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Quantifying the Effects of Root and Soil Properties on Soil Detachment Capacity in Agricultural Land Use of Southern China

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Abstract: Unsustainable agricultural land use will lead to an increased risk of soil erosion and soil degradation. However, few studies have investigated impacts of changes in root and soil properties on the soil detachment process. Therefore, we investigated the effects of agricultural land use on the relative contribution of root and soil properties to soil detachment capacity. Soil samples were collected from six different land use types and subjected to flow scouring under six shear stresses ranging from 4.98 to 16.37 Pa. Agricultural land use influenced root distribution and soil properties in the soil surface layer. Root length density, root surface area density, and root volume density in orchards with no cover, orchards with grass cover, and farmland were less than those of grassland samples. Different land use types affected soil detachment capacity. Bare land, farmland, and orchards with no cover were more vulnerable to erosion, while forest, orchard with grass cover, and grassland showed little soil detachment. Soil detachment capacity decreased exponentially with increasing soil bulk density, aggregate stability, organic matter, and root mass density. The root mass density and aggregate stability had the greatest contribution to the soil detachment capacity. Agricultural land use increases the risk of soil erosion; a groundcover management strategy, such as planting grass in orchard, could effectively increase the fine root distribution and aggregate stability to control soil erosion.

Keywords: soil erosion; soil detachment capacity; land use change; vegetation roots; soil properties

1. Introduction

Soil erosion and degradation caused by climate change and human activities have become two of the most serious ecological and environmental problems in the world because they destabilize the ecosystem and severely hinder the sustainable development of agriculture [1,2]. Recently, due to increasing population pressure and the need for economic development, an increasing amount of land is being used for agricultural land use such as the conversion of forest land and barren land so on to orchards and farmland. [3]. While the economic benefits of agricultural land use are increasing, the developed land faces the risk of degradation and increased soil erosion due to excessive development and unsustainable management measures [4–6]. Therefore, it is necessary to further understand the process of soil erosion in different land use types, which will illuminate sustainable management strategies to alleviate soil erosion.

There are three main processes of soil erosion caused by water: soil detachment, sediment transport, and sediment deposition [7,8]. Among these three processes, the soil detachment process is crucial in erosion because it provides material for sediment transport, deposition, and sediment re-detachment [9,10]. With erosion caused by surface runoff, the speed of soil detachment is usually expressed by the soil detachment rate. When the amount of sand entering the flow is zero, the maximum soil detachment rate is considered...
the soil detachment capacity [11,12]. Soil detachment capacity represents the maximum possibility of detached surface runoff soil, and it is also an important parameter to study the soil detachment process. However, the soil detachment capacity varies based on surface runoff, roots, and soil properties. Therefore, studying the relationship between the factors influencing soil detachment and soil detachment capacity is crucial for understanding the water erosion process.

The growth of vegetation can change soil properties, thereby affecting the soil detachment capacity. Vegetation is often used to reduce soil detachment capacity because of its functions of rainfall retention, runoff mitigation, sand prevention and control, and soil retention and consolidation [13]. Among them, the role of root systems on soil stability is particularly significant. Related studies have shown that during the growth of vegetation, roots are interspersed in the soil and form a root–soil complex with the soil [14]. Through the mechanical properties of the root system itself, it effectively improves the stability of the soil on the slope and reduces the soil detachment capacity on the slope [15]. However, due to the different root diameters, the tensile resistance of roots is different, so the root system has different effects on soil stability [16,17]. In addition to the mechanical properties of the root system, root system characteristics such as root length density, root mass density, root volume density, root mean diameter, and root surface area density all affect the soil detachment capacity [18,19]. In addition, Baets et al. [20] indicated that soil detachment capacity is related to root architecture, and the effect of fine fibrous roots on reducing soil detachment capacity was better than that of tap roots. Through root exudates, roots promote soil particle binding in topsoil, which increases soil strength, thereby reducing soil detachment capacity [1,21,22]. However, some studies have pointed out that the root system, which is related to the vegetation type, also affects the soil detachment capacity. When the root diameter of the vegetation is larger than the soil pores, it will increase the bulk density; when smaller than the soil pores, it will reduce the bulk density [23,24].

