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The effects of three micro-catchment practices on erosion and runoff dynamics for a typical soil slope on the Loess Plateau of China

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Abstract: Three micro-catchment measures that are named fish-scale pits (FSPs), artificial digging (AD), and contour plowing (CP) for soil erosion prevention are widely used in the Loess Plateau. In order to clarify the effectiveness of these measures in intercepting runoff and reducing erosion and the mechanism of water flow movement, intermittent simulated rainfall events was carried out in the 15° slopes with FSPs, AD, CP and control slope (CK). The results showed: (1) For cumulative rainfall less than 83 mm, three measures effectively intercepted runoff and reduced sediment compared with the CK. The runoff and sediment reduction effect of three measures gradually disappeared when cumulative rainfall increased to 83, 99, and 108mm, and the sediment generation of the three measures successively exceeded that of the CK and was more than 2 times higher. (2) Laminar or transition flow occurred for the CK, and the flow pattern changed from subcritical to supercritical at 101 mm of cumulative rainfall. For three measures, the flow patterns became turbulent within a short time, but remained sub-critical. (3) A correlation analysis showed the soil detachment rate, hydraulic shear stress, and stream power in the

micro-catchment measures can be described using linear functions, which reduced the rill erodibility and enhanced the soil's resistance to concentrated flow erosion. This research has important guiding significance on the rational and effective implementation of micro-catchment practices to prevent severe soil erosion and increase water storage for crop production on the Loess Plateau of China.

Keywords: Loess Plateau, micro-catchment techniques; intermittent rainfall; hydrodynamics; soil detachment rate

Introduction

The growth and development of crops, forests, and grasses are limited by soil water deficiencies in the arid and semi-arid areas of the Loess Plateau. Precipitation is the primary source of soil water as well as the major driver of soil erosion in this loess region. According to the results of the third remote sensing census of the ministry of water resources, the current soil erosion area in China is 3,569,200 km², of which the hydraulic erosion area is 1,6122 km², accounting for 17.0% of the total land area. The total soil loss in the Yellow River basin from 1950 to 2005 has reached 1.464t, accounting for 32.8% of the soil loss in major rivers in China, and the loess plateau erosion area has reached 450,000km², accounting for 70% of the total area. The rainfall from July to September accounts for 60%–70% of the annual rainfall (Shi and Shao, 2000) and primarily occurs in the form of intense rainfall events. The resulting runoff contributes to soil erosion, which is particularly intense on sloping farmland. Sediment generation on sloping farmland in this loess region has been shown to exceed the total sediment yield by 40% (Zhang et al., 2015). Important and urgent problems for the soils on the Loess Plateau is how to effectively protect and use water and soil resources, improve water use

efficiency, and adopt appropriate tillage practices for the sloping farmland according to local conditions so as to guard against further soil degradation.

The China Grain for Green Project is presently being implemented on China's Loess Plateau for increased food production to help meet the needs of a growing population, but places more pressure on existing soil and water resources in the region and the potential for increased soil degradation. Several tillage management practices, including fish-scale pits (FSPs), contour plowing (CP), and artificial digging (AD), are widely used on sloping farmland on the Loess Plateau. The FSPs change the soil micro-topography to shorten the runoff path and enhance localized interception and infiltration of precipitation to significantly increase the soil water content, thereby improving soil water conditions for vegetative growth (Wu, 2006). In the implementation of the AD practice, the summer fallow land is usually plowed and dried after harvesting the crop every year. Pits are dug on the soil surface from the bottom to the top of the slope using a hoe, forming a rugged micro-topography for water conservation. The CP practice is implemented along the contours of a slope to form furrows and ridges. Crops are planted in the furrows or on the ridges and the alternating arrangement of furrows and ridges can effectively reduce runoff scouring and reduce soil erosion.

These human tillage activities alter the slope's micro-topography and change the performance of soil water infiltration and runoff thus affecting soil erosion. Studies of the erosion of sloping farmland in this region have primarily focused on water erosion, whereas the impacts of tillage on erosion have oftentimes been overlooked. Long-term tillage may result in large amounts of soil particles being transported downslope to sites that are favorable for hydraulic transport, and its interaction with water erosion may be detrimental to the farmland

slope landscape patterns (Li et al., 2008; Tiessen et al., 2009; Su and Zhang, 2007). Jia(2008) showed that different tillage patterns and tools resulted in varying depths, widths, and soil contact surfaces, thus influenced soil particle movement to different degrees. Wang et al.(2016) found that the tillage intensity led to a significant increase in soil and water loss during water erosion. Other studies have shown that proper protective tillage practices may alter the underlying surface conditions, increase water infiltration, and reduce the splashing and scouring of the slope soil by rainwater and runoff (Thierfelder and Wall, 2009). Practices that reduce slope runoff would also help reduce soil erosion and may help reduce the impacts of drought (Zhao et al., 2009; Wu et al., 2010). Zhao(2012; 2013) investigated the effects of three tillage methods on soil and water conservation on the Loess Plateau under simulated rainfall and found that contour tillage, artificial hoeing, and AD achieved significant impacts on runoff interception and sediment reduction compared with smooth bare ground. Zheng et al.(2010) analyzed the effects of the soil surface roughness on sheet erosion under simulated rainfall conditions and found that the tillage soil surface had a greater effect of slowing slope sediment generation than did smooth bare land with a relatively low roughness and that the effects of tillage on erosion was closely related to the duration of the rainfall events. Basic et al.(2001) evaluated the effects of different tillage practices on runoff and sediment generation and suggested that the tillage practices had both positive and negative impacts on slope erosion. They found that appropriate tillage management practices could slow down soil erosion, but not prevent its occurrence. These studies demonstrated the importance of tillage practices in the process of slope erosion. However, all artificial tillage methods have their limitations and scopes

of application. In the case of persistent heavy rainfall, the timeliness of water storage and sediment detention needs to be investigated more thoroughly.

