their relative roles changed with the level of water application, which had induced different levels of cover and water content.

3.3. Infiltration

Total infiltration volumes during the simulated rainstorms decreased from 69.5 to 55.9 mm as the applied water treatment increased from 30 to 70 mm and induced increases in both the wheat-seedling cover and the antecedent soil water content (Table 2). Total infiltration volume (69.5 mm) for the 30-mm water level was significantly higher than those for all other water levels \( (P < 0.05) \). The only other significant difference observed for the total infiltration volumes was between those of the 40- and 70-mm water treatments \( (P < 0.05) \).

**Fig. 3.** Change over time of infiltration rates for different applied water treatments. Mean values with standard deviation bars for three replications.

In previous studies, antecedent soil moisture and vegetation cover have been found to play opposing roles in determining infiltration rates (Bradford et al., 1987; Bochet et al., 1999; Wangemann et al., 2000; Thompson et al., 2005; Durán and Rodríguez, 2008; Liu et al., 2012). The general conclusion has been that, as antecedent soil moisture increases, the infiltration rate decreases, while as vegetation cover increases, the infiltration rate increases (Wangemann et al., 2000). In this study, the infiltration rates decreased as wheat-seedling cover and antecedent soil moisture increased together. The effect of wheat-seedling cover on the infiltration rate appeared to be inconsistent with the previous findings (Dunkerley, 2000; Williams et al., 2006). However, this was due to the dominating effect of the antecedent soil moisture on the infiltration rates. These results indicated that, under these experimental conditions, the effect of antecedent soil moisture on the infiltration process was much stronger than that of the wheat-seedling cover, effectively concealing it.

Vermang et al. (2009) found that the changes in infiltration rate with cumulative rainfall were significantly different \( (P < 0.05) \), but that the final infiltration rates were not significantly different \( (P > 0.05) \), between antecedent soil water contents of 4% and 12% for a Belgian silt loam soil without vegetation. However, in our study the effects of antecedent soil moisture on the infiltration rate existed throughout the rainstorm. Notably, the difference between the infiltration rates under the low and high antecedent soil moisture conditions, induced by the 40- and 70-mm water treatments, were significant \( (P < 0.05) \) throughout the rainstorm (Fig. 3). This discrepancy between our results and those of Vermang et al. (2009) may be attributed to differences in soil characteristics, pre-wetting method and, especially, to the wheat-seedling cover. The seedling cover would reduce the kinetic energy.

**Fig. 2.** Relationship between applied water treatments and time to runoff. Mean values with standard deviation bars for three repetitions.
of the raindrops to various extents, thereby affecting the degree of seal formation on the soil surface leading to the differences observed in the infiltration rates for different water treatments throughout the rainstorm.

3.4. Runoff

The runoff rate, which mirrors the infiltration rate, increased with time during the rainstorm for all water treatments (Fig. 4). However, after about 47 min there were some indications that the rates were approaching different quasi-steady states. This is consistent with classically identified trends in runoff rate with cumulative rainfall under controlled laboratory conditions (Fox and Bryan, 1999; Vermang et al., 2009; Oakes et al., 2012). The changes in runoff rates with cumulative rainfall were significantly higher ($P < 0.05$) for the 30- and 70-mm water treatments than for the other treatments. Although the highest rainfall intensity was recorded for the rainstorm applied to the 30-mm water treatment, the highest total runoff volume and runoff coefficient for the entire rainstorm occurred for the 70-mm water treatment (Table 2). The total runoff volume for the 70-mm water treatment was 15–37% greater than those for the other treatments. The lowest values were observed for the 40-mm water treatment.

The antecedent soil moisture mainly affected the infiltration rate and, consequently, influenced runoff (Liu et al., 2012). Increases in the antecedent soil water contents reduced the initial infiltration rates, which led to increases in the runoff rates (Philip, 1957). Vegetation cover can intercept rainfall, thereby retarding runoff initiation, and reducing the total runoff amount (Ziegler and Giambelluca, 1998; Wainwright et al., 2002; Casermeiro et al., 2004). The two studied factors thus had opposing effects on runoff. From our results, it was clear that infiltration rates decreased as wheat-seedling cover and antecedent soil moisture increased (Table 2 and Fig. 3). Ignoring the 30-mm water treatment under which the applied rainfall intensity was significantly greater ($P < 0.05$), runoff tended to increase as the applied water level increased from 40 to 70 mm (Table 2 and Fig. 4). However, the changes in runoff rate and the total runoff volumes among the 40-, 50- and 60-mm water treatments were not significantly different ($P > 0.05$). Furthermore, there was an abrupt increase in the runoff rate and total runoff (14.1–18.4 mm), which was also reflected clearly by the runoff coefficient that changed from 0.19 to 0.25, when the applied water level increased from 60 to 70 mm. These results can be ascribed to the effect of the antecedent soil moisture. It is possible that there is a critical value of antecedent soil water content (between 11.4% and 12.2%) above which the effects of the antecedent soil moisture on runoff would be much stronger.

Similar results were reported in other studies (Mamedov et al., 2006).

In contrast, the effect of the wheat-seedling cover on runoff in this study was not consistent with those observed in previous studies (Ziegler and Giambelluca, 1998; Durán et al., 2006; Durán and Rodríguez, 2008). The role of the wheat-seedling cover was obscured by the more powerful effect of the antecedent soil moisture in our study. These results suggested that antecedent soil moisture predominantly controlled the runoff process under our experimental conditions. Among all of the water treatments, the 30-mm water treatment had a rainfall intensity and wheat-seedling cover with the highest and lowest values, respectively, but the runoff value was not the highest. Thus, the data from the 30-mm water treatment further indicated that it was the antecedent soil moisture that predominantly controlled runoff production under these experimental conditions.