Soil properties, such as soil type, particle size distribution, bulk density, porosity, cohesion, aggregate stability, organic matter, and infiltration rate, have a significant impact on the soil detachment capacity [25,26]. Wang et al. [13] found that under different vegetation restoration models, soil detachment capacity was negatively correlated with soil bulk density and cohesion, and positively correlated with soil total porosity clay content. In typical grasslands, soil detachment capacity decreased exponentially with the increase in soil bulk density, soil cohesion, and soil aggregates [13]. In addition, a previous study indicated that soil detachment capacity was closely related to soil texture [27]. Related studies have shown that the critical shear stress of clay soil is higher than that of silt and sand soil, and rill erodibility is lower than that of silt and sand soil [28]. Because of the influence of roots, soil microbial activity was improved and soil nutrient decomposition was effectively promoted, which increased soil organic matter [29], strengthening the stability of soil aggregates and improving soil anti-detachment capacity [30]. Wang et al. [31] also indicated that the soil detachment capacity decreased with the increase in soil organic matter. Although the effects of root and soil properties on soil detachment capacity have been discussed in previous studies, the relationship between root properties, soil properties, and the soil detachment capacity is complex. The effects of root and soil properties on the soil detachment capacity in agricultural land use have yet to be examined.

Changes in land use lead to changes in root and soil properties, which in turn lead to changes in the soil detachment capacity. Related studies have shown that under hydraulic erosion, the soil detachment capacity is significantly different in different land use types [8,10]. Jiao et al. [32] found that changes in land use led to changes in soil bulk density, total porosity, and capillary porosity of the surface soil layer. These changes in root and soil properties caused by land use change impact the soil detachment capacity, potentially leading to an increase in soil erosion. An increasing number of studies have shown the influence of root and soil properties on soil detachment capacity [12,30,33]. However, there are few studies that quantify the relative contribution of root and soil properties to the soil detachment capacity.
The red soil region of southern China has been facing severe soil and water loss due to high precipitation, hilly landforms, and unsustainable human activities. Over the past several decades, land use type has substantially changed because of the conflict between the rapid growth of the human population and the lack of land available for agriculture [34]. An increasing area of barren, sloping land has been developed into economically profitable citrus orchards and farmlands [3,35–37]. However, though these lands have improved economic efficiency, they are exposed to serious risk of soil and water loss due to the strong soil disturbances from large-scale mechanized excavation and lack of surface vegetation [38,39]. Thus, a quantitative study of the effects of root and soil properties on soil detachment capacity during agricultural land use can predict soil detachment capacity more accurately and can be more targeted in soil erosion management.

At present, few studies have been conducted quantifying the influence of roots and soil properties on the soil detachment capacity and their relative contribution to different land utilization in southern China’s agricultural land use. Therefore, the principal objectives of this study follow: (a) to explore the variation in root and soil properties in different land uses; (b) to identify the effects of the root system and soil properties on soil detachment capacity; and (c) to quantify the contribution of each root system and soil property variable to the effect of soil detachment capacity. The results of this study provide insight into the soil detachment capacity and present suggestions for targeted soil erosion control.

2. Materials and Methods

2.1. Study Area

The experiments were conducted in the Jiangxi Ecological Park of Soil and Water Conservation (29°17′ N, 115°43′ E). It is located in Yangou’s small watershed, De’an County, Jiangxi Province, southern China (Figure 1). This region has a subtropical humid monsoon climate, with an average annual temperature of 16.9 °C, and maximum and minimum temperatures of 40.3 °C and −10.7 °C, respectively. The average annual sunshine ranges from 1700 to 2100 h. The average annual rainfall is 142 days. The average annual precipitation and evaporation are 1469 mm and 1000–1200 mm, respectively.

Figure 1. Location of the study area, China (a), Jiangxi Province (b), Jiangxi Ecological Park of Soil and Water Conservation (c).
The Yangou small watershed is the center of the red soil region in southern China. Soil condition, land use type, and population density have typical characteristics of hilly and mountainous areas in southern China. The terrain is high in the northwest and low in the southeast, with an elevation ranging from 30 to 90 m above sea level. The main soil type in the watershed is red clay soil, produced by the weathering of Quaternary sediments. The soil depth in the study area was approximately 100 cm. Owing to the need for economic development, a large area of low-efficiency forests and bare lands with slope aspects between 8° and 15° has been transformed into citrus orchards and farmlands, which are more economically beneficial. The current land use types in the watershed mainly include farmland, orchard, forest, grassland, and wasteland.

2.2. Sampling Site

Samples were taken from bare land, grassland (main plant species: Eremochloa ophiuroides), orchard with no cover (main plant species: Citrus sinensis), orchard with grass cover (main plant species: Citrus sinensis), farmland (main plant species: Brassica napus), and forest (main plant species: Pinus massoniana). The slope aspect, slope gradient, elevation, and soil type of the selected sites were similar to minimize the effects of these factors on experimental results. Tillage operations, such as planting, plowing, hoeing, and harvesting, were carried out on farmland, while no tillage operations were used on bare land, grassland, forest, and the orchard with grass cover. In orchards with no groundcover, weeds were removed by manual hoeing every two months. The time from the weeds removed by hoeing to sampling was two months; the time from the tillage operations to sampling was two months in farmland. In all sites, the main erosion type was hydraulic erosion.

