Effect of natural rainfall on the migration characteristics of runoff and sediment on purple soil sloping cropland during different planting stages

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ABSTRACT

Due to the difficulty in monitoring subsurface runoff and sediment migration, their loss loads are still not clear and need further study. This study monitored water and soil loss occurring within experimental field plots for two calendar years under natural rainfall events. The sediment loss load was quantified by considering the corresponding water flow flux and its sediment concentration. The results showed that 60.04% of the runoff and 2.83% of the sediment were lost underground. The annual underground sediment loss reached up to 54.6 kg·ha⁻¹·yr⁻¹. A total of 69.68% of the runoff yield and 67.25% of the sediment yield were produced during the corn planting stage (CPS: March–July). Heavy rain and torrential rain events produced 94.45%, 76.21% of the annual runoff and sediment yields during the corn-planting stage and summer fallow period (SFP: August–September). The rain frequency, rainfall, and rainfall duration of each planting stage significantly affected the resulting runoff and sediment yield. Measures aimed at the prevention and control of water-soil loss from purple soil sloping land should focus heavily on torrential rain and heavy rain events during the CPS and SFP. This paper aims to provide a practical reference for quantifying the water and soil loss from purple soil sloping cropland.

Key words: natural rain, purple soil sloping land, runoff and sediment yield, soil and water loss

HIGHLIGHTS

- Subsurface loss was more than 60% of total water loss of purple soil sloping cropland.
- Annual accumulated underground sediment loss was considerable and noteworthy.
- Surface and subsurface water and soil loss mainly happened in the corn planting stage.
- Rainfall pattern controls the surface and subsurface loss of water and soil.

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INTRODUCTION

Purple soil, classified as Regosols in the Food and Agriculture Organization of the United Nations (FAO) taxonomy system or Entisols in the United States Department of Agriculture (USDA) taxonomy system, is a unique soil type in China. The cultivated land area of purple soil (approximately 0.22 million km²) accounts for 3% of the total arable land area in China and is distributed mainly to the south of the Yangtze River Basin (Stolte et al. 2009). More than 70% of the cultivated land soil in this region is purple soil. Its loose purple parent rock readily disintegrates into the soil via rapid weathering (Ding et al. 2017). Moreover, the purple soil area is one of China’s most densely populated agricultural regions (Zhang et al. 2004). Almost all the purple soil area has been reclaimed and tilled to meet the region’s grain need, excluding the tops of hills or steep slopes, which are considered unsuitable for plants (Zhu et al. 2008).

Purple soil cultivated land has the characteristics of a dualistic geotechnical structure of its overlying soil and underlying rock (Zhong et al. 2019). The plentiful soil pores, strong permeability, and weak water-holding capacity of purple soil has the potential to cause severe soil loss under concentrated rainfall and heat (Khan et al. 2016; Qian et al. 2020). It is more severe in slope cultivated land areas (Zheng et al. 2007). Additionally, purple soil is rich in small rock fragments that are completely incorporated into the topsoil and could considerably influence the percolation, runoff, and soil loss rates of stony soil (Smets et al. 2011). Hydrological processes play important roles in hillslope soil migration processes (Qian et al. 2016). Runoff is generally the result of unique weather and soil conditions (Douglas et al. 1998), while slope runoff is the basic erosion force and sediment transport mechanism of hydraulic erosion.

The variability in precipitation (P) and the complexity of natural geographical conditions determine the complexity of the runoff formation process. When falling on the ground, rainwater first infiltrates into the soil. Part of the rainwater might be intercepted in the soil in the form of soil water. The other rainwater component flows laterally out of the soil or continues to infiltrate downwards in the form of subsurface flow. When the soil moisture content reaches saturation or the rainfall intensity is greater than the water infiltration intensity, rainwater will form surface runoff. Soil pores and cracks in the soil can provide flow paths for water flow and sediment migration (Gachter et al. 2004), thereby accelerating subsurface flow and sediment migration and loss. Surface erosion and subsurface infiltration processes often co-occur. Rainfall runoff is the driving force and carrier of sediment migration. Water and sediment migrations often occur simultaneously. Previous studies have shown that runoff and sediment migration are complex processes with multiple influencing factors (Bronick & Lal 2005; Komatsu et al. 2018; Zhang et al. 2020). Rainfall is the main driving force for the generation and development of runoff and sediment transport processes (Liu 2016). With increasing rainfall intensity, the infiltration depth and total infiltration amount of rainwater will decrease. The higher the fragmentation degree of sediment
MATERIALS AND METHODS

Description of the experimental plot

The experimental plots are located in the National Monitoring Base for Purple Soil Fertility and Fertilizer Efficiency (29°48′58″N, 106°24′40.6″E), Beibei, Chongqing, China. The climate is a typical subtropical humid climate according to the Climatological Classification of China. The national meteorological station of Beibei (Station No.: 57511) reported that the annual average temperature is 18.3 °C, and the mean annual P is 1,105.4 mm. The test plots were built on February 28, 2018. The size of each plot was 9 m (length) × 3 m (width) × 0.8 m (depth). The flank walls and floors of these grids were made from reinforced concrete. The soil layers of each plot from top to bottom are as follows: 20 cm depth of surface cultivated mellow soil (L1), 20 cm depth of plow pan soil (L2), and 20 cm depth of clastic purple shale parent material layer (L3) (shown in Figure 1). The soil of all layers is a type of sandy clay taken from the same plot near the test plot, which belongs to the Jurassic
Shaximiao Formation soil. Table 1 presents the basic physical and chemical properties of the experimental soil. The surface slope of all plots was 15° (He et al. 2018; Luo et al. 2019; Wang et al. 2019).

