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The impacts of *Robinia pseudoacacia* litter cover and roots on soil erosion in the Loess Plateau, China

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**ABSTRACT**

The impacts of vegetation on soil erosion are closely associated with the combined effects of above- and below-ground components. In this study, we explore the effects and contributions of *Robinia pseudoacacia* litter cover and roots on soil erosion. Experiment sites under natural conditions with vegetation cover, plant roots and bare ground plots were investigated for overland flow discharges of 0.5, 1.0 and 2.0 L s$^{-1}$ and slope gradients of 8.7%, 17.6%, 26.8%, 36.4% and 46.6%. Results indicate that litter cover and roots have a significant impact on sediment reduction; soil loss was reduced by about 57% and plant roots had a greater impact on the reduction of soil erosion than litter cover. The combination of litter cover and plant roots had a significant effect on decreasing $K_r$, increasing $\tau_c$ and consequently strengthening soil resistance capacity to erosion. When plants and roots existed on the slopes, $K_r$ decreased by 81% and 66%, and $\tau_c$ increased by 319% and 246%, respectively, in comparison with bare slopes. These results illustrate the importance of high-forest in controlling soil erosion by quantifying the specific contributions of litter cover and plant roots in erosion reduction in the Loess Plateau.

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**KEYWORDS**

Critical shear stress; litter cover; roots; *Robinia pseudoacacia*; soil erodibility; soil erosion

**Introduction**

Soil erosion has become a serious and widespread eco-environmental problem, resulting in partial removal of topsoil, the loss of soil nutrients, which can significantly decrease soil productivity; soil erosion is also a natural disaster that can directly threaten human safety [1–3]. The Loess Plateau of China has been severely affected by soil erosion; approximately one-third of this region (2.5 × 10$^5$ km$^2$) suffers from serious soil erosion and two-thirds of the region (about 4.3 × 10$^5$ km$^2$) is affected to some extent by soil loss. Research has shown that, large amounts of sediment eroded form the Loess Plateau has been transported into the Yellow River. Investigations into reducing soil loss in this area to ameliorate the ecosystem have therefore become increasingly significant [4–7]. Planting vegetation has been considered as the most effective method to reduce soil erosion, and has been used effectively in soil and water conservation [8]. In order to decrease soil and water...
loss and to improve the ecological state of the environment in the Loess Plateau, the Chinese Government implemented the ‘Grain for Green’ policy in 1999, which aimed to reduce soil erosion by converting farmland on steep slopes of the plateau to woodlands and grasslands [9].

In general, soil erosion can be divided into three processes: detachment, transportation and deposition of soil material [10] and it is affected by many factors, such as soil properties (e.g. soil type, organic matter, soil water content, cohesion and soil consolidation), plant properties (e.g. litter cover, roots and residue), hydraulic characteristics (e.g. velocity, flow discharge and slope gradient) and land use. Brown et al. [11] showed that soil erosion decreased when soil consolidation increased. Knapen et al. [12] demonstrated that soil erodibility \((K_c)\) decreased and critical shear stress \((\tau_c)\) increased with an increase of soil water content and organic matter, and they developed a regression equation to show that soil parameters can control soil erodibility. Soil erosion also increases significantly with an increase of slope gradient and flow discharge [10,13]. Zhang et al. [14] showed that soil detachment rates are greatly influenced by land use: croplands, grasslands, shrub-lands, wastelands and woodlands were characterised in order of decreasing soil detachment capacity.

Apart from soil properties, hydraulic characteristics and land use, soil erosion is also strongly affected by vegetation cover. Previous studies have reported that vegetation cover has an important impact on the amount of soil loss. It is difficult however to identify which specific component of vegetation cover is the most important. Litter cover has been considered to be the only factor in reducing soil erosion by enhancing topsoil roughness, absorption of raindrops and scattering runoff, but the impact of plant roots on soil loss has not been extensively investigated. As highlighted by De Beats et al. [15], soil erosion rates due to overland flow were significantly reduced after the occurrence of fires or intensive grazing, suggesting that, even in a situation where the above-ground biomass has been removed, plant roots remaining in the soil play an important role in reducing soil erosion. Therefore, the combination of litter cover and plant roots may result in a reduction in the amount of soil loss during erosion [16]. Another issue that remains unresolved is the specific contribution of both above- and below-ground biomass to the reduction of soil erosion. Gyssels et al. [16] suggested that for splash and rill erosion, litter cover was more important than plant roots. In contrast to Gyssels et al. [16], Zhou and ShangGuan [17] reported that plant roots can decrease sediment yields by up to 96% in rainfall simulation experiments. The different findings of these investigations may be due to different climatic conditions and vegetation cover.