2.3. Soil Sampling and Soil Properties Measurement

Undisturbed soil samples were collected from November to December 2021 from the topsoil layer (0 to 5 cm) using steel rings with interior diameters of 9.8 cm and heights of 5 cm. Soil samples were collected to measure soil detachment capacity. The soil sampling procedures were the same as that described by Zhang et al. [12,40]. Briefly, the sampling procedures were almost identical for all sites except for the treatment of weeds. Before sampling, a relatively flat position in the sample plot was selected and scissors were used along the surface to carefully cut off the aboveground part of the plant. Surface litter was carefully removed to avoid disturbing the soil. When taking the sample, the rhizome was included within the steel ring, the steel ring was pressed into the soil slowly, and then the soil was cut around the steel ring to reduce damage of the steel ring to the soil sample. When the top of the steel ring was flat with the soil surface, the soil sample was carefully taken out. Then, the bottom of the core was trimmed to level with the rim of the ring. Using cotton cushions and lids covering both ends of the steel ring, the soil sample was put into the special box to avoid disturbance during sample transport.

Thirty-three samples were collected from each plot, and a total of 198 samples were collected from the six land uses types. In addition, mixed soil was collected from top soil (0–10 cm) around each sampling point to test soil moisture and estimate the dry soil weight for the corresponding sample. The soil bulk density and porosity were measured by using a ring knife (100 cm³) taking soil samples from top soil (0–10 cm) around each sampling point, with five replicates per plot. Soil organic matter, particle size composition, and water-stable aggregates were determined by taking mixed soil (using S-shaped sampling) from top soil (0–10 cm) at five sample points in each sample plot.

Soil bulk density and soil porosity were determined following the ring-knife weighing method [41]. Soil particle size distribution was determined using the hydrometer method [42], water-stable aggregates were determined by the wet sieving method [43], and soil organic matter was measured using the potassium dichromate colorimetric method [44]. In addition, soil shear strength was determined using the digital display miniature cross-plate shearing instrument with 10 replicates per sample plot. Aggregate stability was
expressed as the mean weight diameter without coarse sand and gravel, and was calculated using the following equation:

\[ MWD = \sum_{i} \frac{r_i - 1 + r_i}{2} \times m_i \]  

where \( r_i \) is the aperture of the \( i \)th mesh (mm), \( r_0 = 0 \) mm and \( r_n = r_n + 1 \), \( m_i \) is the weight fraction of the aggregates (without coarse sand and gravel) on \( i \)th sieve, and \( n \) is the number of the sieves.

2.4. Hydraulic Parameter Measurement

Soil detachment capacity was measured in a 4 m long and 0.35 m wide water flume, as previously described in Zhang et al. [12,40]. The slope of the flume was freely adjustable, there was a stable flow channel at the upper end of the flume, and a hole (10 cm in diameter) was present in the lower part for placing the soil samples collected using the ring cutter. The water supply system consisted of water storage buckets, constant power pumps, flowmeters, hoses, and valves. The flow rate was controlled by flowmeters and valves. In the experiment, potassium permanganate dye was used to determine the flow velocity. Potassium permanganate was applied at 12 horizontal positions evenly distributed across the flume, and each position was repeated five times. The maximum and minimum values in each position were removed to obtain the mean flow velocity. Flow depth was calculated using mean velocity as:

\[ h = \frac{Q}{B} \]

where \( h \) is the flow depth (m), \( Q \) is the flow discharge (m\(^3\) s\(^{-1}\)), \( B \) is the width of the flume (m), and \( V \) is the mean flow velocity (m s\(^{-1}\)). In order to measure the soil detachment capacity under different hydraulic conditions, six groups of single-width flow and slope combinations (0.002 m\(^3\) s\(^{-1}\) and 26.2%, 0.003 m\(^3\) s\(^{-1}\) and 26.2%, 0.004 m\(^3\) s\(^{-1}\) and 36.4%, 0.005 m\(^3\) s\(^{-1}\) and 36.4%, 0.006 m\(^3\) s\(^{-1}\) and 46.6%, 0.007 m\(^3\) s\(^{-1}\) and 46.6%) were utilized in this study. Flow shear stress (\( \tau \), Pa; 4.14, 5.99, 9.88, 11.72, 15.64, 18.24 Pa), stream power (\( \omega \), kg m\(^{-3}\)), and unit stream power (\( p \), m s\(^{-1}\)) were calculated using Equations (3)–(5).

\[ \tau = \rho ghS \]  
\[ \omega = \tau V \]  
\[ p = Sv \]

where \( \rho \) is the density of water (kg m\(^{-3}\)), \( g \) is the constant of gravity (m s\(^{-2}\)), and \( S \) is the sine value of slope (m m\(^{-1}\)).

