Experimental Study on the Effects of Rainfall and Runoff Convergence on Hillslope Soil Erosion in the Black Soil Region (Postprint)

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Abstract

Overland flow from upslope areas has a significant impact on slope soil erosion in the black soil region of Northeast China; therefore, distinguishing the effects of rainfall and overland flow on slope soil erosion in this region is of great importance for farmland soil erosion prevention and control. Through simulated rainfall and overland flow experiments designed with different rainfall intensities and flow rates, as well as their combinations, the effects and contributions of rainfall and overland flow on black soil slope erosion were analyzed. The experimental treatments included two rainfall intensities (50 mm/h and 100 mm/h), two overland flow rates (50 mm/h and 100 mm/h, i.e., 10 L/min and 20 L/min), and four combinations of different rainfall intensities and flow rates ((50+50) mm/h, (50+100) mm/h, (100+50) mm/h, and (100+100) mm/h). The results showed that the slope erosion caused by overland flow at 50 mm/h and 100 mm/h was only 1.9% and 0.6% of that caused by rainfall at 50 mm/h and 100 mm/h, respectively; when rainfall intensity and upslope overland flow rate were increased from 50 mm/h to 100 mm/h, slope erosion under rainfall treatment increased by 6.1-fold, while under overland flow treatment it increased by 3.2-fold, indicating that rainfall has a significantly greater effect on slope soil erosion than overland flow. In the combined rainfall and overland flow experiments, when the total water supply intensity (rainfall intensity + flow rate) was 150 mm/h, the slope erosion in the combination of rainfall intensity 100 mm/h and flow rate 50 mm/h was 7.9 times that in the combination of rainfall intensity 50 mm/h and flow rate 100 mm/h. Under the same overland flow conditions, when rainfall intensity increased from 50 mm/h to 100 mm/h, the contribution rate of rainfall intensity increase to slope erosion was 89.6%-99.5%; whereas under the same rainfall conditions, when slope overland flow rate increased from 50 mm/h to 100 mm/h, the contribution rate of flow rate increase to slope erosion was 17.2%-78.7%, demonstrating that controlling overland flow is also particularly

important for slope soil erosion prevention in the black soil region of Northeast China.

Full Text

Preamble

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An Experimental Study on the Impacts of Rainfall and Inflow on Hillslope Soil Erosion in Typical Black Soil Regions

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Abstract

Upslope runoff has a significant influence on hillslope soil erosion in typical black soil regions of Northeast China. However, few attempts have been made to clearly distinguish the effects of rainfall and upslope runoff on hillslope soil erosion. Quantifying the contributions of rainfall and upslope runoff to hillslope soil loss is important for providing a scientific basis for preventing and controlling hillslope erosion in black soil regions. This study used simulated rainfall and inflow experiments to investigate how rainfall and inflow affect hillslope soil erosion and estimated their contributions to soil loss in typical black soil regions.

The black soil used in this experiment was collected from Yushu City in Jilin Province, and the experiment was conducted in the simulation rainfall hall of the Institute of Soil and Water Conservation. A rainfall simulator with lateral spraying nozzles, 16 m above the ground, was used to simulate rainfall. An overflow tank attached to the upper end of the soil pan supplied the inflow. The soil pan (8 m long, 3 m wide, and 0.5 m deep) was divided into two sub-pans by PVC sheets.

The experimental design included two rainfall intensities (50 mm/h and 100 mm/h), two inflow rates (50 mm/h and 100 mm/h, equal to 10 L/min and 20 L/min, respectively), and combinations of the two rainfall intensities and two inflow rates (50 mm/h rainfall + 50 mm/h inflow, 50 mm/h rainfall + 100 mm/h inflow, 100 mm/h rainfall + 50 mm/h inflow, 100 mm/h rainfall + 100 mm/h inflow). All experiments were run at a 10° slope gradient for a duration of 100 min, with two replications per treatment. During the experiment, runoff samples were collected every 2 min with a 15 L bucket, and the weight of dried sediment was used to calculate the erosion rate.

Results showed that soil loss caused by 50 mm/h and 100 mm/h inflow rates only occupied 1.9% and 0.6% of soil loss induced by 50 mm/h and 100 mm/h rainfall intensities, respectively. With increasing rainfall intensity from 50 mm/h to 100 mm/h, soil loss increased 6.1 times, and with increasing inflow rate from 50 mm/h to 100 mm/h, soil loss increased 3.2 times, indicating that the influence of rainfall intensity on soil loss is greater than that of inflow rate.