Slope erosion can be divided into three processes: rainfall detachment, runoff detachment and transport, and sediment deposition (Rose et al., 1983). Most of the eroded materials are transported by overland flow, which plays a leading role in the erosion process. Studies of overland flow have mainly focused on the analysis of flow patterns and resistance. Horton (1934) argued that overland sheet flow is a mixed flow zone in which turbulent flow is mixed with laminar flow. Emmett (1978) proposed that despite its turbulent flow characteristics, overland flow still has many laminar flow characteristics, and thus defined it as “disturbed flow” to stress the unique characteristics of the flow. Selby (1993) suggested that overland flow is a mixed flow region of turbulent flow and laminar flow. Jing (2003) proposed the concept of a “virtual laminar flow”. Based on the evolution pattern of a rolling wave, Zhang et al. (2011) suggested the concept of a “laminar flow instability zone” (i.e., rolling wave flow zone).

A research on overland flow resistance has primarily adopted the concept of open-channel flow resistance and has adopted descriptive parameters such as the Darcy-Weisbach resistance coefficient, the Chezy coefficient, and the Manning roughness coefficient. Most researchers have chosen to study the Darcy-Weisbach resistance coefficient because (1) it is a dimensionless parameter that is easy to use and facilitates comparisons between different flow rates; (2) it has a theoretical basis; and (3) it applies to both laminar flow and turbulent flow (Jiang et al., 2012). In investigations of the dynamic mechanism of slope erosion, studies have commonly used the hydraulic shear stress, stream power, or the unit stream power to describe the erosion process. Foster and Meyer (1972) proposed that when the hydraulic shear stress is greater than the critical

shear stress of the soil, soil particles are detached, and the potential soil detachment rate may be mathematically described. Nearing (1999) investigated the soil detachment process under field conditions, and the results showed that this process could be simulated more accurately using the stream power. Shen et al. (2016) studied the soil erosion process under different rainfall intensities and slope gradients and found that the soil detachment rate, hydraulic shear stress, stream power, and unit stream power may be described by linear relationships. The above discussion demonstrates that studies about the hydraulic characteristics and erosion mechanisms of overland flow have primarily focused on bare or covered slopes. However, the flow pattern and resistance coefficient changes on complex slopes following the implementation of tillage practices, such as FSPs and contour tillage that change the soil micro-topography remain unclear. Whether different hydrodynamic mechanisms occur for different tillage practices requires further study through in-depth research.

In order to clarify the effectiveness of these measures in intercepting runoff and reducing erosion and the mechanism of water flow movement, we investigated the effectiveness of these three treatments for protecting water and soil from damage on three 15° slopes treated with FSP, AD, and CP and the hydraulic characteristics of the flow on this slope under several intermittent simulated rainfall events. This study is of great practical value and theoretical significance for evaluating the impacts of these tillage management practices and improving the prediction of soil erosion on soil slopes of the Loess Plateau.

Materials and methods

Study area and experimental materials

A large quantity sample of loess soil was removed from a field location within the Loess Plateau and transported to the Rainfall Simulation Hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau at Yangling, China. A loess soil was selected for this study since it is almost exclusively the soil type found on the Loess Plateau and this soil type is one of the most highly erodible soils in the world. The mechanical composition of the soil was determined using a Mastersizer Model APA2000 laser particle size analyzer. (Malvern Instruments, Ltd.). Sand grains (size: 2–0.02 mm), silt grains (size: 0.02–0.002 mm) and clay grains (size: <0.002 mm) accounted for 35.25%, 54.54% and 10.21% of the soil sample (volume fraction), respectively, and indicated that the soil had a silty loam texture. The soil sample was air-dried and subsequently sieved through a 10-mm mesh sieve.

Three soil bins, measuring 5 m (lgth.) $\times$ 1 m (width) $\times$ 0.5 m (hgt.) with a gradient of 15°, were filled with the loess soil (i.e., three replications of every experiment were performed). Prior to filling each soil bin, a 15-cm-thick layer of natural fine sand was laid on the bottom of the soil bin, and a sheet of water-permeable gauze was laid on top of the sand to ensure that the water permeability of the study soil was close to the soil properties of a natural slope. The soil bulk density was controlled by 1.22 g cm⁻³ and was representative of bulk densities frequently measured in previous field studies on the Loess Plateau (In the range of 1.1 to 1.3 g cm⁻³).

Experimental Design

Artificial digging (AD), fish-scale pits (FSPs), and contour plowing (CP) are the three soil and water conservation management practices that were implemented for study and are practices widely used in the northern region of the Loess Plateau, China. The means of implementation were selected based on previous research results and field investigations (Zheng et al., 2010;

Zhao et al., 2013; Liang et al., 2014). The experimental design is shown in **Figure 1**. To insure that the authenticity of the tillage practices were similar to natural conditions, the practices were implemented by farmers who had been engaged in agricultural production using the same tillage practices for long time periods. The CK slope was prepared by smoothing the soil trough with a straight ruler after it was filled, and a leveling rod was used to ensure that the slope was horizontal to simulate a nearly smooth slope without any tillage practice. The FSP treatments were multiple semicircular pits that were dug in the filled soil trough in the slope direction using a hoe. They were arranged in a triangular shape and each pit was excavated to a 10-cm depth that was surrounded by a 30-cm diam. semicircular berm having a 20-cm height on the downslope side and a 10-cm height on the upslope side. The AD treatments were implemented by using hoes to dig holes on the soil surface from the bottom to the top of the slope to form a rugged micro-topography. The soil surface was retained in this original stage after digging with a tillage depth of 5–7 cm and mound height of 3–5 cm and a spacing of 15 cm. The CP treatments were implemented on the slope to form furrows and ridges along the contour lines and perpendicular to the slope direction. The ridge height and width was 5–7 cm and 5–12 and the ridge spacing was 15 cm. There were three replications of each treatment implemented for the study.