2.5. Soil Detachment Capacity Measurement

Before measuring the soil detachment capacity, the collected soil samples were wetted for 8 h to ensure that the water content of all samples was consistent; soil samples were then left to stand for 30 min to drain water using gravity. The soil sample was put into the hole below the soil flume, and the soil sample was covered with a lid, which did not interfere with the soil sample. When the flow was stabilized, the lid above the soil sample was removed and timing started. When the soured depth of the soil sample reached 2 cm, scouring was stopped and the sample was removed. The overall scouring time was not more than 300 s.

The roots from each core were collected by washing. The washed sediment was filtered and dried in an oven at 105 °C. The collected roots were analyzed using a WinRHIZO (Pro. 2019 a) root analysis system to obtain root length, root surface area, root volume, and root mean diameter. The completed scanned roots were placed in an oven and dried at 65 °C to a constant weight, and the root dry weight was measured. The soil detachment capacity,
root length density, root surface area density, root volume density, and root mass density were calculated using Equations (6)–(10).

\[ D_c = \frac{W - (W_0 + RM)}{A \times t} \]  
\[ RLD = \frac{RL}{A} \]  
\[ RSD = \frac{RS}{A} \]  
\[ RVD = \frac{RV}{A} \]  
\[ RMD = \frac{RM}{A} \] 

where \( W \) is dry soil weight (kg) before scouring, \( W_0 \) is dry soil weight (kg) after scouring, \( A \) is scouring area (m\(^2\)), and \( t \) is scouring time (s). For each shear stress, the mean \( D_c \) of the five replicates was calculated to reflect the effects of that shear stress on soil detachment capacity.

2.6. Statistical Analysis

Significant differences in the mean soil detachment capacity, root characteristics, and soil properties between land use types were detected using a one-way analysis of variance (ANOVA) followed by a least significant difference (LSD) test \((p < 0.05)\). A correlation analysis was utilized to analyze the correlation coefficient between soil detachment capacity, root characteristics, and soil properties. The relationship between soil detachment capacity and all factors (hydraulic parameters, root characteristics, and soil properties) was analyzed employing a simple regression method. A nonlinear regression method was used to estimate the relationships between soil detachment capacity and shear stress, root mass density, and aggregate stability. The results of the regression analysis were evaluated using the coefficient of determination and the Nash–Sutcliffe model efficiency. The hierarchical partitioning method was employed to determine the contribution of the effects of vegetation root characteristics and soil properties on soil detachment capacity via the rdacca.hp package in R [45]. The hierarchical segmentation method can effectively solve the problem of collinearity among explanatory variables affecting soil detachment capacity. All analyses were conducted using SPSS26.0, R.3.5.1, and Origin22.

3. Results

3.1. Root Characteristics in Different Land Use Types

The root characteristics in the topsoil of different land use types varied significantly (Table 1). The root length density (0.72–4.72 cm·cm\(^{-3}\)), root surface area density (0.18–0.56 cm\(^2\)·cm\(^{-3}\)), root volume density (0.0014–0.0058 cm\(^3\)·cm\(^{-3}\)), root mean diameter (0.36–0.92 mm), and root mass density (1.05–2.73 g cm\(^{-3}\)) showed large differences among the different sample plots. The maximum root length density (grassland) was 6.56 times greater than the minimum (forest). The grassland had the maximum root surface area density and root volume density of 3.11 and 4.14 times greater than their respective minimums (farmland). The mean root diameter was largest in forest and smallest in grassland. Among the root mass density, the orchards with grass cover were the highest, followed by grassland, forest, orchard with no cover, and farmland. The root mass density of orchards with grass cover was 2.65 times that of farmland. The root mass density of grassland and forest was significantly higher than that of orchards with no cover and farmland. The results show that the root length density, root surface area density, and root volume density of orchards with grass cover, and orchards with no cover were significantly lower than those of grassland. In addition, the root length density, root surface area density, root volume density, and root mass density of orchards with grass cover were
significantly higher, while the root average diameter was significantly lower compared with orchards with no cover.

Table 1. Total root characteristics in different land use types.