3.5. Soil loss

The trends followed by the sheet erosion rate during the rainstorm were similar under all water treatments (Fig. 5). In general, the sheet erosion rate decreased as the rainstorm progressed. In all cases, fluctuations in the sheet erosion rate were greater during the first part of the rainstorm (until about 40 min) and subsequently diminished. Although the changes in the sheet erosion rates among the different water treatments were not significantly different during the rainstorm, the total soil loss increased as the water application level increased from 30 to 70 mm, with the exception of the 50-mm case (Table 2). There were no significant differences among the total soil losses under the 40-, 50- and 60-mm water treatments ($P > 0.05$), but these were all significantly higher or lower ($P < 0.05$) than those from the 30- and 70-mm water treatments, respectively. The total soil loss under the 70-mm water treatment was between 15% and 45% higher than those under the other treatments.

Previous studies have reported that soil loss generally decreases with increasing vegetation cover (Romero et al., 1999; Durán et al., 2006) and can either increase or decrease with increasing antecedent soil moisture (Sangodoyin and Nwosu, 1997; Vermang et al., 2009). Our results, like those of other studies (Luk, 1985), showed that the greatest soil loss occurred at the highest antecedent soil water content, but were not consistent with other studies on vegetative cover (Wang et al., 2008; Ouyang et al., 2010), since they showed that the highest soil loss also occurred under the highest wheat-seedling cover. Mean soil loss values under the 40-, 50- and 60-mm water treatments were similar while that observed

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**Fig. 4.** Changes in runoff rate over time for different applied water treatments. Mean values with standard deviation bars for three repetitions.

**Fig. 5.** Changes in erosion rate over time for different applied water treatments. Mean values with standard deviation bars for three repetitions.
under the 70-mm treatment was significantly greater \( (P < 0.05) \). As in the case of the runoff, this may be due to the combined effects of antecedent soil moisture and wheat-seeding cover, as well as to the critical value of the antecedent soil water content. Moreover, the role of the wheat-seeding cover on soil loss could not be detected because it was obscured by the much stronger role played by the antecedent soil moisture. An increase in antecedent soil moisture resulted in a decrease in infiltration and an increase in runoff, which then led to a greater soil loss (Mamedov et al., 2006). Antecedent soil moisture thus determined the trends in soil loss in the small-flume under the relatively low wheat-seeding covers (9.7–37.2%) in this study. In addition, Rogers and Schumm (1991) found that a critical density of vegetation (Kentucky bluegrass sod) cover of 15% may exist for a silt enriched sandy loam soil, below which vegetation cover did not effectively reduce erosion in drylands. However, in our experiments the critical value for vegetation cover appears to occur in response to the different antecedent soil water content. More work is required to specifically identify the effects of vegetation cover on sheet erosion loss at the small-plot scale under different antecedent soil moisture conditions.

The lowest soil losses occurred under the 30-mm water treatment even though the rainfall intensity and runoff were the highest and the wheat-seeding cover was the lowest among the 30-, 40-, 50- and 60-mm treatments. This may be due to the longer time to runoff commencement and hence to the initiation of soil erosion. In addition, wheat-seeding cover, biomass, stem height and leaf area were also low (Table 1). This low density of vegetation cover is probably unable to protect the soil surface from detachment by rainfall impact by intercepting them. However, it does likely promote seal formation that can protect soil from detachment (Remley and Bradford, 1989; Ben-Hur et al., 1990). The degree of seal formation decreases as vegetative cover increases. The higher initial seal erosion rate observed under the 30-mm water treatment may indicate the effect of the greater degree of seal formation, since there would be more loose material on the soil surface due to aggregate breakdown that would be washed off the surface during the initial erosion stage (Fig. 5). Detachment by sheet flow in the small-flume would be negligible (Kinnell, 2005; Oakes et al., 2012). Therefore, sheet erosion under the 30-mm water treatment or lower wheat-seeding cover was probably limited due to reduced detachment by rainfall impact leading to lower soil losses from the small-flumes.

4. Conclusions

In this study, variations in infiltration, runoff production and soil loss with different levels of wheat-seeding cover and antecedent soil moisture produced by the application of different water levels were investigated in small-flumes. The lowest infiltration, and the highest runoff and soil losses, were observed for the highest levels of wheat-seeding cover and antecedent soil moisture. A critical value of antecedent soil water content above which the effect of antecedent soil moisture on runoff and soil loss would be markedly enhanced would exist in this study. Antecedent soil moisture mainly determined infiltration, runoff production and soil loss and, in most cases, obscured the effect of wheat-seeding cover; the role of wheat-seeding cover could not be detected under the study experimental conditions that produced relatively low wheat-seeding covers (9.7–37.2%). The effective vegetation cover occurred in response to the different antecedent soil water contents. Further research should investigate these combined effects on infiltration, runoff production and soil loss of vegetation cover and antecedent moisture over a wider range of conditions, including wider ranges of vegetation cover, antecedent soil water content, flume scale, soil types, and vegetation species. However, our current observations lead to the conclusion that the combined effects on soil erosion of vegetation cover and antecedent soil moisture, which should be similarly related in the field, were significant and should be considered together when assessing and predicting soil erosion.

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