The majority of studies on soil loss reduction have focused on the effect of croplands, grasslands and orchards under controlled laboratory circumstances. Few studies have investigated the effect of woodlands on soil erosion reduction, and even less has been conducted in situ; controlled experiments under natural environments are more suitable to reflect changes of samples. The aims of this research are: (i) to investigate the specific role of litter cover in soil erosion, and to further clarify the influence of different litter cover depths on soil erosion due to an increase of overland flow; (ii) to investigate the distribution of plant roots in the top soil layers and examine the effect of root density and root diameter on soil erosion; (iii) to explore the relative contribution of *R. pseudoacacia* litter cover and roots to the reduction of soil erosion under different slope gradients and flow discharges; (iv) to quantify the differences in soil resistance to erosion reflected
by differences in soil erodibility ($K_r$) and critical shear stress ($τ_c$) for slopes containing above-ground vegetation, slopes only with roots present and bare slopes.

**Materials and methods**

**Site description**

Experiments were undertaken in the Caijiachuan watershed in Ji County, Shanxi Province, China (E 110°39′45″–110°47′45″, N 36°14′27″–36°18′23″, 950–1370 m altitude) (Figure 1). This area is a typical broken and gully region of the Loess Plateau. The watershed has a semi-arid continental climate with a mean annual precipitation of 576 mm, which is unevenly distributed throughout the year. The average annual temperature is around 10°C; the absolute maximum temperature is 38.1°C and the minimum temperature is −20.4°C. The soil in this region is loess parent material with a uniform texture. The major forms of land use are woodlands, shrub-lands, grasslands, secondary forests, orchards, crops and wastelands. The total forest coverage is around 39.8%. The most frequently planted tree species in this region include *Pinus tabuliformis*, *R. pseudoacacia* and *Platycladus orientalis*, which are often interspersed with shrubs such as *Hippophae rhamnoides* and *Ostryopsis davidiana*. The orchard species are mainly *Malus pumila*, *Prunus armeniaca* and *Pirus*.

**The experiment plot**

As *R. pseudoacacia* was the most commonly planted species in the study region since 1994, we selected this species as the investigation vegetation. The mean height and
diameter at breast height of this tree species were 9.8 m and 29.6 cm, respectively. Some understory vegetation was present in the studied plots, and the surface soil of the study areas was completely covered by a litter layer. To investigate the impact on soil erosion on both slope gradient and flow discharge, five slope gradients (8.7%, 17.6%, 26.8%, 36.4% and 46.6%) and three flow discharges (0.5, 1.0 and 2.0 L/s) were tested in 20 × 20 m plots. For each slope gradient, a control reference plot having a bare slope surface was also tested. The experiments were conducted over the course of June–August 2012.

**Soil erosion test**

To measure soil erosion, we inserted a steel plate (4 m long and 0.15 m wide) along the soils that had an enclosed rectangular flume separated by 0.1 m, and a scouring area of 0.4 m². A Mario Bottle with a volume of 200 L was placed at the upper end of the flume to supply water to the flume system. Water release was controlled by a valve to ensure a stable water yield and flow rate. In the bottom of the flume, a steel box and a plastic bottle were positioned to collect sediment and runoff. The flow velocity (\(V_f\)) of the slopes was measured using KMnO₄ colouration technique with five replicates under a stable flow condition. The average flow velocity (\(V_a\)) was calculated as follows:

\[
V_a = KV_f,
\]  

where \(K\) is a coefficient value of 0.8 [18,19].

Flow depth was achieved using the equation of:

\[
H = \frac{Q}{BV_a},
\]  

where \(H\) is the flow depth (m); \(Q\) is the flow discharge (m³ s⁻¹); \(B\) is the flume width (m); and \(V_a\) is the average value of the flow velocity (m s⁻¹) [4,10]. Shear stress was calculated as

\[
\tau = \rho ghS,
\]  

where \(\tau\) is the shear stress(Pa); \(\rho\) is the water mass density (kg m⁻³); \(g\) is the gravity constant (m s⁻²); \(h\) is the flow depth; and \(S\) (fraction) is the slope gradient.