Regarding the combination treatments of rainfall and inflow, when the total water supply was 150 mm/h, the soil loss under 100 mm/h rainfall intensity + 50 mm/h inflow rate was 11.52 kg, which was 7.9 times higher than that under 50 mm/h rainfall intensity + 100 mm/h inflow rate. Under a constant 50 mm/h inflow rate or 100 mm/h inflow rate, when rainfall intensity changed from 50 mm/h to 100 mm/h, the increased rainfall intensity contributed to 89.6%-99.5% of the soil loss. Under constant 50 mm/h rainfall intensity or 100 mm/h rainfall intensity, when inflow rate varied from 50 mm/h to 100 mm/h, the increased inflow rate contributed to 17.2%-78.7% of the soil loss. These results indicate that controlling upslope runoff is also an important way to reduce hillslope soil erosion in typical black soil regions.

Keywords: rainfall; upslope inflow; contribution rate; black soil hillslope; soil erosion

Introduction

Soil erosion in Northeast China' s black soil region causes the black topsoil to decrease at a rate of 0.3-1.0 cm per year. The average soil thickness has decreased from 60-70 cm to the current 20-30 cm, leading to severe soil degradation and reduced land productivity, which constrains the sustainable utilization of black soil resources and affects national food security [1-2]. Due to differences in soil anti-erodibility and the influence of hillslope runoff convergence, the effects of raindrop impact and runoff transport on hillslope soil erosion vary under different environmental conditions [3]. Walker et al. found that the sediment yield rate under rainfall erosion is several times higher than that under runoff erosion with equivalent runoff volume [4]. Zheng Fenli et al., based on double-cumulative simulated rainfall experiments, found that sediment yield from rainfall erosion was greater than that from water-supply runoff erosion under the same slope gradient and runoff conditions [5-6]. Other scholars have found that rainfall and runoff interact to either assist or constrain each other during the erosion process [7-8]. Guy et al. found that raindrop contribution to sediment transport capacity in disturbed flow was 46% [9], while Palmer et al. found that when flow depth exceeds raindrop diameter, the effect of raindrop impact on soil erosion decreases significantly [10-11]. Although research on the effects and contributions of rainfall and runoff to hillslope erosion has made progress, it remains difficult to distinguish their roles in the erosion process due to experimental conditions and erosion processes [12].

In Northeast China' s black soil region, the long and gentle slope topography makes it easy to form large hillslope runoff when rainfall amount and intensity are high, which causes concentrated scouring of hillslope soil and severe erosion [13-16]. Currently, research on the roles of rainfall and runoff in hillslope erosion in black soil regions is scarce. Therefore, it is urgent to investigate the combined effects of rainfall and runoff on black soil hillslope erosion to provide theoretical guidance for erosion control. Based on simulated rainfall and upslope inflow experiments, this study designed experimental treatments with different rainfall intensities, inflow rates, and their combinations to investigate the effects of rainfall and inflow on black soil hillslope erosion, analyze their contributions to hillslope erosion, and provide theoretical support and scientific basis for the layout of farmland soil erosion control measures in black soil regions.

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1. Experimental Materials

The experimental soil was collected from Heixin Village, Liujia Town, Yushu City, Jilin Province (44°43 28 N, 126°11 47 E). Yushu City belongs to the typical black soil region, and the soil is representative of the study area. The soil particle size classification standard used was the USDA system. The 0-20 cm soil layer had a bulk density of 1.15 g/cm^3, organic matter content of 23.8 g/kg, pH of 6.5, and soil texture classified as silt loam with 76.4% silt (0.05-0.002 mm), 20.3% clay (<0.002 mm), and 3.3% sand (>0.05 mm).

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2. Experimental Apparatus and Design

The experiment was conducted in the artificial simulation rainfall hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau in June 2016. The rainfall equipment was a lateral-spray automatic rainfall simulator [17] with a rainfall height of 16 m, intensity range of 20-300 mm/h, and uniformity greater than 85%. The simulated rainfall characteristics were similar to natural rainfall.