<table>
<thead>
<tr>
<th>Site Code</th>
<th>Root Length Density (cm cm⁻³)</th>
<th>Root Surface Area Density (cm² cm⁻³)</th>
<th>Root Volume Density (cm³ cm⁻³)</th>
<th>Average Root Diameter (mm)</th>
<th>Root Mass Density (kg m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GL</td>
<td>4.72 ± 0.61 a</td>
<td>0.56 ± 0.10 a</td>
<td>0.0058 ± 0.0013 a</td>
<td>0.36 ± 0.02 d</td>
<td>2.5 ± 0.2 ab</td>
</tr>
<tr>
<td>SCL</td>
<td>3.08 ± 0.30 b</td>
<td>0.38 ± 0.10 b</td>
<td>0.0051 ± 0.0002 a</td>
<td>0.39 ± 0.07 d</td>
<td>1.05 ± 0.2 c</td>
</tr>
<tr>
<td>GO</td>
<td>2.71 ± 0.10 b</td>
<td>0.36 ± 0.02 b</td>
<td>0.0044 ± 0.0005 a</td>
<td>0.49 ± 0.03 c</td>
<td>2.73 ± 0.36 a</td>
</tr>
<tr>
<td>FL</td>
<td>0.72 ± 0.10 c</td>
<td>0.21 ± 0.02 c</td>
<td>0.0048 ± 0.0003 a</td>
<td>0.92 ± 0.03 a</td>
<td>2.17 ± 0.25 b</td>
</tr>
<tr>
<td>CFO</td>
<td>0.84 ± 0.02 c</td>
<td>0.18 ± 0.02 c</td>
<td>0.0014 ± 0.0006 b</td>
<td>0.68 ± 0.07 b</td>
<td>1.13 ± 0.15 c</td>
</tr>
</tbody>
</table>

Notes: All data were the mean ± SD (n = 30). Values in a column with the same lowercase letter are not significantly different at p < 0.05. GL, grassland; SCL, farmland; GO, orchard with grass cover; FL, forest; CFO, orchard with no cover.

The proportion of root length density, root surface area density, and root volume density of different diameter classes is shown in Figure 2. The proportion of root length density and root volume density in different land use types in the D ≤ 0.5 mm diameter class was in the following order: grassland (37.17 and 36.81%, respectively) > farmland (32.10 and 31.90%, respectively) > orchard with grass cover (21.96 and 22.30%, respectively) > forest (4.44 and 6.56%, respectively) > orchard with no cover (4.33 and 2.42%, respectively) (Figure 2a,c). The proportion of root surface area density of different land use types in the D ≤ 0.5 mm diameter class was highest in the grassland (36.18%), followed by the farmland (27.21%), the orchard with grass cover (24.73%), the orchard with no cover (6.57%), and the forest (5.31%) (Figure 2b). Among them, the proportions of root length density, root surface area density, and root length density of the D ≤ 0.5 mm diameter class in the orchard with grass cover were 5.07, 3.78, and 9.20 times of that in farmland, respectively. These findings indicate that agricultural land use reduced the root length density, root surface area density, and root volume density of roots in surface soil, while the grass coverage could effectively improve the distribution of roots in surface soil, especially fine roots.

Figure 2. The percentage changes in different diameter classes for root length density (a), root surface area (b), and root volume (c) under different land use change. Notes: GL, grassland; SCL, farmland; GO, orchard with grass cover; FL, forest; CFO, orchard with no cover. RLDs, root length density of D ≤ 0.5 mm diameter class; RLDm, root length density of 0.5 mm < D ≤ 1 mm diameter class; RLDc, root length density of D≤ 0.5 mm diameter class; RSDs, root surface area density of D ≤ 0.5 mm diameter class; RSDm, root surface area density of 0.5 mm < D ≤ 1 mm diameter class; RVDc, root surface area density of D ≤ 0.5 mm diameter class; RVDm, root volume density of 0.5 mm < D ≤ 1 mm diameter class; RVDc, root volume density of D ≤ 0.5 mm diameter class.

3.2. Soil Properties in Different Land Use Types

Soil properties varied greatly among the different land use types (Table 2). The soil bulk density (1190–1570 kg m⁻³), soil porosity (40.66%–55.58%), aggregate stability (0.34–0.78 mm), organic matter (1.16–18.13 g kg⁻¹), and shear strength (4.78–40.49 Pa) showed significant differences in different land use types. The mean bulk density of bare land was the largest,
followed by grassland, forest, orchard with grass cover, orchard with no cover, and farmland. The aggregate stability had the following order: grassland > forest > orchard with grass cover > orchard with no cover > farmland > bare land. Farmland had the greatest soil porosity; the smallest soil porosity was found in the soil collected from bare land. These results confirm that agricultural land use negatively affected soil properties, while the grass coverage could effectively improve the soil properties.

Table 2. Soil properties of different land of use types.