**Experimental treatments**

This study monitored the flow and sediment movement of surface and subsurface soils under every natural rainfall event that occurred throughout the entire test period. As shown in Figure 1, subsurface flow ($R_{sub}$) in each test plot is collected by a subdrain with quartz sand (particle size of 2–4 mm) and then drained into a bucket with a water tube. An open trench collects surface runoff ($R_{sur}$) in each test plot and then drains it into a bucket with a water tube. Each bucket has nine shunt holes, and one of the holes is connected to a subbucket by a water pipeline.

The experimental period was two consecutive cycle years, lasting from March 1, 2018, to February 29, 2020. As shown in Figure 2, each research cycle year contains four planting stages: the corn planting stage (CPS: March–July), the fallow period in summer (SFP: August–September), the mustard planting stage (MPS: October–following January), and the fallow period in winter (WFP: following February). The CPS is the stage lasting from the day of corn seedling transplant to the corn harvest day. The SFP is the stage lasting from the day after the corn harvest to the day before mustard seedling transplant. The MPS is the period lasting from the day of mustard seedling transplant to that of the mustard harvest. The WFP is the stage lasting from the day after mustard harvest to the day before the corn seedling transplant. Natural rainfall events in the test period were divided into four patterns according to their maximum P in 24 h (China Meteorological Standard): torrential rain (TR) (50 mm < maximum P in 24 h < 100 mm), heavy rain (HR) (25 mm < maximum P of 24 h < 50 mm), moderate rain pattern (MR) (10 mm < maximum P of 24 h < 25 mm), and light rain pattern (LR) (0.1 mm < maximum P of 24 h < 10 mm). Corn (*Zea mays* L.) and mustard (*Brassica juncea* var. *tumida*) were planted each year in this study. Both crops were planted along the slope with a 0.3 m plant spacing, but the

![Figure 1](image1.png) The location and design of the experimental plots.

![Figure 2](image2.png) The location and design of the experimental plots.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>The basic properties of experimental soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil depth (cm)</td>
<td>PH</td>
</tr>
<tr>
<td>0–20</td>
<td>6.29</td>
</tr>
<tr>
<td>20–40</td>
<td>7.34</td>
</tr>
</tbody>
</table>

TN, total nitrogen; AN, available nitrogen; TP, total phosphorus; AP, available phosphorus; TK, total potassium; RAK, rapidly available potassium; OM, organic matter; SVW, volume weight of soil; SP, soil porosity; ST, soil texture.
row spacing was 0.6 m and 0.4 m for corn and mustard, respectively. Conventional fertilization, including two traditional fertilizer applications for the summer corn and one fertilizer application for the winter mustard, was established in this study. Fertilizer was applied at a depth of 5–10 cm to avoid surface loss. This study was conducted over two consecutive years. Three treatment duplicates were performed.

**Experiment data collections and processing**

The surface runoff (mm) and subsurface flow (mm) in the $i^{th}$ rainfall event were calculated as follows:

\[
R_{suri} = \frac{a \cdot H_{suri} + 9b \cdot h_{suri}}{A \cdot \cos(15^\circ) \cdot 1000} \tag{1}
\]

\[
R_{subi} = \frac{a \cdot H_{subi} + 9b \cdot h_{subi}}{A \cdot \cos(15^\circ) \cdot 1000} \tag{2}
\]

\[
R_i = R_{suri} + R_{subi} \tag{3}
\]

where $a$ and $b$ are the cross-sectional areas (m$^2$) of the bucket and sub-bucket; $H_{suri}$ and $h_{suri}$ are water depths (m) of the bucket and sub-bucket; $A$ is the slope area (m$^2$) of each research plot; $R_{suri}$ and $R_{subi}$ are yield (mm) of surface and subsurface flow, and $R_i$ is the total runoff yield (mm) in the $i^{th}$ rainfall event.

In a specified period, the accumulated surface runoff ($R_{sur}$) (mm) and subsurface flow ($R_{sub}$) (mm) is calculated as the following equations:

\[
R_{sur} = \sum_{i=1}^{n} (R_{suri}) \tag{4}
\]

\[
R_{sub} = \sum_{i=1}^{n} (R_{subi}) \tag{5}
\]

\[
R_t = R_{sur} + R_{sub} \tag{6}
\]

where $n$ is the number of rainfall events in a specified period, and $n \geq 2$. The $R_t$ is the total runoff yield (mm).

Sediment concentration was acquired by suction filtration from 1-L water samples. The water in the buckets should be mixed thoroughly by stirring before taking the samples. When the collected water was more than 1 L, we sampled 1 L for the sediment concentration analysis. When less than 1 L, we took no samples.