For different combinations of slope gradients and flow discharges, shear stress of plant, roots and bare slopes ranged from 4.06 to 15.73, 3.57 to 11.29, and 1.17 to 6.88 Pa, respectively.

In order to attain the uniform antecedent soil moisture content among different treatments, different volumes of water were added to the soil with a household sprayer, prior to the experiment. The tests were stopped when the amount of sediment water in the plastic bottles reached 500 mL; after which the sediment in the steel box was transferred into the plastic bottle. After completing the tests with the litter cover, litter cover was removed and the experiment was repeated using the same methodology. For each flow discharge and slope gradient combination, all treatments had five repetitions with the litter cover present, litter cover removed and under bare soil conditions. A total of 225 experiment runs were undertaken. All of the sediment containers were returned to the laboratory, where the sediments were oven dried at 105°C for 24 h and weighed after being filtered. The average value of the dried soil weights was then considered to represent the amount of soil erosion.
The rates of soil loss reduction by total plant \((E_p)\), roots \((E_r)\) and litter cover \((E_l)\) were calculated as follows:

\[
E_p = \frac{S_b - S_p}{S_b} \times 100\%,
\]

\[
E_r = \frac{S_b - S_r}{S_b} \times 100\%,
\]

\[
E_l = E_p - E_r,
\]

where \(S_b\), \(S_p\) and \(S_r\) are the sediment yields of the bare, total plant and root slopes, respectively. Soil reduction on the slope with plants was attributed to the combined effects of roots and litter cover. Contribution rate of roots \((C_r)\) and litter cover \((C_l)\) were then separately calculated as

\[
C_r = \frac{E_r}{E_p} \times 100\%
\]

\[
C_l = \frac{E_l}{E_p} \times 100\%.
\]

The relative soil erosion capacity \((RE_c)\) was calculated as the proportion of soil erosion for the five litter cover depths to soil erosion of the bare slopes. Rill erodibility \((K_r)\) and critical shear stress \((\tau_c)\) were viewed as the most important indicators of soil resistance capacity to erosion [20]. Nearing et al. [21] established a linear regression relationship between erodibility and shear stress using a WEPP model, which is expressed as

\[
E_c = K_r(\tau - \tau_c),
\]

where \(E_c\) is soil erosion rate \((g \, L^{-1})\) and \(\tau\) is the shear stress \((Pa)\).

**Measurements of leaf litter depth and roots**

To analyse the effect of litter depth and roots on soil erosion, five slopes for each plot were used with five repetitions to obtain a mean value. The litter of *R. pseudoacacia*, being composed of leaves and several twigs, was measured (accuracy to the nearest cm) from the top of the level that was not decomposed to the bottom of the semi-decomposed level before the soil erosion test. The litter depths were classified into the following ranges: 0–1, 1–2, 2–3, 3–4 and 4–5 cm. After each soil erosion test was completed, soil samples were excavated from the top 40 cm soil layers with a 10 cm interval (0–10, 10–20, 20–30 and 30–40 cm), using a circular root drill with a 7 cm diameter. The drill was pressed down slowly into the soil to fill the drill chamber with roots and soil, after which the samples were stored in sealed bags [19]. Roots were extracted by hand washing in the laboratory [22]. The samples were immersed in tap water for about 1 h to increase soil dispersion, then being placed on a 0.5 mm sieve and washed with water. Material collected in the sieve consisted of roots, some soil particles and plant debris. Roots were selected individually using tweezers and placed on paper carefully to ensure they did not overlap. The roots were then divided into three categories on the basis of their diameter: fine roots \((<1.0 \, mm)\), medium roots \((1.0–5.0 \, mm)\) and coarse roots \((>5.0 \, mm)\). All roots were then oven dried for about 48 h at \(\sim 60^\circ C\) and weighed to calculate root density \((RD \, kg \, m^{-3})\).
RD was calculated as:

$$RD = \frac{M_d}{V}, \quad (7)$$

where $M_d$ is the mass of dry living roots (kg) and $V$ is the volume of the soil samples (m$^3$).