<table>
<thead>
<tr>
<th>Site Code</th>
<th>Bulk Density (kg m⁻²)</th>
<th>Total Porosity (%)</th>
<th>MWD (mm)</th>
<th>Organic Matter (g kg⁻¹)</th>
<th>Shear Strength (Pa)</th>
<th>Particle-Size Distribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Clay</td>
</tr>
<tr>
<td>CK</td>
<td>1570 ± 46 a</td>
<td>40.66 ± 3.7 c</td>
<td>0.34 ± 0.04 e</td>
<td>1.16 ± 0.43 d</td>
<td>4.78 ± 0.22 c</td>
<td>18.83 ± 2.16 b</td>
</tr>
<tr>
<td>GL</td>
<td>1420 ± 25 b</td>
<td>47.85 ± 0.6 b</td>
<td>0.78 ± 0.09 a</td>
<td>12.99 ± 0.76 b</td>
<td>40.49 ± 5.34 a</td>
<td>25.36 ± 3.27 ab</td>
</tr>
<tr>
<td>SCL</td>
<td>1190 ± 30 c</td>
<td>55.36 ± 0.96 a</td>
<td>0.48 ± 0.09 d</td>
<td>5.76 ± 0.36 c</td>
<td>12.96 ± 0.66 c</td>
<td>26.39 ± 0.36 ab</td>
</tr>
<tr>
<td>GO</td>
<td>1360 ± 71 bc</td>
<td>49.68 ± 2.58 ab</td>
<td>0.67 ± 0.12 c</td>
<td>7.64 ± 0.60 c</td>
<td>18.32 ± 1.22 b</td>
<td>28.45 ± 2.15 ab</td>
</tr>
<tr>
<td>FL</td>
<td>1370 ± 54 bc</td>
<td>46.95 ± 4.74 b</td>
<td>0.72 ± 0.08 b</td>
<td>18.13 ± 0.22 a</td>
<td>12.24 ± 1.21 c</td>
<td>19.18 ± 4.21 b</td>
</tr>
<tr>
<td>CFO</td>
<td>1250 ± 57 bc</td>
<td>52.98 ± 0.81 ab</td>
<td>0.42 ± 0.05 e</td>
<td>7.09 ± 0.72 c</td>
<td>9.72 ± 1.25 d</td>
<td>24.33 ± 3.86 ab</td>
</tr>
</tbody>
</table>

Notes: All data were the mean ± SD (n = 30). Values in a column with the same lowercase letter are not significantly different at p < 0.05. CK, bare land; GL, grassland; SCL, farmland; GO, orchard with grass cover; FL, forest; CFO, orchard with no cover.

3.3. Soil Detachment Capacity in Different Land Use Types

As shown in Figure 3, there were significant differences in soil detachment capacity among the different land use types. The variation in the mean soil detachment capacity ranged from 0.037 to 3.67 kg·m⁻²·s⁻¹ in the different land use types; the maximum soil detachment capacity was found in the bare land, followed by the orchard with no cover, farmland, the orchard with grass cover, the forest, and the grassland. Results of the one-way ANOVA indicate that there was no significant difference in soil detachment capacity between farmland and the orchard with no cover, but the measure was significantly higher than that of the grassland, the orchard with grass cover, and forest. There was no significant difference in soil detachment capacity between grassland, the orchard with grass cover, and forest. The variation in mean soil detachment capacity in the forest, the orchard with grass cover, and forest ranged from 0.037 to 0.069 kg·m⁻²·s⁻¹. The mean soil detachment capacity of the orchard with no cover and farmland was 20.09–37.46 and 18.70–34.87 times that of grassland, the orchard with grass cover, and forest. These findings show that grassland and forest were more stable than bare land, the orchard with grass cover, the orchard with no cover, and farmland.

Figure 3. Soil detachment capacity of different land use types. Notes: Different letters indicate significant differences in soil detachment capacity among the different land use types (p < 0.05). CK, bare land; CFO, orchard with no cover; SCL, farmland; GL, grassland; GO, orchard with grass cover; FL, forest.
As shown in Figure 4, for soil properties, the soil detachment capacity was significantly negatively correlated with soil bulk density, aggregate stability, and organic matter; soil detachment capacity was significantly positively correlated with the soil porosity ($p < 0.001$). Root length density, root surface area density, root volume density, root mean diameter, root mass density, root length density of the 0.5 mm < D ≤ 1 mm diameter class, and root surface area density of 0.5 mm < D ≤ 1 mm diameter class were significantly negatively correlated with soil detachment capacity ($p < 0.05$). Soil bulk density, soil porosity, aggregate stability, organic matter, root surface area density, root volume density, and root mean diameter were positively correlated with soil detachment capacity ($p < 0.001$).