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Figure 2 | Temporal distribution of natural daily rainfall in the experimental plot during the testing period. WFP, winter fallow period; CPS, corn planting stage; SFP, summer fallow period; MPS, mustard planting stage. TR, HR, MR, and LR represent the torrential rain, heavy rain, moderate rain, and light rain grades, respectively.
water samples, including surface runoff and subsurface flow samples, were obtained. The sediment yields also can be got analogously:

\[
S_{\text{sur}} = \frac{(a + H_{\text{sur}} \times C_{\text{sur}} + 9b \times H_{\text{sur}} \times C_{\text{sur}})}{A \cdot \cos(15^\circ)} + 10
\]  

(7)

\[
S_{\text{sub}} = \frac{(a + H_{\text{sub}} \times C_{\text{sub}} + 9b \times H_{\text{sub}} \times C_{\text{sub}})}{A \cdot \cos(15^\circ)} + 10
\]  

(8)

\[
S_{t} = S_{\text{sur}} + S_{\text{sub}}
\]  

(9)

\[
S_{\text{sur}} = \sum_{i=1}^{n} (S_{\text{sur}})
\]  

(10)

\[
S_{\text{sub}} = \sum_{i=1}^{n} (S_{\text{sub}})
\]  

(11)

\[
S_{t} = S_{\text{sur}} + S_{\text{sub}}
\]  

(12)

where \(C_{\text{sur}}, C_{\text{sur}}\) are concentrations (g/m\(^3\)) of surface sediment, and \(C_{\text{sub}}, C_{\text{sub}}\) are concentrations (g/cm\(^3\)) of subsurface sediment in the bucket and sub-bucket in the \(i^{\text{th}}\) rainfall event. \(S_{\text{sur}}, S_{\text{sub}}\) are the sediment yields (kg/ha) of surface and subsurface, and \(R_{t}\) is the total runoff yield in the \(i^{\text{th}}\) rainfall event. The \(S_{t}\) is the total sediment yield (kg/ha) in the specified period.

Hourly meteorological observed data were obtained from a small automatic weather station near the research plot. Daily rainfall was calculated as the summed hourly precipitation from 0 to 24 h. Rainfall event frequency (RE) was considered as the number of days with daily precipitation exceeding 0 mm in a given period. The daily effective rainfall duration (RD) was the accumulated hours of rainfall within an event from the beginning to the end, excluding the interruption period. Rainfall was frequent and abundant throughout the trial period, but rainfall events were inconsistent. A total of 312 rainfall events produced a total rainfall amount of 2,018.4 mm during two consecutive research cycle years (shown in Figure 2). This study selected weekly natural rainfall indicators to analyze the impact of rainfall events on water and soil migration processes during different planting stages. The impact of weekly rainfall amounts, rainfall intensities, rainfall events, and rainfall durations on runoff, subsurface flow, and sediment yields are studied under different planting stages. Additionally, the size distribution of sediment particles is determined by the Pipette method. Data on soil bulk density, moisture content, and porosity are acquired mainly through the ring knife method.

**Statistical analysis**

The IBM SPSS Statistics 25 software was the data analysis tool, while the Graph Pad Prism 8 was the mapping software in this paper. The Pearson correlation was used for the correlation analysis. The least significant difference (LSD) method at \(p = 0.05\) was performed to elucidate any significant differences.

**RESULTS**

**Characteristics of rainfall-runoff and sediment**

Rainfall events produced different amounts of runoff and sediment loss. Figure 3 indicates that the runoff and sediment yield also presented the same temporal distribution as that of rainfall during the entire test period. Runoff and sediment migration occurred from April to October during the first planting year and from April to June and November during the second planting year. Notably, the distribution of runoff and sediment in the second cycle year was more concentrated. However, the total runoff increased by 46.41%, while the total sediment yield decreased to 63.72% compared with that in the first cycle year.

Table 2 shows that the rainfall of different planting stages dominated the runoff and sediment migration amounts. A total of 38.78% and 25.64% of rainfall events occurred in the CPS and SFP, contributing to 56.61% and 27.89% of the annual rainfall, respectively. Remarkably, the LR event in each stage was the main rain pattern, accounting for 74.38%, 76.25%, 87.8, and 100% of the total rainfall events in the CPS, SFP, MSP, and WFP, respectively. The rainfall events (REs) and rainfall durations (RDs) under the LR pattern during each stage were substantially higher than those occurring under other rainfall patterns. The rainfall occurring...
under each rain pattern during each stage exhibited no significant difference, excluding that under the WFP. However, the rainfall amount during the CPS was significantly higher than that during other planting stages. The average annual rainfall-runoff flux was 364.7 mm, with 145.7 mm of surface flow and 219.0 mm of subsurface flow. The total average annual sediment ($S_a$) yield was 1,932.8 kg/ha, 97.17% of which was from $R_{sur}$ (1,878.2 kg*ha$^{-1}$*yr$^{-1}$).