Intermittent simulated rainfall events

The rainfall simulations and all subsequent experimental measurements were performed in the Rainfall Simulation Hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau. An automated rainfall simulation system with a downward spraying nozzle was used to simulate rainfall with a sprinkle height of 16 m. (Zheng and Zhao, 2004). The final

speed of the simulated raindrops reached 98% of the terminal velocity of natural raindrops, and the rainfall uniformity was greater than 85%. The rainfall intensity was based on the meteorological data of natural rainfall for several years in the study area and used the maximum 30-min rainfall intensity that is common for rainstorm events in the study area of the Loess Plateau and was set to $90 \text{ mm} \cdot \text{h}^{-1}$. Rainfall calibration trials were conducted before the start of the study. The error of the calibrated rainfall intensity was controlled within 5% of the designed rainfall intensity. The rainfall simulator was used to apply five intermittent rainfall events at intervals of 1–2 d. Table 2 shows the rainfall duration and other parameters of the rainfall events. Runoff and sediment samples were collected every 2 min after runoff was generated on the slope. After rainfall simulation was terminated, the runoff was measured using a graduated cylinder and the quantities of runoff were calculated. The sediment contents of the runoff were determined by taking an aliquot of well mixed runoff containing sediment, placing the aliquot in an oven at 70°C until apparent dryness was obtained, and then increasing the temperature to 105°C for 24 hours. The flow velocities inside the rills were measured using a QYLS–303 slope thin-sheet flow velocity measuring instrument (Qinyuan Instruments, Inc.). In addition, the flow velocities at locations 1, 3, and 5 m from the top of the slope were measured at 4-min time intervals and 1-m distance intervals using the potassium permanganate staining method (Horton et al., 1934; Emmett, 1970; Bresler, 1973; Abrahams et al. 1986). The water depths on the upper, middle, and down slopes and inside the rills were measured using a water-level gauge.

To verify the slope thin layer water flow rate automatic measuring instrument and permanganate staining method between the flow velocity, the difference of the test before, in the good earth within 3 m soil bin to have certain artificial formation on the surface of the groove, in

the form of network within the groove on the velocity measured with the two methods respectively, and the measurement results are shown in table 1, the error is within 10% of the two methods, aiming at this situation, this test use the measured value of the two methods to determine the correction factor (0.96), as far as possible to ensure the consistency of the data.

Indexes calculation

(1) Reynolds number (Re): the ratio of the inertial force to the viscous force. The greater the Reynolds number is, the greater the inertial force of the flow and the higher the likelihood of the occurrence of turbulent flow. The formula is:

$$Re = \frac{VR}{\nu} \quad (1)$$

where Re is the Reynolds number; V is the average flow velocity of a cross-section, $\text{m}\cdot\text{s}^{-1}$; R is the hydraulic radius of the slope which is the ratio between area and wetted perimeter of water cross section, m ; and ν is the kinematic viscosity coefficient of water, $\text{m}^2\cdot\text{s}^{-1}$, which is a function of the water temperature.

(2) Froude number (Fr): the ratio of the inertial to gravity forces in the flow. The open channel flow is supercritical or subcritical when Fr is greater than or less than 1, respectively. The formula is:

$$Fr = \frac{v}{\sqrt{gh}} \quad (2)$$

where Fr is the Froude number and g is the gravitational acceleration, $9.8 \text{ m}\cdot\text{s}^{-2}$.

(3) Resistance coefficient (f): the composite force retarding the flow along the slope by friction from the water-soil interface and the force hindering the flow movement produced by the turbulence of particles within the flow. It is a comprehensive reflection of multiple factors, such as the runoff flow pattern, slope roughness, sectional characteristics, raindrop diameter, and

surface tension coefficient of the flow. The formula is:

$$f = \frac{8gRJ}{V^2} \quad (3)$$

where f is the resistance coefficient and J is the runoff energy slope, which approximates the sine of the slope gradient.

(4) **The surface roughness (R)**: Based on the elevation data acquired using the 3D laser scanner, the surface roughness before and after rainfall events was estimated using the absolute average elevation difference method (Linden D K, Van D M, Doren J R, 1986) in MATLAB and Microsoft Excel. The calculation equation is as follows:

$$\Delta Z_h = \sum_{i=1}^n \frac{|Z_i - Z_{i+h}|}{n} \quad (4)$$

where ΔZ_h is the absolute elevation difference; Z_i is the elevation at the point i ; Z_{i+h} is the elevation at the point $i+h$; h is the distance from the point i ; and n is the sample size. Based on the obtained ΔZ_h and Equation (11), the following relation is established:

$$1/\Delta Z_h = a + b(1/\Delta x_h) \quad (5)$$

where a and b are undetermined parameters and Δx_h is the horizontal distance. Now, the following parameters are defined:

$$LD = 1/a; \quad LS = 1/b \quad (6)$$

where LS is the limit gradient and LD is the limit elevation.