![Figure 4. Pearson correlation between root characteristics, soil properties, and soil detachment capacity for different land use types.](image)

Notes: DC, soil detachment capacity; RLD, root length density; RSD, root surface area density; RVD, root volume density; RD, root diameter; RMD root mass density; RLDs, root length density of D ≤ 0.5 mm diameter class; RLDm, root length density of 0.5 mm < D ≤ 1 mm diameter class; RLDc, root length density of D ≥ 0.5 mm diameter class; RSDs, root surface area density of D ≤ 0.5 mm diameter class; RSDm, root surface area density of 0.5 mm < D ≤ 1 mm diameter class; RVDC, root surface area density of D ≤ 0.5 mm diameter class; RLDm, root volume density of 0.5 mm < D ≤ 1 mm diameter class; RVDC, root volume density of D ≤ 0.5 mm diameter class; BD, soil bulk density; TP, soil porosity; MWD, aggregate stability; OM, organic matter; SS, shear strength.

4. Discussion

4.1. Effects of Overland Flow Hydraulics on Soil Detachment

As an erosion agent for soil detachment, overland flow was an important influencing factor in the process of soil detachment. Hydraulic parameters of overland flow, such as flow rate, velocity, and flow regime, all significantly affected soil detachment capacity [40,46]. The flow velocity, shear stress, stream power, and unit stream power of overland flow are often used to predict soil detachment capacity [12,47–49]. We found that the soil detachment capacity increased with the increase in shear stress (Table 3, Figure 5a), stream power (Table 3, Figure 5b), unit stream power (Table 3, Figure 5c), and flow velocity (Table 3, Figure 5d). In contrast with the findings from Wang et al. [21], the soil detachment capacity in this study was more appropriately expressed as a linear function of shear stress, stream power, unit stream power, and flow velocity, rather than as a power function. This could be attributed to differences in soil texture, resulting in different soil stability, which in turn affects the relationship between soil detachment capacity and hydraulic parameters. The shear stress ($R^2$ range from 0.93 to 0.97 with a mean of 0.95), stream power ($R^2$ range from 0.94 to 0.97 with a mean of 0.96), unit stream power ($R^2$ from 0.94 to 0.97 with a mean of 0.95), and flow velocity ($R^2$ range from 0.92 to 0.97 with a mean of 0.94) were satisfactory predictors for soil detachment capacity. These findings suggest that shear stress, stream power, unit stream power, and flow velocity have good effects as hydraulic parameters for predicting the soil detachment process [8,47].
detachment capacity. These findings suggest that shear stress, stream power, unit stream power, and flow velocity have good effects as hydraulic parameters for predicting the soil detachment process \[8,47\].

Table 3. Regression results of soil detachment capacity with shear stress, stream power, unit stream power, and flow velocity under different land use types.

<table>
<thead>
<tr>
<th>Site Code</th>
<th>Shear Stress (τ, Pa)</th>
<th>Stream Power (ω, kg s(^{-3}))</th>
<th>Unit Stream Power (p, m s(^{-1}))</th>
<th>Flow Velocity (v, m s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equation R(^2)</td>
<td>Equation R(^2)</td>
<td>Equation R(^2)</td>
<td>Equation R(^2)</td>
</tr>
<tr>
<td>CK</td>
<td>(Dc = 0.386) ((\tau - 1.36)) 0.93 ***</td>
<td>(Dc = 0.221) ((\omega + 0.41)) 0.94 ***</td>
<td>(Dc = 10.530) ((p - 0.19)) 0.94 ***</td>
<td>(Dc = 6.489) ((v - 0.93)) 0.92 ***</td>
</tr>
<tr>
<td>GL</td>
<td>(Dc = 0.005) ((\tau - 3.21)) 0.96 ***</td>
<td>(Dc = 0.002) ((\omega - 3.21)) 0.95 ***</td>
<td>(Dc = 0.184) ((p - 0.21)) 0.94 ***</td>
<td>(Dc = 0.073) ((v - 1.06)) 0.92 ***</td>
</tr>
<tr>
<td>SCL</td>
<td>(Dc = 0.140) ((\tau - 1.66)) 0.93 ***</td>
<td>(Dc = 0.056) ((\omega + 4.29)) 0.97 ***</td>
<td>(Dc = 2.586) ((p - 0.10)) 0.95 ***</td>
<td>(Dc = 1.738) ((v - 0.82)) 0.93 ***</td>
</tr>
<tr>
<td>GO</td>
<td>(Dc = 0.008) ((\tau - 2.22)) 0.96 ***</td>
<td>(Dc = 0.004) ((\omega - 0.52)) 0.95 ***</td>
<td>(Dc = 0.165) ((p - 0.16)) 0.94 ***</td>
<td>(Dc = 0.136) ((v - 1.01)) 0.96 ***</td>
</tr>
<tr>
<td>FL</td>
<td>(Dc = 0.006) ((\tau - 2.66)) 0.94 ***</td>
<td>(Dc = 0.003) ((\omega - 1.16)) 0.97 ***</td>
<td>(Dc = 0.153) ((p - 0.22)) 0.96 ***</td>
<td>(Dc = 0.110) ((v - 1.02)) 0.97 ***</td>
</tr>
<tr>
<td>CFO</td>
<td>(Dc = 0.152) ((\tau - 1.75)) 0.97 ***</td>
<td>(Dc = 0.072) ((\omega + 1.91)) 0.97 ***</td>
<td>(Dc = 3.159) ((p - 0.16)) 0.97 ***</td>
<td>(Dc = 2.445) ((v - 0.97)) 0.94 ***</td>
</tr>
</tbody>
</table>

Notes: CK, bare land; CFO, orchard with no cover; SCL, farmland; GL, grassland; GO, orchard with grass cover; FL, forest. (**p < 0.001).