The subsurface sediment yield ($S_{sub}$) of each rainfall event was too small to be noted and compared to the surface sediment yield. However, the annual accumulative underground sediment loss load reached up to 54.6 kg*ha$^{-1}$*yr$^{-1}$, accounting for 2.83% of the annual total sediment loss load. A total of 69.69% and 23.32% of the annual runoff and 67.25% and 32.36% of the annual sediment loss load were mainly distributed in the CPS and SFP, respectively. The $R_{sur}$ and $R_t$ yields under the TR and HR events during the CPS were significantly higher than those under the MR and LR events ($p < 0.05$). The annual runoff and sediment yield under each rainfall pattern in the SFP, MPS, and WFP presented no significant difference ($p > 0.05$). The annual TR and HR $R_{sur}$ yields were significantly higher than those under other rainfall patterns ($p < 0.05$). There was no significant difference among the annual $R_{sub}$ yields under different rainfall patterns ($p > 0.05$). The annual $R_{sur}$, $R_t$, and $R_{sub}$ yields
during the CPS and SFP were significantly higher than those during other stages \((p < 0.05)\). The \(S_{\text{f}}\) and \(S_{\text{sur}}\) yields under the TR events in the CPS were significantly higher than those under the other rainfall patterns \((p < 0.05)\). There was no significant difference among the annual \(S_{\text{sub}}\) yields under different rainfall patterns \((p > 0.05)\). The annual \(S_{\text{sub}}, S_{\text{f}},\) and \(S_{\text{sur}}\) yields in the CPS and SFP were significantly higher than those at other stages \((p < 0.05)\).

### Relationship of water and soil migration with rainfall intensity

Figure 4 shows that the rainfall-runoff rate and sediment migration amount showed significant relationships with the maximum 24 h rainfall. Increasing the rainfall intensity could improve the yields of runoff and sediment but would decrease the subsurface flow rate. The runoff rate \((R/R)\) increased from 0.00% to 76.59% as the maximum \(P\) of 24 h increased, while the subsurface flow rate \((R_{\text{sub}}/R)\) decreased from 100% to 24.68% (Figure 4(Ia)). The surface sediment and subsurface sediment yields also increased from 0.00 kg/ha to 725.1 kg/ha and from 0.00 kg/ha to 2.07 kg/ha, respectively, as rainfall intensity increased from 4.2 mm to 85.6 mm (Figure 4(Ib)). The runoff rate and subsurface flow rate presented significant simple linear relationships with the maximum weekly 24 h rainfall. Figure 4(II), 4(III) and 4(IV) show that the rainfall-runoff rate and sediment migration amount occurring during each planting stage also showed significant relationships with the maximum \(P\) of 24 h. The \(R^2\) values of the runoff rate sharply decreased from 0.8204 under the CPS to 0.2000 under the SFP and then suddenly rose to 0.6194 during the MPS, while those of the subsurface flow rate decreased from 0.8728 in the CPS to 0.4687 in the MPS. The \(R^2\) values of surface sediment yield decreased from 0.7091 in the CPS to 0.5424 in the MPS. The changing trend of subsurface sediment yield was opposite. In summary, the influence of rainfall intensity on runoff and sediment processes in the CPS was more obvious than that in other planting stages.

Additionally, rainfall intensity also affected the size distribution of sediment particles (PSD). The proportion of large surface sediment particles increased significantly with increased rainfall intensities (Figure 5). In particular, the accumulated proportions of particles \((>0.001\) mm) were 32.95% under TR events, 26.77% under HR events, and 19.32% under MR events, while the PSD of the \(S_{\text{sub}}\) particle remained little change. Generally, larger grain size soil particles were more likely to be carried and moved by runoff under HR and TR events.

### Table 2 | Statistical data of annual average rainfall, runoff, and sediment yield under different rainfall patterns and different planting stages