Finally, the equation for calculating the surface roughness is obtained:

$$SSR = (LD \times LS)^{1/2} \quad (7)$$

(5) **Runoff shear stress (τ)**: the shear stress produced in the direction of the slope gradient during runoff flow on the slope, which reflects the force of slope soil detachment by runoff

during its flow (Lyle and Smerdon, 1965). The formula is:

$$\tau = \rho_m g R J \quad (8)$$

where τ is the runoff shear stress, Pa, and ρ_m is the mixed water density, $\text{kg}\cdot\text{m}^{-3}$.

(5) Stream power (ω): the runoff power represents the power consumed by the flow per unit area, which reflects the power required to detach a certain amount of soil (Bagnold, 1977). The formula is:

$$\omega = \rho_m g R J V \quad (9)$$

where ω is the stream power, $\text{kg}\cdot\text{s}^{-3}$.

(6) Soil detachment rate (D_r): the sediment mass transported by slope runoff per unit time per unit area (Yu et al., 2014). The formula is:

$$D_r = \frac{M}{bLt} \quad (10)$$

where D_r is the soil detachment rate, $\text{g}\cdot\text{m}^{-2}\cdot\text{min}^{-1}$; M is the sediment yield during the measurement period $t(\text{s})$, g; L is the slope length, $L = 5 \text{ m}$; and b is the slope width, $b = 1 \text{ m}$.

(7) Runoff reduction benefit (RRB): the benefit of runoff reduction compared with the control slope (Zhao et al., 2014b; Wang et al., 2017):

$$\text{RRB} = \frac{R_{CT} - R_{TM}}{R_{CT}} \times 100\% \quad (11)$$

where R_{CT} and R_{TM} are the runoff rates of the control slope and the treated slope, respectively.

(8) Sediment reduction benefit (SRB): the benefit of sediment reduction compared with the control slope (Zhao et al., 2014b; Wang et al., 2017):

$$\text{SRB} = \frac{S_{CT} - S_{TM}}{S_{CT}} \times 100\% \quad (12)$$

where S_{CT} and S_{TM} are the sediment yields of the control slope and the treated slope, respectively.

Results

Slope runoff and sediment generation under three micro-catchment treatments

Slope runoff generation process

Figure 2 shows the variations of the runoff rates during the five intermittent rainfall events under the four treatments. With increasing rainfall duration, the slope runoff rates of the different treatments showed upward trends of varying degrees. Before 83 mm of rainfall, namely during the first 55 minutes rainfall of rainfall, the runoff rate increased slowly with increasing rainfall duration, and the trend was that the CK always ranked the highest, followed by FSP, AD, and CP. When 83 mm of cumulative rainfall had fallen, the runoff rates of the treatments were 1440 ml·min⁻¹ (CK), 1054 ml·min⁻¹ (FSP), 843 ml·min⁻¹ (AD), and 755 ml·min⁻¹ (CP). Thereafter, the runoff rates of the slopes increased significantly with the rainfall duration, whereas the increase was relatively small for the CK treatment. The runoff rates of the FSP, AD, and CP treatments exceeded the runoff rates of the CK treatment after 62 min, 66 min, and 72 min of rainfall event duration, respectively. At the end of the rainfall events, the runoff rates of the FSP, AD, and CP treatments were 1.39 times, 1.33 times, and 1.34 times that of the CK treatment, respectively.

Figure 3 shows that during the first two rainfall events, all of the three micro-catchment treatments performed a better role in runoff reduction than the CK treatment, and the RRBs followed the trend that FSP < AD < CP. However, the RRBs gradually decreased with increased rainfall event duration from 41%, 61%, and 79%, respectively, during the first rainfall event to 27%, 49%, and 69%, respectively, during the second rainfall event. After the third rainfall event, the RRBs of the FSP and AD slopes became negative; that is, the runoff yield exceeded the yield

of the CK treatment. However, the CP treatment still achieved a runoff reduction of 19%, although the effects were minimal. The subsequent rainfall events resulted in negative RRBs for all three micro-catchment treatments.

Slope sediment generation

Figure 4 shows the variation of the sediment concentrations with rainfall for the four soil treatments. It should be noted that these results were similar to the variation of the slope runoff rates. As the cumulative rainfall reached 83 mm, the sediment concentrations for all four treatments increased slowly with increasing rainfall duration. The sediment concentrations were within a range of $0.03 \text{ g}\cdot\text{ml}^{-1}$ and followed a trend of $\text{CK} > \text{FSP} > \text{AD} > \text{CP}$. When the cumulative rainfall increased from 83 mm to 150 mm, the sediment concentrations of all treatments drastically increased. At the end of the rainfall events, the sediment generation of the slopes with the FSP, AD, and CP micro-catchment treatments successively exceeded that of the CK treatment and were more than 2 times higher.

Figure 5 shows that compared with the CK, the Sediment Reduction Benefits (SRBs) of the three micro-catchment treatments decreased with increased rainfall events until negative values were being obtained during the third rainfall event. In the first two rainfall events, the three micro-catchment treatments had better sediment reductions than the CK treatment. The best sediment reduction benefits were observed for the CP treatment ($\text{SRB} \geq 80\%$), followed by the AD treatment ($\text{SRB} \geq 56\%$) and the FSP treatment ($\text{SRB} \geq 38\%$). With increased rainfall duration, the SRBs rapidly decreased. Following the third rainfall event, the SRBs of the FSP and AD treatments was -135% and -105%, respectively, and in this case, the slope sediment generation exceeded the values obtained for the CK treatment. Following the fourth rainfall

event, the SRB of the CP treatment was -56%, and the corresponding sediment generation also exceeded the values measured for the CK treatment. Therefore, it is postulated that the CP treatments lost its capabilities to resist soil erosion following the fourth rainfall event.