The experimental soil pan measured 8 m (length) × 3 m (width) × 0.6 m (depth) and was divided into two 8 m × 1.5 m sub-pans by a PVC sheet for replicate experiments. The pan bottom had drainage holes every 10 cm, filled with gauze to ensure good drainage. To simulate farmland conditions, the pan was filled in layers: a 10 cm layer of fine sand at the bottom, followed by 10 cm of black soil with bulk density of 1.35 g/cm^3 to simulate the plow pan, and 20 cm of black soil with bulk density of 1.20 g/cm^3 to simulate the cultivated layer. During filling, each 5 cm layer was tamped to ensure uniformity. After filling, the surface was raked with a 20 cm deep rake to create roughness and ensure good adhesion between layers.

The upslope inflow apparatus consisted of a water supply pipe, constant pressure tank, and flow stabilizing trough. Water first entered the constant pressure tank to maintain stable pressure, with excess water returning via an overflow pipe. The water valve then regulated the designed inflow rate, which was delivered to the stabilizing trough at the top of the soil pan to create uniform flow over the slope, simulating upslope runoff effects.

Based on field investigations, rainfall in Northeast black soil region is characterized by short-duration, high-intensity events, mostly lasting less than 100 minutes with high instantaneous intensity [2, 18]. Slope gradients vary from 3° to 10° [19]. Therefore, this experiment used a 10° slope gradient and 100 min duration. Two rainfall intensities were designed: 50 mm/h (0.83 mm/min) and 100 mm/h (1.67 mm/min) [20]. To compare rainfall and inflow effects at equivalent intensities, two inflow rates were set: 50 mm/h (10 L/min) and 100 mm/h (20 L/min). Four combined treatments were created from different rainfall intensity and inflow rate combinations (Table 1).

[Figure 1: see original paper] Experimental devices

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3. Experimental Procedure

Before each experiment, to maintain consistent initial soil moisture, a pre-rainfall at 25 mm/h was applied until continuous flow appeared at the outlet, then the pan was covered with plastic sheeting for 24 h to allow water infiltration and approach natural soil moisture distribution. Measured soil moisture data showed that 0–20 cm surface soil moisture content was basically consistent across experiments at 28.6%–29.7%.

Before each formal experiment, the designed rainfall intensity and inflow rate were calibrated. Experiments proceeded only when the difference between measured and target values was less than 5%. When slope runoff began, runoff samples were collected every 2 min at the outlet using plastic buckets. Flow velocity was measured using the dye method. After the experiment, all runoff samples were weighed, clear supernatant was decanted, and sediment was oven-dried at 105°C for 24 h, then weighed to calculate sediment amount.

Experimental design

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4. Data Analysis

Data were processed and analyzed using Excel 2003 and SPSS 13.0, with charts created accordingly. Duncan' s method was used for multiple comparisons.

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5. Results and Discussion

5.1 Comparison of Hillslope Erosion and Sediment Yield Under Rainfall and Inflow

When rainfall intensity and upslope inflow rate were both 50 mm/h (inflow rate = 10 L/min), runoff differences were not significant, but hillslope erosion and sediment concentration showed significant differences. Erosion and sediment concentration under inflow conditions were only 2.6% and 0.9% of those under rainfall conditions, respectively.

When rainfall intensity and upslope inflow rate were both 100 mm/h (inflow rate = 20 L/min), runoff, erosion, and sediment concentration also showed significant differences. Under inflow conditions, runoff, erosion, and sediment concentration were 80.1%, 0.6%, and 0.6% of those under rainfall conditions, respectively.

When rainfall intensity and upslope inflow rate increased from 50 mm/h to 100 mm/h, erosion under rainfall treatments increased 6.1 times, while erosion under inflow treatments increased 3.2 times. This indicates that rainfall impact on hillslope soil erosion and sediment yield is significantly greater than inflow effects. The main reason is that the experimental soil was organic-rich Northeast black soil with high aggregate and clay content [21], making it less susceptible to destruction and transport by inflow [22], far less than inflow effects on loess slopes [23]. During rainfall, rapid wetting by raindrop impact not only destroys soil aggregate structure but also increases flow turbulence, enhancing runoff dispersion and transport capacity [24]. An Juan et al. showed that eliminating raindrop impact with mesh covering could reduce black soil hillslope erosion by over 80% [25], demonstrating that rainfall is the main driver of soil erosion on black soil slopes. After eliminating raindrop impact, runoff effects on black soil erosion decreased, indicating that for effective erosion control, measures like straw mulching can reduce raindrop impact force and prevent slope erosion [26].