**Data analysis**

Relationships between soil erosion, root density and root diameter were analysed using Pearson correlation coefficients. The simple linear and nonlinear regression models were calculated to investigate the effects of root density on sediment yield, the relationship between $RE_c$ and litter cover depths, and soil erosion rate and $\tau$. The regression results were determined by the coefficient of determination. All statistical analyses were performed in SPSS 19.0.

**Results and discussion**

**Effects of litter cover on soil erosion**

Results from our analysis showed that different depths of litter cover markedly influenced soil erosion capacity and that slopes with litter cover had much smaller sediment yields than bare slopes (Figure 2). The mean sediment yields for the five slope gradients (8.7%, 17.6%, 26.8%, 36.4% and 46.6%) with litter cover ranged from 0.2 to 0.8, 0.41 to 0.9, 0.53 to 1.15, 1.03 to 1.67 and 1.62 to 2.52 g/L, having mean values of 0.43, 0.58, 0.80, 1.34 and 1.95 g/L, respectively. Sediment yields for bare slopes ranged from 1.03 to 6.48 g/L. In comparison to bare slopes, the mean volume of soil erosion for each of the slope gradient decreased by 57.9%, 61.6%, 63.6%, 66.3% and 70%, respectively. However, for a slope gradient of 8.7% and 17.6%, the lower quartile of the box and the minimum value at litter cover depths of 0–1 cm were slightly higher than those of the bare slopes (Figure 2). A possible explanation may be that soil consolidation and soil erosion resistance were fragile under conditions of sparse litter cover; litter cover was therefore not sufficient to properly protect the surface soil.

Soil erosion presented a similar decreasing trend with an increase in litter cover depth. Results for the five litter cover depths showed that soil erosion was much smaller than that recorded on the bare slopes. Significant differences between litter cover depths were recorded for 0–1, 1–2 and 2–3 cm depths; no significant differences were recorded for depths of 3–4 and 4–5 cm (Figure 2). This indicated that a litter cover depth of 3 cm seems to effectively protect against soil erosion due to water flow, soil erosion related to higher litter cover depths maintained a stable low value. Brown et al. [11] suggested that the impact of vegetation cover on soil erosion consisted of mechanical and biological components, while sediment decrease was related to the biological decomposition rate. In our investigation, undecomposed litter cover inhibited raindrops from directly striking the soil surface and enhancing the surface roughness. It thereby effectively reduced the flow velocity and increased soil infiltration due to delayed runoff.

The mean relative soil erosion ($RE_c$) varied from 0.37 to 0.48, 0.29 to 0.41, 0.25 to 0.36, 0.16 to 0.28 and 0.13 to 0.27 for the five litter cover depths, respectively. The
RE_c decreased exponentially with increasing litter cover depth in each of the five slope gradients; all of the correlation coefficients ($R^2$) were higher than 0.9 (Figure 3). Relative soil erosion and litter cover depth had a negative exponential relationship, results which were consistent with previous studies on plant litter [16,23] and grass litter [19,24]. The coefficients of the exponential equations for the different slopes were: $-0.253$, $-0.219$, $-0.203$, $-0.162$ and $-0.129$. Poesen et al. [25] suggested that the regression coefficient indicated the effectiveness of plant litter cover in reducing soil erosion, thereby implied that the coefficient described the impact of litter cover depth on erosion processes. Differences between the regression coefficients from our experiment slopes may be due to litter shapes, soil properties, decomposition rates and climate [11]. In our investigation, soil properties and climate were the same and plant litter cover had a relatively low decomposition rate. This therefore suggested that the differences in coefficients were due to the combined effect of different slopes and litter shapes.

**Analysis of correlation between soil erosion and plant roots**

The roots of *R. pseudoacacia* in all slopes were predominantly distributed in the upper-most layers in the soil (Figure 4). With an increase in soil depth, the biomass of the roots significantly decreased and the three diameter root types had an uneven
Figure 3. Relationships between REc and Litter cover depth (Lc) for different slope gradients. The signs are the mean relative soil erosion under three flow discharges. (REc = e^{-0.253Lc}; R^2 = 0.97; P < .001; ●, solid line; 8.7%, REc = e^{-0.219Lc}; R^2 = 0.90; P < .001; ○, dashed line; 17.6%, REc = e^{-0.203Lc}; R^2 = 0.95; P < .001; ▽, dot line; 26.8%, REc = e^{-0.162Lc}; R^2 = 0.97; P < .001; △, dashed line; 36.4%, REc = e^{-0.129Lc}; R^2 = 0.98; P < .001; ■, solid line; 46.6%).