Hydraulic characteristics of overland flow under three micro-catchment treatments

The overland flow velocity is directly related to soil detachment by the flow and sediment transport and deposition. This parameter is the basis for calculating other hydrodynamic parameters; thus, it is critical to study the distribution of the overland flow velocity. Figure 6 shows the distributions of the flow velocities with rainfall duration under the four treatments. Compared with the values obtained for the CK treatment, the flow velocities of the micro-catchment treatments fluctuated, but continually increased with increased quantities of rainfall. The initiation of runoff generation was delayed for the FSP, AD, and CP treatments relative to the CK treatment. It was noted that the ability to prevent runoff and sediment generation didn't always consistently work for the micro-catchment treatments. When the structure on the micro-catchment treatments was damaged, the rills evolved relatively rapidly, so the increase of the flow velocity was relatively large. At the termination of the rainfall events, the flow velocities of the FSB, AD, and CP micro-catchment treatments reached values of $0.24 \text{ m}\cdot\text{s}^{-1}$, $0.36 \text{ m}\cdot\text{s}^{-1}$, and $0.26 \text{ m}\cdot\text{s}^{-1}$, respectively.

The occurrence of slope erosion is primarily affected by the hydrodynamic characteristics of the slope runoff and the soil conditions on the slope. Erosion only occurs when the overland flow reaches a certain hydraulic index. As shown in Table 3, both Re and Fr significantly increased with increased rainfall for the different treatments, but there were significant differences between the treatments. Laminar flow occurred for the CK treatments before the

cumulative rainfall reached 124 mm and, thereafter, the flow slowly transitioned from laminar to turbulent flow. The flow pattern changed to turbulent flow under the micro-catchment treatments before the cumulative rainfall reached 83 mm. Due to increased rainfall duration, increased overland flow concentration and the effects of the micro-topography, the degree of turbulence became more intense. In the control treatment, Fr was greater than 1 after the cumulative rainfall exceeded 101 mm and indicated the presence of a supercritical flow. In the other treatments, Fr in the overland flow and rill flow was always less than 1 and indicated the existence of subcritical flows. The f parameter is influenced by the slope's topography and landform, soil texture, and rainfall. The variations in f for the four treatments during rainfall showed that the initial f values were the highest for the CK and micro-catchment treatments, such that the FSP, AD, and CP treatments displayed decreasing trends with increasing rainfall. At the end of the rainfall, f had decreased for the FSB, AD, and CP treatments from 6.14, 12.5, 14.66, and 15.4 to 1.61, 6.89, 5.24, and 6.54, respectively.

Dynamic mechanisms of tillage slope erosion

As shown in Figure 7, the D_r Values for all the treatments increased linearly with increased τ and ω . For the different treatments, the coefficients of determination for τ and ω varied in the ranges of 0.887–0.926 and 0.89–0.962, respectively, which were all close to 1. Thus, we considered the goodness of fit to be relatively high, and both τ and ω could be used to predict the slope erosion of the different treatments.

During erosion, the rill erodibility parameter K_r , the critical τ (τ_c) and the critical ω (ω_c) reflected the resistance to soil erosion: $D_r = K_r(\tau - \tau_c)$, and $D_r = K_r(\omega - \omega_c)$ (Mirzaee et al., 2017; Wang et al., 2016). As shown in Fig. 7 and Table 4, the soil surface roughness

increased gradually from the CK to the FSP, AD, and CP treatments. The treatments and intercepts of the linear relationships between D_r and the dynamic parameters of erosion varied significantly. The CK treatment had the lowest τ_c of erosion, 2.702 Pa, followed by FSP (12.444 Pa), CP (16.652 Pa), and AD (17.359 Pa) and displayed the corresponding K_r values of 13.219, 8.52, 8.341, and 7.703, respectively. The ω_c of erosion for the CK treatment was $0.233 \text{ N}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$, followed by FSP ($1.061 \text{ N}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$), AD ($1.718 \text{ N}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$), and CP ($1.777 \text{ N}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$) and the corresponding K_r values were 57.102, 33.954, 23.828, and 30.383, respectively. The τ_c and ω_c values of the three micro-catchment treatments differed by varying amounts compared with the values obtained for the CK treatment and indicated that the implementation of the micro-catchment treatments increased the critical parameters of the slope erosion, reduced the rill erodibility, and enhanced the resistance of the soil mass to runoff scouring.

Discussion

Effects of tillage methods on runoff and sediment generation on the slope

Slope runoff generation is influenced by multiple factors, such as the rainfall intensity, slope soil water content, and slope topographic features. Slope sediment generation is associated with runoff generation, and the capacity of overland flow for soil erosion varies with the undulating soil surface. The three micro-catchment treatments (FSPs, AD, and CP) increased the detention depressions on the land surface due to the undulating micro-topography. The detention depressions on the soil surface may intercept slope runoff layer by layer and accelerate rainfall infiltration, which results in a slower rate of increase for the runoff rate compared to the CK treatment. Because runoff is the primary driver of sediment transport, the sediment transport capacity of the runoff for the micro-catchment treatments was also weak, and the concentration

of sediment carried by the runoff was lower than the values observed for the CK treatment. These results are similar to those of Haytham(2014) and Wang(2017), which showed that micro-catchment methods similar to FSPs and AD significantly improved rainwater infiltration and reduced slope erosion.