<table>
<thead>
<tr>
<th>Stage</th>
<th>Rain pattern</th>
<th>Rainfall (mm)</th>
<th>RE (unit: 1)</th>
<th>RD (h)</th>
<th>Rainfall-runoff (mm/yr)</th>
<th>Sediment (kg·ha⁻¹·yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(R_{\text{sub}})</td>
<td>(R_{\text{sur}})</td>
</tr>
<tr>
<td>CPS</td>
<td>TR</td>
<td>108.3a</td>
<td>1.5b</td>
<td>24.5b</td>
<td>24.4a</td>
<td>53.1a</td>
</tr>
<tr>
<td></td>
<td>HR</td>
<td>179.2a</td>
<td>5.0b</td>
<td>56.5b</td>
<td>63.9a</td>
<td>35.5ab</td>
</tr>
<tr>
<td></td>
<td>MR</td>
<td>156.3a</td>
<td>9.0b</td>
<td>84.0b</td>
<td>51.8a</td>
<td>10.8b</td>
</tr>
<tr>
<td></td>
<td>LR</td>
<td>127.6a</td>
<td>45b</td>
<td>204.0a</td>
<td>14.0b</td>
<td>0.7b</td>
</tr>
<tr>
<td>SFP</td>
<td>TR</td>
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<td>0.5b</td>
<td>8.0c</td>
<td>7.2a</td>
<td>16.4a</td>
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<tr>
<td></td>
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<td>1.5b</td>
<td>15.5b</td>
<td>17.6a</td>
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<td>134.0a</td>
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<tr>
<td>MPS</td>
<td>TR</td>
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<td>0b</td>
<td>0b</td>
<td>0.0a</td>
<td>0.0a</td>
</tr>
<tr>
<td></td>
<td>HR</td>
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<td>0.5b</td>
<td>8.5b</td>
<td>5.5a</td>
<td>1.4a</td>
</tr>
<tr>
<td></td>
<td>MR</td>
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<td>4.5b</td>
<td>65.0ab</td>
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<tr>
<td></td>
<td>LR</td>
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<td>36a</td>
<td>154.0a</td>
<td>0.9a</td>
<td>0.0a</td>
</tr>
<tr>
<td>WFP</td>
<td>TR</td>
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<td>0b</td>
<td>0b</td>
<td>0.0a</td>
<td>0.0a</td>
</tr>
<tr>
<td></td>
<td>HR</td>
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<td>0b</td>
<td>0b</td>
<td>0.0a</td>
<td>0.0a</td>
</tr>
<tr>
<td></td>
<td>MR</td>
<td>0.0b</td>
<td>0b</td>
<td>0b</td>
<td>0.0a</td>
<td>0.0a</td>
</tr>
<tr>
<td></td>
<td>LR</td>
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<td>14.5a</td>
<td>62.0a</td>
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<td>Annual</td>
<td>TR</td>
<td>137.9a</td>
<td>2.0b</td>
<td>32.5a</td>
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<td>7.0b</td>
<td>80.5b</td>
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<tr>
<td></td>
<td>MR</td>
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<td>21.0b</td>
<td>220.0b</td>
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<tr>
<td></td>
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<td>126.0a</td>
<td>554.0b</td>
<td>14.9a</td>
<td>7.2c</td>
</tr>
</tbody>
</table>

TR, torrential rain; HR, heavy rain; MR, moderate rain; LR, light rain; RE, rainfall event frequency; RD, rain duration.

Different superscript letters indicate significantly different variables between different rainfall patterns under each stage by the LSD method at the \(p < 0.05\) level.
Figure 4 | Relationship of maximum rainfall of 24 h in the trial period (I), corn planting stage (CPS) (II), summer fallow period (SFP) (III) and mustard planting stage (MPS) (IV) with (a) runoff rate ($R_t/P$) and subsurface flow rate ($R_{sub}/R_t$), (b) surface sediment yield ($S_{sur}$) and subsurface sediment yield ($S_{sub}$). The solid line is the best-fit line; the dotted lines are the 95% confidence bands.
Relationship of water and soil migration with rainfall amount

Increasing the weekly rainfall amount could increase runoff and sediment yields but would decrease the subsurface flow rate. The rainfall variation might mainly explain the difference in the runoff yield (Douglas et al. 1998). Figure 6 shows that the runoff rate and sediment amount were heavily affected by the weekly rainfall amount. The weekly rainfall amount influenced the runoff rates during the SFP and MPS more obviously than that during the CPS. At the same time, it affected the subsurface flow rate in the CPS and SFP more remarkably than that in the MPS. Additionally, the surface sediment yield in each planting stage was influenced by the weekly rainfall amount. Simultaneously, subsurface flow occurring during the MPS was affected more obviously than that of other stages.

The weekly P ranged from 0.0 mm to 101.8 mm over the whole trial period. Figure 6(Ia) shows that the runoff rate ($R_t/P$) increased from 0.00% to 76.59% as the rainfall amount increased. In comparison, the subsurface flow rate ($R_{sub}/R_t$) decreased from 100% to 24.68%. Figure 6( Ib) shows that the surface sediment ($S_{sur}$) and subsurface sediment ($S_{sub}$) yields also increased from 0.00 kg/ha to 725.1 kg/ha and from 0.00 kg/ha to 20.7 kg/ha, respectively, with increasing rainfall amounts. As shown in Table 3, the runoff rate ($R_t/P$) and subsurface flow rate ($R_{sub}/R_t$) presented significant simple linear relationships with the rainfall amount ($P$). The rainfall amount of torrential rain (TRP) showed extreme correlations with the runoff rate ($R_t/P$), subsurface flow rate ($R_{sub}/R_t$), surface sediment ($S_{sur}$) yield, and subsurface sediment ($S_{sub}$) yield. In contrast, the rainfall amount of heavy rain (HRP) and moderate rain (MRP) only showed extremely significant correlations with the runoff rate. TRP presented an extremely significant correlation with the $R_t/P$, $R_{sub}/R_t$, and $S_{sur}$, $S_{sub}$, while HRP only indicated a significant correlation with $R_t/P$ during the CPS (shown in Figure 6(II)). TRP presented significant correlations with the $R_t/P$, $S_{sur}$ and $S_{sub}$, while the HRP and MRP only indicated an extremely significant or significant correlation with the $R_t/P$ in the SFP (as shown in Figure 6(III)). MRP presented a significant or extremely significant correlation with $R_t/P$, $R_{sub}/R_t$, $S_{sur}$, and $S_{sub}$ in the MPS (as shown in Figure 6(IV)). LRP showed no significant relationship with each factor in each stage.