Hillslope runoff, soil loss, and sediment concentration under different rainfall and inflow treatments

5.2 Effects of Rainfall on Black Soil Hillslope Erosion Processes

Under 50 mm/h rainfall intensity, runoff began at 22 min; under 100 mm/h, at 12 min. The erosion rate under 100 mm/h was significantly greater than under 50 mm/h. Under both intensities, erosion rate increased rapidly then stabilized. The main reason is that erosion patterns changed. Initially, raindrop splash produced large amounts of dispersed particles transported by thin water layers, creating the first erosion peak. Subsequently, temporary crust formation reduced erosion capacity, causing erosion rate to decline and stabilize. As rainfall continued, the slope surface became uneven from raindrop impact, thin flow concentrated into rills, and multiple rill heads formed, creating a second erosion peak. The erosion rate fluctuated in waves. This process is consistent with Zheng Fenli' s research on loess slope erosion processes [27].

[Figure 2: see original paper] Erosion rate versus rainfall duration at rainfall intensities of 50 mm/h and 100 mm/h

5.3 Effects of Inflow on Black Soil Hillslope Erosion Processes

Under 50 mm/h inflow rate, runoff began at 24 min; under 100 mm/h, at 17 min. After runoff began, erosion rate decreased rapidly then stabilized. The maximum erosion rate occurred at 1-4 $g/m^2 \cdot min$, then stabilized and fluctuated between 1-4 $g/m^2 \cdot min$. The reason is that during initial inflow, the loose soil surface was easily dispersed, separated, and transported. As the experiment progressed, broken surface materials clogged soil pores, forming temporary crust that reduced inflow erosion capacity, maintaining low erosion rates. Slope erosion was dominated by sheet erosion [28].

[Figure 3: see original paper] Erosion rate versus inflow duration at inflow rates of 50 mm/h and 100 mm/h

5.4 Combined Effects of Rainfall and Inflow on Black Soil Hillslope Erosion

5.4.1 Hillslope Erosion and Sediment Yield Under Different Rainfall-Inflow Combinations When rainfall intensity and upslope inflow rate increased from 50 mm/h to 100 mm/h ($R_{50}I_{50}$ to $R_{100}I_{100}$), runoff increased only 16.2%, while erosion and sediment concentration increased 181.7% and 132.2%, respectively. This shows that under combined raindrop impact and inflow scouring, hillslope erosion increased significantly.

Comparing treatments with the same total water supply but different rainfall and inflow rates revealed their relative importance. At 150 mm/h total supply, the $R_{100}I_{50}$ and $R_{50}I_{100}$ treatments showed significant differences in runoff, erosion, and sediment concentration. $R_{100}I_{50}$ runoff, erosion, and sediment concentration were 81.2%, 12.6%, and 16.2% higher than $R_{50}I_{100}$, respectively. This demonstrates that while upslope inflow affects black soil erosion, its effect is smaller than raindrop impact.

At 100 mm/h total supply, comparing $R_{50}I_{50}$ and R_{100} treatments (same rainfall, different inflow) showed similar runoff but significantly different erosion. R_{100} erosion was 18 times that of $R_{50}I_{50}$, and its sediment concentration was 7.9 times higher, indicating that inflow rate increase accelerates rill erosion development [29].

Comparison of total runoff, soil loss, and sediment concentration under different rainfall and inflow combination treatments

5.4.2 Combined Effects on Erosion Processes For $R_{50}I_{50}$ and $R_{50}I_{100}$ treatments, runoff began at 16 min and 13 min, respectively. After runoff began, erosion rate decreased rapidly then stabilized. Compared to R_{50} treatment, adding upslope inflow enhanced flow turbulence, increasing inflow' s soil detachment capacity and causing erosion rate to increase sharply.

Comparing $R_{100}I_{50}$ and $R_{100}I_{100}$ treatments (runoff at 9 min and 6 min), erosion rate fluctuated with rainfall duration. Raindrop impact dispersed soil particles while inflow transported them. Increased inflow rate accelerated rill development [29]. The analysis shows that rainfall and inflow contributions to hillslope soil erosion interact and should be examined together.