After 60 mm (40min) of rainfall, the surface soil water content of the slope was higher; thus, the infiltration intensity decreased compared to the rate observed at the beginning of rainfall, slope runoff generation increased, and slope erosion increased dramatically. Zheng (2010) investigated the effects of soil surface roughness on sheet erosion under simulated rainfall conditions and found that under continuous rainfall, the runoff rate and sediment yield of erosion for the three treatments with high values of surface roughness were lower than those on the control straight slope during the first two rainfall episodes.

In our study, the erosion of slopes with higher values of surface roughness resulted in higher rates of sediment generation compared to the control treatment during the third rainfall event. The results of this research are similar to the results reported by Zheng (2010). During the first two rainfall events, all of micro-catchment treatments displayed a beneficial role in runoff reduction when compared with the CK treatment with the RRBs values following the trend of $FSP < AD < CP$. However, the RRBs values gradually decreased with increased rainfall duration. For the FSP and AD treatments, continuous rainfall resulted in the filling and overflowing of the slope depressions. The hydrodynamic pressure generated on the pit walls increased the scouring on the edges of the low-lying pits, which gradually produced rills and increased the erosion intensity. When 101 mm of cumulative rainfall was reached, the runoff and sediment yield for the FSB and AD treatments significantly exceeded the values observed for the CK treatment. For

the CP treatment, after the concentration of overland flow moved into the furrows, the flow within the furrows could not be rapidly discharged and increased the hydrostatic pressure in the furrow. In addition, it is hypothesized that the infiltration of water produced osmotic pressure within the soil water. Due to these two forces, sufficient pressure would be generated to break through the ridge, and the converged flow would be immediately released that resulted in a rapid increase in the runoff rate within a short period of time. Thus, the ability to intercept rainfall gradually decreased with increased quantities of rainfall. When 124 mm of cumulative rainfall had been applied, the runoff rate of the CP treatment also exceeded the runoff rate of the CK treatment. In this process, a large amount of sediment was carried by the flow, which resulted in increased erosion intensity.

Effects of three micro-catchment treatments on hydraulic characteristics

The initial stages of rill evolution primarily occurred before the cumulative rainfall reached 88 mm. Very small rills formed on the slope with minimal flow concentration within the rills; thus, the rill flow velocity was relatively low. Thereafter, as the infiltration rate of the surface soil decreased, the rills received concentrated overland flow with a constantly increasing flow rate. In addition, the morphological parameters of the rills, including their length, width, and depth, increased by different amounts. The overland flow velocity is related to the runoff rate and the evolution of the erosion pattern. A study showed that the rill flow velocity increased with increased runoff rate (Nearing et al., 2017). Another study noted that the morphological characteristics of rills have a significant influence on the rill flow velocity and that the velocity significantly decreased with increased rill width (Wang et al., 2014). In this study, we concluded that the runoff rate and cross-sectional morphology jointly affected the evolution and

development of the flow velocity. However, the runoff rate had a greater effect on the flow velocity, which caused a fluctuating rate of increased flow velocity. By considering the runoff and sediment generation, we found that the evolution of rill erosion became more intense for the FSP, AD, and CP treatments, where the variability was more significant.

All of the micro-catchment treatments had greater Re values than the CK treatment, whereas the tillage treatment's Fr values were always less than 1. Peng et al. (2015) found that during rill erosion, the Re values varied between 1200 and 7700 at different flow rates on different slope gradients, and when the slope gradient was constant, the Re value increased significantly as the flow rate increased. In our study, no clear trends for Fr were found with changes of the slope gradient and flow rate; nonetheless, Fr remained greater than 1. The previous study focused on smooth bare land, whereas three micro-catchment treatments had complex topography and artificially implemented. When the soil accumulated on the slope after digging and excavation, the soil density and other soil properties were not consistent. Consequently, even after the rills had formed, their bottoms were undulating. The presence of soil surface roughness which reflected the variation of micro-topography in the micro-catchment treatments may have increased the flow turbulence while reducing the runoff rate and increasing the runoff depth (Liang et al., 2014). Moreover, the duration of our study was longer, which resulted in constant increased flow velocities and water depth. Thus, although Re was relatively high, Fr was still lower than 1 at the end of the rainfall events. On the slope of the CK treatment, the soil surface roughness was lower, and the sediment concentration changed less with increasing rainfall duration compared to the slope under the other three treatments. Therefore, after the increase of the overland flow concentration, its effect on the flow velocity increased.

The CK slope was relatively smooth, and backwater rarely occurred after the flow became concentrated. The water depth was relatively small in the rills, so Fr was greater than 1.

The resistance of the micro-catchment treatments to overland flow was significantly higher than the resistance of the CK slope; however, both had decreasing trends. This trend occurred because the different micro-catchment treatments resulted in random amounts of roughness on the soil surface, and the surface with a greater random roughness would also have a greater f value for the flow, thus the roughness significantly hindering the development of overland flow (Gilley and Finkner, 1991). The sediment generated during the rainfall was deposited in low-lying areas, and the protruding portions of the slope were reduced by flow scouring, which reduced the soil surface roughness and gradually decreased the f value of the flow. The resistance to overland flow on the CK slope was mainly caused by the interactions between soil surface particles and rainfall. At the beginning of the rainfall event, the adhesion of the soil particles, the presence of soil aggregates, and the overland sheet flow disturbance by the rainfall contributed to a high f value. With increased generation of slope runoff, the aggregates were destroyed, rills formed on the slope, and the flow depth increased. Thus, the effects of rainfall and the role of the viscous sub-layer decreased, and the flow resistance was reduced.