Relationship of water and soil migration with rainfall frequency

Figure 7 indicates that the runoff rate and sediment yield in each stage were also affected by the weekly rainfall frequency. Figure 7(I) shows that weekly rainfall event frequency (RE) also significantly affected the resulting runoff and sediment yields. A total of 58.10% of the weeks in the research period contained more than three rainfall events, while 10.48% experienced no rainfall events. The runoff rate ($R_t/P$), surface sediment ($S_{sur}$), and subsurface sediment ($S_{sub}$) yield presented significant simple linear relationships with the RE, but the $R_2$ values were too low. The weekly RE influenced the $R_t/P$ and $R_{sub}/R_t$ in the SFP and MPS more obviously than those in the CPS (as shown in Figure 7(II)), while it affected the $S_{sur}$ and $S_{sub}$ in the SFP more remarkably than those in the CPS and MPS. Notably, $R_{sub}/R_t$ expressed positive significant relationships with RE in the CPS and MPS (as shown in Figure 7(III) and 7(IV)), which meant that the more weekly RE there was, the more subsurface flow yield would be produced.

As shown in Table 3, the TRE presented extremely significant correlations with the $R_t/P$, $R_{sub}/R_t$, $S_{sur}$, $S_{sub}$ components, while the HRE only showed significant correlations with the $R_t/P$ in the CPS. TREs presented significant or extremely significant correlations with $R_t/P$, $S_{sur}$, $S_{sub}$. Simultaneously, HREs only indicated an extremely significant correlation with $R_t/P$, and HREs presented significant correlations with the $R_t/P$ and
Figure 6 | Relationship of weekly cumulative precipitation (P) in the study period (I), corn planting stage (CPS) (II), summer fallow period (SFP) (III), and mustard planting stage (MPS) (IV) with (a) runoff rate ($R_t/P$) and subsurface flow rate ($R_{sub}/R_t$), (b) surface sediment yield ($S_{sur}$) and subsurface sediment yield ($S_{sub}$). The solid line is the best-fit line; the dotted lines are the 95% confidence bands.
### Table 3