Figure 4. Vertical distribution of root biomass for soils with different slopes.
occurrence with depth. For all of the slope gradients, results showed that fine roots varied more significantly than medium roots or coarse roots, especially on the slope gradient of 46.6%. In order to investigate soil erosion reduction caused by roots, we separately applied a correlation analysis between soil erosion and both root diameter and root density (Table 1). The results showed that soil erosion was positively correlated with root density in the top soil layers (0–30 cm depth) and the distribution of the roots directly influenced sediment yields; for each slope gradient, the mean sediment yield decreased as root density increased (Figure 5). Similar to the findings of Zhang et al. [26], the reduction in sediment yields mainly occurred with a root density interval of 0–0.5 kg m$^{-3}$, the mean sediment yield for this root density interval was about one half of the yield for bare slopes. An increase in root density interval (0.5–1.0 kg m$^{-3}$) recorded a further decrease in sediment yields, the mean sediment

Table 1. Pearson correlation coefficients between soil erosion and root density and root diameter.

<table>
<thead>
<tr>
<th>Item</th>
<th>Variable</th>
<th>Correlation coefficient</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil erosion</td>
<td>0–10 cm root density</td>
<td>.668**</td>
<td>&lt;.01</td>
</tr>
<tr>
<td></td>
<td>10–20 cm root density</td>
<td>.609*</td>
<td>&lt;.05</td>
</tr>
<tr>
<td></td>
<td>20–30 cm root density</td>
<td>.357*</td>
<td>&lt;.05</td>
</tr>
<tr>
<td></td>
<td>30–40 cm root density</td>
<td>.453</td>
<td>.090</td>
</tr>
<tr>
<td></td>
<td>0–10 cm fine root</td>
<td>.674**</td>
<td>&lt;.01</td>
</tr>
<tr>
<td></td>
<td>0–10 cm medium root</td>
<td>.412*</td>
<td>&lt;.05</td>
</tr>
<tr>
<td></td>
<td>10–20 cm fine root</td>
<td>.482*</td>
<td>&lt;.05</td>
</tr>
<tr>
<td></td>
<td>10–20 cm medium root</td>
<td>.374</td>
<td>.061</td>
</tr>
</tbody>
</table>

**Significant at P < .01.
*Significant at P < .05.

Figure 5. Function of sediment yield and root density with different slopes.
yield being about one-third that of the bare slopes. When root density was greater than 1.0 kg m\(^{-3}\), soil erosion rate was almost stable with a low value.

The mean proportions of different root diameter (D) classes of *R. pseudoacacia* were: 42.8% for fine roots \((D < 1.0 \text{ mm})\); 37.3% for medium roots \((1.0 < D < 5.0 \text{ mm})\) and 19.8% for coarse roots \((D > 5.0 \text{ mm})\). The proportion of fine roots was greater than that of medium or coarse roots in the top soil layers. Soil erosion also had a significant correlation with the amount of fine roots \((0–20 \text{ cm depth})\) and medium roots \((0–10 \text{ cm depth})\) (Table 1). In other words, fine roots and medium roots at these depths were more effective in reducing soil erosion. This is mainly due to the presence of roots, resulting in a decline in soil bulk density and enhancing soil porosity, thus improving water movement within the soil and decreasing runoff [27]. Our results were in accordance with those of De Baets et al. [28] that plant roots played a central role in preventing soil erosion from over-land flow by increasing topsoil resistance.

**The contribution of litter cover and roots on soil erosion**

Erosion rates varied between 0.34–6.48, 0.22–1.96 and 0.26–3.14 g m\(^{-2}\) min\(^{-1}\) for bare, plant and root samples, respectively. With increasing slope gradients and flow discharges, sediment yields increased and significant differences were identified between plant and bare samples (Table 2). In comparison to bare slopes, sediment yields of plant slopes were reduced by 35–70%, with a mean reduction of 57%. This showed that vegetation is an important factor in reducing soil erosion in the Loess Plateau. Previous studies have obtained similar conclusions for different plant species [3,14]. With slope gradient of 17.6% and flow discharge from 0.5 to 2.0 L s\(^{-1}\), the reduction of sediment yields caused by plant ranged from 48% to 56%. This indicated that the presence of *R. pseudoacacia* influenced the soil infiltration capacity. Furthermore, the structure, porosity and organic matter of the soil also significantly changed due to plant growth. Soil aggregation stabilised to some degree.