Effect of three micro-catchment treatments on the dynamic mechanism of erosion

During slope erosion, two primary factors that control slope detachment are the slope features (slope gradient, soil type, and soil surface roughness) and the hydraulic characteristics (e.g., flow velocity and water depth). In this study, we used a fixed slope gradient and soil type to primarily explore the effects of the soil surface roughness and hydraulic characteristics on slope runoff generation and sediment transport. The results showed that both τ and ω showed

significant positive correlations with D_r on treatment slopes with different values of soil surface roughness. In particular, ω was completely positively correlated with the D_r Values of the different treatments. Wang(2017) and Liu(2010) found that τ and ω have good linear relationships with D_r .

In the Water Erosion Prediction Project (WEPP) erosion model, which is based on physical processes, K_r and τ_c reflect the soil resistance to concentrated flow in rills (Knapen et al., 2007). In our simulation study, there were significant differences in the K_r values under the different tillage methods, and the overall trend was K_r (CK) > K_r (FSP) > K_r (AD) > K_r (CT). This trend indicates that tillage methods could change the rill erodibility on sloping farmland. The micro-catchment treatments had higher values of surface roughness and lower values of K_r in comparison to the CK treatment. These results suggest that during the plowing of summer fallow land, implementing these protective micro-catchment treatments could slow the occurrence of erosion.

The primary factors that affect the soil erodibility parameters are the physical and chemical properties of the soil, including the aggregate content and organic matter content. Protective micro-catchment treatments can effectively maintain the organic matter content in the soil, protect large aggregates from being destroyed, and enhance soil stability, thereby, resulting in stronger resistance to erosion (Zhang et al., 2012). In this study, the micro-catchment treatments increased the soil surface roughness, improved rainfall infiltration, and reduced slope runoff generation, thereby, reducing the loss of aggregates and organic matter and decreasing soil erodibility. The increase of the soil surface roughness in the micro-catchment treatments also increased the hydrodynamic thresholds, such as τ_c and ω_c . It should be noted that it is not always

possible to reduce erosion by increasing the soil surface roughness through micro-catchment treatments. With high rain intensity and long rainfall duration, once the limit of rainfall storage in slope detentions is reached, the undulating slope is broken, and the flow rate and water depth in the rills constantly increases. This constant increased flow leads to rapid increases of τ and ω , which, after exceeding the critical values, will enhance rill erosion and sediment generation.

There have been many studies on the micro-catchment treatments on the loess plateau (Zhang et al., 2016; Ta et al., 2016; Liang, 2015; Zheng et al., 2007), most of which were carried out under simulated rainfall conditions, and the results showed that the runoff and sediment in bare slope was larger than micro-catchment treatments (FSP, CP, AD), which proved that the micro-catchment measures had good soil and water conservation benefits. Because this study was carried out under the condition of intermittent simulated rainfall instead of continuous rainfall, in addition, rain intensity, slope, artificial operation and other factors will affect the effect of rain collection measures, so the results are different. In this paper, the fixed slope and rainfall intensity are analyzed, while the different slope, rainfall intensity and rainfall time need to be further studied. In addition, how to apply the results of indoor analysis to field research needs more in-depth exploration.

Conclusions

Through determining the patterns of runoff, sediment generation, and hydrodynamic characteristics of three micro-catchment treatments, the following conclusions were resolved. (1) Before the cumulative rainfall had reached 83 mm, the runoff rates and sediment concentrations for the CP, AD, and FSP treatments were significantly lower than those values for the CK treatment. Both the RRBs and SRBs had the following treatment trend with $CP > AD > FSP$.

After 83 mm of cumulative rainfall had been applied, the effects of water retention and soil conservation gradually disappeared. At the termination of the rainfall events, the sediment generation was 2.39 times (FSP), 2.56 times (AD), and 2.85 times (CP) the values measured for the bare CK treatment. (2) During the erosion under the different treatments, the flow velocity fluctuated, but continually increased, Re and Fr values constantly increased, and the f parameter gradually decreased. For the three micro-catchment treatments, Re was greater than 500 when 88 mm of cumulative rainfall had been applied, but Re increased sharply during additional rainfall. Although the flow was turbulent, the Fr remained lower than 1. Compared with the smooth bare CK treatment, the micro-catchment treatments increased the soil surface roughness and significantly improved the f values. (3) Compared with the CK treatment, three micro-catchment treatments could reduce the soil erodibility by more than 40% on silt loam slopes that are typical for the Loess Plateau. The micro-catchment treatments increased the critical hydraulic parameters of the slope and enhanced the soil's resistance to scouring.

In this study, the process, dynamic mechanism, the evolution law of runoff, sediment yield, hydraulic parameters and the relationship between water and sediment process and water flow energy were studied, which can provide valuable theoretical basis for farmers to rationally adopt and lay cultivated slope surface. In addition, it is of great significance to the establishment of soil erosion model and the prediction of soil erosion.

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Table 1. The contrast of velocity between automatic measuring instrument and dyeing method

Test distance (m)	Automatic measuring Instrument (m s^{-1})	Dyeing method (m s^{-1})	Error (%)
0.5	0.721	0.651	9.7
1.0	0.723	0.666	7.8
1.5	0.728	0.717	1.5
2.0	0.735	0.739	0.5
2.5	0.742	0.715	3.6
3.0	0.742	0.725	2.5

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Table 2. Parameters of the rainfall during the simulated rainfall events and the soil moisture for the 0-20 cm soil depth immediately following the termination of each rainfall event.