The results of Pearson correlation analysis between runoff rate ($Rt/P$), subsurface flow rate ($R_{sub}/R_t$), surface sediment ($S_{sur}$), and subsurface sediment yields ($S_{sub}$) with weekly rainfall amount ($P$), rainfall event (RE), and rainfall duration (RD) under each rainfall pattern in different planting stages.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Indicator</th>
<th>Weekly P</th>
<th></th>
<th></th>
<th>Weekly RE</th>
<th></th>
<th></th>
<th>Weekly RD</th>
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<th></th>
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<tr>
<td></td>
<td></td>
<td>TR</td>
<td>HR</td>
<td>MR</td>
<td>LR</td>
<td>TR</td>
<td>HR</td>
<td>MR</td>
<td>LR</td>
<td>TR</td>
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<tr>
<td>CPS</td>
<td>$R_t/P$</td>
<td>0.462**</td>
<td>0.412*</td>
<td>0.196</td>
<td>−0.002</td>
<td>0.478**</td>
<td>0.420*</td>
<td>0.148</td>
<td>−0.109</td>
<td>0.464**</td>
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<tr>
<td></td>
<td>$R_{sub}/R_t$</td>
<td>−0.749**</td>
<td>−0.219</td>
<td>0.188</td>
<td>0.399</td>
<td>−0.746**</td>
<td>−0.212</td>
<td>0.183</td>
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<td>−0.748**</td>
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<tr>
<td></td>
<td>$S_{sur}$</td>
<td>0.882**</td>
<td>0.151</td>
<td>−0.110</td>
<td>−0.055</td>
<td>0.853**</td>
<td>0.126</td>
<td>−0.132</td>
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<tr>
<td></td>
<td>$S_{sub}$</td>
<td>0.481**</td>
<td>−0.024</td>
<td>0.071</td>
<td>−0.137</td>
<td>0.500**</td>
<td>−0.039</td>
<td>0.042</td>
<td>−0.243</td>
<td>0.490**</td>
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<tr>
<td>SFP</td>
<td>$R_t/P$</td>
<td>0.502*</td>
<td>0.534**</td>
<td>0.513*</td>
<td>0.273</td>
<td>0.502*</td>
<td>0.561**</td>
<td>0.520**</td>
<td>0.164</td>
<td>0.502*</td>
</tr>
<tr>
<td></td>
<td>$R_{sub}/R_t$</td>
<td>−0.591</td>
<td>−0.126</td>
<td>−0.138</td>
<td>0.001</td>
<td>−0.591</td>
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<td>−0.021</td>
<td>−0.312</td>
<td>−0.591</td>
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<tr>
<td></td>
<td>$S_{sur}$</td>
<td>0.879**</td>
<td>0.087</td>
<td>0.348</td>
<td>0.041</td>
<td>0.879**</td>
<td>0.089</td>
<td>0.31</td>
<td>0.197</td>
<td>0.879**</td>
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<tr>
<td></td>
<td>$S_{sub}$</td>
<td>0.601**</td>
<td>0.039</td>
<td>0.519*</td>
<td>0.171</td>
<td>0.601**</td>
<td>0.079</td>
<td>0.417*</td>
<td>0.212</td>
<td>0.601**</td>
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<td>MPS</td>
<td>$R_t/P$</td>
<td>N</td>
<td>N</td>
<td>0.823**</td>
<td>0.098</td>
<td>N</td>
<td>N</td>
<td>0.795**</td>
<td>0.068</td>
<td>N</td>
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<tr>
<td></td>
<td>$R_{sub}/R_t$</td>
<td>N</td>
<td>N</td>
<td>−0.711*</td>
<td>0.659</td>
<td>N</td>
<td>N</td>
<td>−0.519</td>
<td>0.695</td>
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<tr>
<td></td>
<td>$S_{sur}$</td>
<td>N</td>
<td>N</td>
<td>0.807**</td>
<td>0.011</td>
<td>N</td>
<td>N</td>
<td>0.819**</td>
<td>−0.148</td>
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<tr>
<td></td>
<td>$S_{sub}$</td>
<td>N</td>
<td>N</td>
<td>0.608**</td>
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<td>N</td>
<td>N</td>
<td>0.577**</td>
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<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
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</tr>
<tr>
<td></td>
<td>$R_{sub}/R_t$</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>$S_{sur}$</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
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<td>N</td>
</tr>
<tr>
<td></td>
<td>$S_{sub}$</td>
<td>N</td>
<td>N</td>
<td>N</td>
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<td>N</td>
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<tr>
<td>Entire test period</td>
<td>$R_t/P$</td>
<td>0.473**</td>
<td>0.495**</td>
<td>0.387**</td>
<td>0.182</td>
<td>0.483**</td>
<td>0.507**</td>
<td>0.358</td>
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<td>0.474**</td>
</tr>
<tr>
<td></td>
<td>$R_{sub}/R_t$</td>
<td>−0.668**</td>
<td>−0.279</td>
<td>−0.034</td>
<td>0.227</td>
<td>−0.670**</td>
<td>−0.286</td>
<td>0.026</td>
<td>0.227</td>
<td>−0.671**</td>
</tr>
<tr>
<td></td>
<td>$S_{sur}$</td>
<td>0.878**</td>
<td>0.196</td>
<td>0.111</td>
<td>0.048</td>
<td>0.865**</td>
<td>0.181</td>
<td>0.073</td>
<td>−0.01</td>
<td>0.884**</td>
</tr>
<tr>
<td></td>
<td>$S_{sub}$</td>
<td>0.511**</td>
<td>0.065</td>
<td>0.309**</td>
<td>0.057</td>
<td>0.539**</td>
<td>0.072</td>
<td>0.235</td>
<td>−0.048</td>
<td>0.531**</td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.01 level (two-tailed); *correlation is significant at the 0.05 level (two-tailed).
Figure 7 | Relationship of weekly rainfall event times (RE) in the trial period (I), corn planting stage (CPS) (II), summer fallow period (SFP) (III) and mustard planting stage (MPS) (IV) with (a) runoff rate ($R_t/P$) and subsurface flow rate ($R_{sub}/R_t$), (b) surface sediment yield ($S_{sur}$) and subsurface sediment yield ($S_{sub}$). The solid line is the best-fit line; the dotted lines are the 95% confidence bands. The NS represents no significant relationship at $p = 0.05$. NS represents no significant correlation.
S_{sub} in the SFP. MREs presented significant or extremely significant correlations with R_t/P, S_{sur}, and S_{sub} in the MPS. LREs showed no significant relationship with each factor in every stage. TREs presented extremely significant relationships with R_t/P, R_{sub}/R_t, S_{sur}, and S_{sub} throughout the entire test period. HREs only showed a significant relationship with R_t/P. Additionally, MRE and LRE showed no significant relationship with any factor.

Relationship of water and soil migration with rainfall duration

Figure 8 indicates that the weekly RD affected runoff and sediment yield. A total of 66.67% of the weeks in the research period experienced more than 10 hours of accumulated rainfall. A total of 10.48% of the weeks did not experience rainfall (as shown in Figure 8(I)). Figure 8(II), 8(III) and 8(IV) show that weekly RD influenced the R_t/P and S_{sur} in the SFP and MPS, more obviously than those in the CPS. The runoff rate (R_t/P), surface sediment (S_{sur}), and subsurface sediment (S_{sub}) yield presented significant simple linear relationships with RD, but the R^2 values were small. Table 3 shows that the torrential rainfall duration (TRD) was extremely significant with R_t/P, R_{sub}/R_t, S_{sur}, and S_{sub} throughout the entire test period. Heavy rainfall duration (HRD) and moderate rainfall duration (MRD) only showed significant relationships with R_t/P. Additionally, the light rainfall duration (LRD) showed no significant relationship with each factor. The TRD presented extremely significant correlations with the R_t/P, R_{sub}/R_t, S_{sur} and S_{sub}, while the HRD only showed an extremely significant correlation with R_t/P in the CPS. The TRD presented significant or extremely significant correlations with R_t/P, S_{sur}, and S_{sub}, while the HRD only indicated a significant correlation with R_t/P in the SFP. The MRES presented extremely significant correlations with R_t/P and S_{sur} in the MPS. The LRD showed no significant relationship with each factor in every stage.