[Figure 4: see original paper] Erosion rate versus rainfall duration under different rainfall and inflow combination treatments

5.5 Contribution Analysis of Rainfall and Inflow to Black Soil Hillslope Erosion

The contribution rate of increased rainfall intensity to runoff and erosion can be calculated as:

$$RR = (R_{100} - R_{50}) / (R_{100} - R_0) \times 100\%$$

where RR is the contribution rate of increased rainfall intensity to runoff, R_{100} and R_{50} are runoff under 100 mm/h and 50 mm/h rainfall with same inflow rate, and R_0 is runoff under 0 mm/h rainfall (inflow only).

Similarly for erosion contribution:

$$RE = (E_{100} - E_{50}) / (E_{100} - E_0) \times 100\%$$

The contribution rate of increased inflow rate can be calculated analogously.

5.5.1 Rainfall Contribution Analysis Comparing $R_{50}I_{50}$ vs R_0I_{50} and $R_{100}I_{50}$ vs R_0I_{50} (same inflow, different rainfall), rainfall contributed 41.44%–58.65% to runoff and 89.58%–99.50% to erosion. Comparing $R_{50}I_{100}$ vs R_0I_{100} and $R_{100}I_{100}$ vs R_0I_{100}, rainfall contributed 46.94%–48.13% to runoff and 97.93%–99.95% to erosion. The average contribution to erosion was 73.90% under 50 mm/h inflow and 99.9% under 100 mm/h inflow.

Increased rainfall intensity significantly contributed to erosion because it enhanced soil particle dispersion and transport. Besides raindrop splash, increased rainfall intensity intensified thin flow turbulence, increasing disturbance and friction between soil particles, making them easier to transport. More importantly, increased rainfall intensity shifted erosion from sheet to rill erosion. Sediment transport capacity is proportional to flow velocity cubed. Measured flow velocity data showed that increasing rainfall from 50 mm/h to 100 mm/h increased flow velocity by 72.40% under 50 mm/h inflow and 28.21% under 100 mm/h inflow, significantly increasing runoff scouring force and erosion.

5.5.2 Inflow Contribution Analysis Comparing $R_{50}I_{50}$ vs $R_{50}I_0$ and $R_{50}I_{100}$ vs $R_{50}I_0$ (same rainfall, different inflow), inflow contributed 28.64%-58.81% to runoff and 17.24%-78.74% to erosion. Comparing $R_{100}I_{50}$ vs $R_{100}I_0$ and $R_{100}I_{100}$ vs $R_{100}I_0$, inflow contributed 61.28%-72.12% to runoff and 46.90%-89.94% to erosion.

Increased inflow rate also significantly contributed to erosion because upslope inflow is the medium for water energy transfer between different slope positions. Its magnitude affects infiltration and runoff rates downstream and shifts erosion from sheet to rill erosion, increasing transport capacity. Measured flow velocity showed that increasing inflow from 50 mm/h to 100 mm/h increased velocity by 10.55%-19.84% under 50 mm/h rainfall and 28.21% under 100 mm/h rainfall, enhancing runoff scouring force and increasing erosion.

Contribution rates of rainfall to runoff and erosion on black soil slopes

Contribution rates of inflow to runoff and erosion on black soil slopes

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6. Conclusions

Based on simulated rainfall and upslope inflow experiments with different rainfall intensities, inflow rates, and their combinations, this study investigated rainfall and inflow effects on black soil hillslope erosion and analyzed their contributions. Main conclusions are:

1. In separate rainfall and inflow experiments, when rainfall intensity increased from 50 mm/h to 100 mm/h, runoff and erosion increased 6.1 times and 3.2 times, respectively. When inflow rate increased from 50 mm/h to 100 mm/h, runoff and erosion increased accordingly. This demonstrates that rainfall impact on hillslope soil erosion is significantly greater than inflow effects.

2. In combined rainfall-inflow experiments, at 150 mm/h total water supply, the $R_{100}I_{50}$ treatment (100 mm/h rainfall + 50 mm/h inflow) produced runoff and erosion 7.9 times greater than the $R_{50}I_{100}$ treatment (50 mm/h rainfall + 100 mm/h inflow). The former was dominated by rill erosion, while the latter was dominated by sheet erosion.

3. Under constant inflow conditions, increased rainfall intensity contributed 89.6%-99.5% to erosion. Under constant rainfall conditions, increased inflow rate contributed 17.2%-78.7% to erosion. This indicates that controlling upslope runoff is also crucial for erosion control in Northeast black soil regions.

Further research is needed on the interaction mechanisms between rainfall and inflow affecting hillslope soil erosion characteristics.

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