In previous studies, the main focus of studies concentrated on above-ground biomass; the effect of below-ground plant components on soil erosion rates has largely been

<table>
<thead>
<tr>
<th>Slope gradient (%)</th>
<th>Flow discharge (L s(^{-1}))</th>
<th>Erosion rate (g m(^{-2}) min(^{-1}))</th>
<th>Sediment reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Bare slopes</td>
<td>Plant slopes</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>0.34a</td>
<td>0.22ab</td>
</tr>
<tr>
<td></td>
<td>8.7</td>
<td>0.62a</td>
<td>0.31b</td>
</tr>
<tr>
<td></td>
<td>17.6</td>
<td>0.84a</td>
<td>0.39b</td>
</tr>
<tr>
<td></td>
<td>26.8</td>
<td>1.03a</td>
<td>0.54b</td>
</tr>
<tr>
<td></td>
<td>36.4</td>
<td>1.19a</td>
<td>0.58b</td>
</tr>
<tr>
<td></td>
<td>46.6</td>
<td>1.41a</td>
<td>0.62b</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1.81a</td>
<td>0.76b</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>2.34a</td>
<td>0.91b</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>2.76a</td>
<td>1.03b</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>2.83a</td>
<td>1.26b</td>
</tr>
<tr>
<td>0.5</td>
<td>2</td>
<td>3.06a</td>
<td>1.09b</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3.92a</td>
<td>1.34b</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>4.27a</td>
<td>1.68b</td>
</tr>
<tr>
<td>0.5</td>
<td>4</td>
<td>4.97a</td>
<td>1.79b</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6.48a</td>
<td>1.96b</td>
</tr>
</tbody>
</table>

Table 2. The sediment reduction of plant roots and litter cover on five slope gradients and three flow discharges.
ignored. Our results however showed that both above- and below-ground components of plants have a significant effect on soil erosion. Furthermore, the contribution of roots and litter cover due to the presence of *R. pseudoacacia* towards the reduction in sediment yields was separated (Figure 6). Sediment reduction caused by roots and litter cover ranged between 24–51% and 11–25%, respectively. Corresponding mean values were 37% and 19%. Compared with litter cover, plant roots were significant in reducing sediment erosion. Interestingly, when slope gradients ranged from 8.7% to 46.6%, the specific contribution of roots to sediment reduction increased from 60% to 70% (Figure 6(A)). The contribution of roots to soil erosion was characterised by a parabolic relationship for three flow discharges; with the flow discharge of 2.0 L s$^{-1}$, the role of roots in sediment reduction reached the maximum (Figure 6(B)). In contrast, litter cover had a relatively lower contribution rate to soil erosion. The mean value of contribution rates of plant roots and litter cover to the reduction in soil erosion were 69% and 31%, respectively. Differences between contribution rates of roots and litter cover may be attributed to the fact that litter cover predominantly determined the amount of rainfall interception, thus reducing the influence of rainfall on soil and improving the ability of soil to absorb effective rainfall. The presence of plant roots however improved soil aggregate stability, organic content, water movement and infiltration ability, which resulted in a more stable soil. The results of this study further increased the knowledge on the important effect of plant roots on soil loss control in situations where the litter cover was removed or destroyed. These results were consistent with the findings of Zhou et al. [17] and Zhao et al. [3]. However, several studies have obtained different results. Field-simulated rainfall experiments reported by Zhang et al. [29] were conducted in Tianshui City, Gansu Province, which indicated that depending on the slope gradient, the contribution of the above-ground component and of the plant roots were almost equivalent under grassland conditions. Experiments by Bui and Box [30] concluded that corn (*Zea mays* L.) canopies provided more protection from soil erosion than that provided by the roots. The same conclusion was reported by Gyssels et al. [16], indicating that the

![Figure 6](image_url)

**Figure 6.** Contributions of *R. pseudoacacia* root and litter cover to soil erosion reduction for five slope gradients (A), and three flow discharges (B).
contribution of the above-ground components of plants to the reduction in soil erosion was greater than that provided by cereal and grass roots in the loess Belt of Central Belgium. These conflicting conclusions were believed to be a result of differences in study areas, soil categories and plant species.