DISCUSSION

In this study, the annual total loss of surface and subsurface runoff reached 364.7 mm. The annual surface runoff loss was 145.7 mm, basically consistent with the runoff loss amount of 1,431 m^3 ha^{-1} yr^{-1} (converted to 143.1 mm) from research by Luo et al. (2017). The annual loss of subsurface runoff was 219.0 mm, accounting for 60.05% of the total runoff, which is consistent with results from research by Zhu et al. (2009) that showed the annual underground runoff loss accounted for 63% of the total runoff. During a single rainfall event, the amount of underground loss was too small to be noticeable, especially during small rainfall events. However, the average annual cumulative loss load was significant, reaching up to 54.6 kg ha^{-1} yr^{-1}. This is mainly due to the abundance of pores in the cultivated layers of purple soil, which provided channels for prefered flow and sediment migration (Gachter et al. 2004; Kumar et al. 2017). During the rainfall process, raindrops eroded the soil, causing the soil aggregates to break into fine particles (Ramos et al. 2007), resulting in erosion and sediment yield by runoff transport (Shen et al. 2016). Simultaneously, the sediment yields gradually increased with increasing rainfall intensity (Wang et al. 2018). During the infiltration of rainwater, fine sediment particles were carried under partial splash erosion by subsurface flow, especially that of the preferential flow, and migrated downward through soil pores or cracks. The subsoil areas with dense structures and few soil pores (Peng et al. 2014; Zuo et al. 2020) intercepted most of the migrated sediment particles (Wang et al. 2021). However, the parent layer of clastic rock has a large number of cracks, a strong permeability, and a weak water-holding capacity (Qian et al. 2020), which are conducive to the loss of sediment and nutrients. Therefore, sediment appears in the eventual subsurface flow water of the soil. This result is consistent with the discovery by Wang et al. (2021) that the phenomenon of underground sediment migration loss exists in cultivated land with purple soil slopes.

Rainfall is the main driving force of soil and water loss and nutrient loss on sloping cropland. This study found that weekly rainfall, rainfall intensity, rainfall duration, and rainfall frequency have vital effects on runoff and sediment transport. This result is consistent with Liu’s (2016) discovery that rainfall intensity and duration are the main factors affecting runoff and sediment. In addition, the proportion of soil flow to the total rainfall is negatively correlated with rainfall intensity (Ding et al. 2008). Issa et al. (2006) also found that the longer the rainfall duration, the more significant was the effect of the particle size ratio of eroded sediment. Under the same rainfall amount, a longer duration with a lighter rainfall intensity in purple soil would produce more subsurface runoff than a shorter duration with a higher rainfall intensity (Jia et al. 2007). In this study, the increase in weekly rainfall frequency aggravated the runoff and sediment migration of purple soil in sloping croplands. This is mainly because continuous rainfall affects the erodibility of the soil. This result is consistent with findings by Ping (2013) and Zhang et al. (2009) that the steady runoff intensity, runoff amount, and eroded sediment volume in
Figure 8 | Relationship of weekly rainfall duration (RD) in the trial period (I), corn planting stage (CPS) (II), summer fallow period (SFP) (III), and mustard planting stage (MPS) (IV) with (a) runoff rate \( R_t/P \) and subsurface flow rate \( R_{sub}/R_t \), (b) surface sediment yield \( S_{sur} \) and subsurface sediment yield \( S_{sub} \). The solid line is the best-fit line; the dotted lines are the 95% confidence bands. NS means no significant relationship at \( p = 0.05 \). NS represents no significant correlation.
subsequent rainfall events are greater than those in initial rainfall events. This study concluded that runoff and sediment mainly occurred during the maize season and summer fallow period, especially because the rainy season in purple soil area overlapped these two periods, which was actually consistent with the conclusion of Fang et al. (2011) that continuous rainfall in summer was likely to cause soil loss.

CONCLUSION

The time distribution of water and soil loss in the purple soil sloping cropland was uneven. A total of 92.98% of the annual rainfall-runoff loss amount and 99.61% of the annual sediment loss loads occurred during the corn planting stage and the summer fallow period. A total of 60.05% of the annual rainfall-runoff loss occurred underground. Even though the sediment underground loss was small within a single rainfall event, its annual accumulated loss load was considerable, reaching up to 54.6 kg ha\(^{-1}\) yr\(^{-1}\). The rainfall intensity, weekly rainfall frequency, rainfall amount, and rainfall duration significantly affected the runoff rate and surface sediment yield, especially under torrential rain and heavy rain events. The rainfall frequency and duration under torrential rain pattern and heavy rain pattern events exhibited significant relationships with the migrated sediment and runoff. Therefore, the prevention and control of water-soil loss and nutrient loss in purple soil sloping lands should emphatically focus on TR and HR events during the CPS and SFP. This paper aims to provide a theoretical reference for preventing and controlling water, soil, and nutrient loss on purple soil slope cultivated land.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES


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