Rainfall Event	Rainfall duration (min)	Rainfall intensity (mm h ⁻¹)	Amount of rainfall (mm)	Surface soil moisture (%)
1	40	91.2 ± 5.73	60.8	16.43 ± 2.56
2	15	92.3 ± 7.12	23.08	18.42 ± 3.14
3	15	91.5 ± 5.89	22.87	20.23 ± 3.64
4	15	89.3 ± 9.12	22.33	25.92 ± 2.03
5	15	90.5 ± 3.24	22.63	27.80 ± 1.06

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Table 3. Characteristics of the hydrodynamic parameters for the bare soil control slope (CK) and the three micro-catchment treatments: fish-scale pits (FSP), artificial digging (AD), and contour plowing (CP) for the five simulated rainfall events. Values plotted are the means of three replications.

Treat- ment	Rainfall event	Flow velocity (m.s ⁻¹)	Reynolds number	Froude number	Resistance coefficient	Surface roughness (cm)
CK	1	0.057±0.003	55±3.20	0.58±0.044	6.14±0.387	0.491±0.06
	2	0.083±0.014	109±6.70	0.91±0.052	2.59±0.403	0.506±0.12
	3	0.152±0.019	409±52.40	0.99±0.152	2.18±0.270	0.551±0.16
	4	0.182±0.020	546±52.90	1.09±0.117	1.78±0.221	0.582±0.13
	5	0.208±0.009	722±41.00	1.14±0.008	1.61±0.175	0.718±0.11
FSP	1	0.070±0.003	205±7.90	0.41±0.042	12.5±1.608	1.186±0.27
	2	0.109±0.008	739±92.70	0.44±0.036	10.96±1.367	1.224±0.73
	3	0.142±0.016	1281±151.00	0.49±0.050	8.52±1.088	1.265±0.27
	4	0.166±0.017	1792±137.10	0.53±0.029	7.58±0.952	1.351±0.38
	5	0.202±0.029	2888±128.50	0.55±0.051	6.89±0.756	1.382±0.57
AD	1	0.060±0.005	155±14.20	0.38±0.017	14.66±0.73	1.669±0.24
	2	0.108±0.011	809±95.30	0.41±0.025	13.56±1.06	1.613±0.31
	3	0.147±0.014	1826±116.40	0.47±0.025	9.97±0.56	1.563±0.27
	4	0.232±0.020	4410±509.70	0.54±0.032	7.59±0.63	1.512±0.23
	5	0.286±0.034	5868±896.20	0.64±0.022	5.24±0.38	1.488±0.17
CP	1	0.071±0.006	264±7.10	0.37±0.030	15.40±1.244	2.201±0.37
	2	0.109±0.009	727±92.90	0.43±0.055	11.73±0.202	2.155±0.24
	3	0.145±0.023	1333±78.10	0.50±0.012	8.33±0.272	2.065±0.35
	4	0.164±0.021	1686±171.90	0.53±0.055	7.38±0.665	2.057±0.29
	5	0.216±0.006	3409±163.20	0.56±0.055	6.54±0.481	2.046±0.31

Table 4. Rill erodibility and critical hydraulic parameters for the bare soil control slope (CK) and the three micro-catchment treatments: fish-scale pits (FSP), artificial digging (AD), and contour plowing (CP) for the five simulated rainfall events. Values plotted are the means of three replications.

Experimental treatment	Critical shear stress		Critical stream power	
	K_r	τ_c (Pa)	K_r	ω_c (N·m ⁻¹ ·s ⁻¹)
Control slope	13.219	2.702	57.102	0.233
Fish-scale pits slope	8.520	12.444	33.954	1.061
Artificial digging slope	7.703	17.359	23.828	1.718
Contour plowing slope	8.341	16.652	30.383	1.777

Fig.1 Schematic of the bare soil control slope (CK) and the three micro-catchment treatments: fish-scale pits (FSP), artificial digging (AD), and contour plowing (CP). All treatments were implemented on a typical 15° slope of a silt loam soil from the Loess Plateau.

Fig. 2 Runoff rates versus cumulative rainfall duration for the bare soil control slope (CK) and the three micro-catchment treatments: fish-scale pits (FSP), artificial digging (AD), and contour plowing (CP) for the five simulated rainfall events. Values plotted are the means of three replications.

Fig.3 The runoff reduction benefit (RRB) during the five rainfall events for the bare soil control slope (CK) and the three micro-catchment treatments: fish-scale pits (FSP), artificial digging (AD), and contour plowing (CP) for the five simulated rainfall events. Values plotted are the means of three replications.

Fig.4 The sediment concentration versus the cumulative rainfall duration for the bare soil control slope (CK) and the three micro-catchment treatments: fish-scale pits (FSP), artificial digging (AD), and contour plowing (CP). Values plotted are the means of three replications.

Fig.5 The sediment reduction benefit (SRB) over the five rainfall events for the bare soil control slope (CK) and the three micro-catchment treatments: fish-scale pits (FSP), artificial digging (AD), and contour plowing (CP) for the five simulated rainfall events. Values plotted are the means of three replications.

Fig.6 Runoff flow velocities versus cumulative rainfall duration for the bare soil control slope (CK) and the three micro-catchment treatments: fish-scale pits (FSP), artificial digging (AD), and contour plowing (CP) for the five simulated rainfall events. Values plotted are the means of three replications.

Fig.7 Regression analyses of the soil detachment rate (D_r) versus the hydraulic shear stress (τ), and the stream power (ω) for the bare soil control slope (CK) and the three micro-catchment

treatments: fish-scale pits (FSP), artificial digging (AD), and contour plowing (CP) for the five simulated rainfall events. Values plotted are the means of three replications.

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