Soil erodibility and critical shear stress

Soil erodibility ($K_r$) and critical shear stress ($\tau_c$) were strongly related with soil erosion, factors which were important indices in expressing the capacity of the soil to resist rainfall and runoff. The function between soil erosion rate and shear stress on slopes with plant, root and bare ground was shown in Figure 7. Results for the soil erosion rate and shear stress had a simple linear correlation (correlation coefficients > 0.80). Soil erodibility of the bare slopes was 1.0012, being 3 and 5.2 times greater than that of root and plant samples, respectively. The presence of plant roots resulted in a greater decrease of soil erodibility than that due to litter cover. The critical shear stress on slopes with plant, root and bare ground was 4.715, 3.884 and 1.124 Pa, respectively. In comparison with bare slopes, critical shear stress of slopes with plant and root improved by 319% and 246%, respectively. These results clearly indicated that $K_r$ declined and $\tau_c$ increased markedly for intact plant and root slopes compared with bare slopes and the influence of roots on the decrease of soil erodibility was far greater than that of litter cover. This further suggested that roots are more influential than litter cover for decreasing sediment erosion.

![Figure 7. Soil erosion as a function of shear stress.](image-url)
The discrepancy between plant and roots in $K_r$ and $\tau_c$ could be attributed to the different soil properties. Litter cover can increase roughness and infiltration rates of the soil, which led to an increase in water content and a decrease in erosion intensity [3]. Roots combined with soil particles can reinforce the soil and develop a stable structure that can enhance soil cohesion. Both of these elements therefore present a positive effect on the reduction of $K_r$ and the improvement of $\tau_c$.

$K_r$ and $\tau_c$ were also influenced by soil types and plant species. Li et al. [31] showed that $K_r$ of shrub-lands was 2.71 times greater than that reported by Nearing et al. [21]. The discrepancy may be due to soil types: a classic silt loam soil was investigated by Li et al. [31], while a sandy loam soil was tested by Nearing et al. [21]. Similarly, Knapen et al. [32] found that $K_r$ of the loamy sand (0.028), silt loam (0.013) and clay loam (0.004) were significantly different. The $\tau_c$ values of the silt loam (3.4 Pa) and the clay loam (6.9 Pa) soils were much greater than that of the loamy sand soil (1.4 Pa), indicating loamy sand soils were more prone to soil erosion. In addition, $K_r$ of woodlands in the Loess Plateau differed significantly. Zhang et al. [14] reported that the $K_r$ of Amorpha fruticosa was 0.0021, while Li et al. [31] noted that the $K_r$ of Black locust, Chinese pine and Simon poplar were 0.013, 0.0058 and 0.0098, respectively. In our study, the $K_r$ value of R. pseudoacacia was 0.193.

Apart from different tree species being investigated, the differences in these results are mainly due to plant properties and restoration years [31].

**Conclusions**

Soil erosion is affected by soil properties, hydraulic characteristics, plant properties and land use. In this study, the impacts and specific contribution of litter cover and plant roots on sediment reduction using R. pseudoacacia sample plots with different slopes and flow discharges were investigated. Our results indicated that soil loss due to the presence of vegetation was reduced by about 57% compared with bare slopes. R. pseudoacacia was shown to control soil erosion due to the combined effects of litter cover and plant roots, and plant roots reducing sediment yields more than litter cover. In other words, the roots occupy the most important position in controlling soil erosion. Additionally, direct or indirect functions from litter cover and plant roots had a noticeable effect on decreasing $K_r$ and increasing $\tau_c$ and then strengthen the capacity of soil resistance to erosion. These results of this research are helpful for understanding the mechanisms of R. pseudoacacia in soil erosion control, and proving an insight into the specific contributions of litter cover and plant roots in reducing soil erosion. Our findings also highlight the importance of suitable vegetation selection for the Loess Plateau. Further studies are needed to investigate the impacts of root systems on soil erosion in different land use and to explore the temporal variation of soil erosion.

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**References**


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