Figure 5. Relationship between soil detachment capacity and shear stress (a), stream power (b), unit stream power (c), flow velocity (d). Note: CK, bare land; CFO, orchard with no cover; SCL, farmland; GL, grassland; GO, orchard with grass cover; FL, forest.

4.2. Effect of Soil Properties on Soil Detachment Capacity

The improvement of soil properties can enhance soil stability, consequently affecting soil detachment capacity. This study found that in different land use types, although the soil bulk density of bare land was the greatest compared with other land use types, its porosity, aggregate stability, and organic matter were the lowest. In general, the greater the soil bulk density, the more compact the soil and the greater the ability to resist erosion [26].
Aggregate stability is typically used as an indicator of soil aggregation: the greater the value, the better the stability of aggregates and the stronger the ability of soil to resist erosion [50]. Soil organic matter can cement soil particles and smaller aggregates together in soil, and the increase in organic matter content makes soil aggregates more stable and enhances the resistance of soil to erosion [30]. Thus, although the soil of bare land is compacted, it is not highly stable. The result also shows that in the land types developed with agroforestry (i.e., the orchard with grass cover, the orchard without grass cover, and farmland), the soil compaction of bare surfaces was insufficient to reduce erosion.

In addition, compared to the orchard with no cover, the orchard with grass cover had higher soil bulk density, aggregate stability, and soil organic content. Overall, the soil stability of the orchard with grass cover was better than that of the orchard with no cover. This was due to the unsustainable human management in the orchard with no cover, such as the extensive use of herbicides and artificial loosening of the soil [34], which not only reduced the soil bulk density and destroyed soil aggregates but also reduced the source of soil organic matter. In the orchard with grass cover, the grass increased the soil bulk density, which can effectively increase the soil organic matter, thus improving the stability of soil aggregates. These results support the effectiveness of vegetation cover in improving soil stability and reducing soil detachment. In addition, these findings show that it is necessary to use vegetation to cover in lands being developed by agroforestry.

In the farmland, the soil bulk density, aggregate stability, and organic matter of farmland were lower than that of grassland, forest, and the orchard with grass cover, so the soil stability was also lower. Vegetation coverage, however, is not appropriate for farmland. Therefore, other methods, such as less tillage, no-till (maintaining soil bulk density, reducing aggregate damage), and straw mulching (reducing runoff erosion, increasing soil organic matter) should be considered in cultivated land to improve soil stability.

The correlation analysis (Figure 4) showed that the soil detachment capacity was significantly correlated with soil bulk density, porosity, aggregate stability, and organic matter in different land use types. In addition, the analysis found that the soil detachment capacity decreased as an exponential function with the increase in soil bulk density, aggregate stability, and organic matter, and increased exponentially with the increase in soil porosity (Figure 6), which was consistent with the findings from Wang et al. [31]. These results demonstrate that in land being developed by agroforestry, the enhancement of soil bulk density, aggregate stability, and organic matter plays a crucial role in reducing soil erosion.

![Figure 6. Relationship between soil detachment capacity and soil bulk density (a), soil porosity (b), organic matter (c), and aggregate stability (d), MWD.](image-url)
4.3. Effect of Roots on Soil Detachment Capacity

Changes in land use can affect root distribution. In this study, compared to the orchard with no cover, the orchard with grass cover had higher root length density, root surface area density, and root mass density because the weed cover effectively increases root distribution in the surface soil. However, the root length density, root surface area density, and root volume density of the orchard with grass cover were lower than that of grassland. This is likely because during orchard development, large-scale mechanical excavation destroyed the soil habitat; thus, in the orchard with grass cover, the groundcover plants primarily consisted of only strongly competitive one-year-old *Digitaria sanguinalis*. However, *Digitaria sanguinalis* has a lower root length density, root surface area density, and root volume density than that of *Eremochloa ophiuroides*, indicating that the mulching of herbaceous plants that have strong competitiveness and developed roots can help to improve the distribution of roots in the soil of the surface layer.

In addition, compared with other land use types, in the farmland, although the root mass density was the lowest due to the high root water content in the middle stage of *Brassica napus* growth, root length density, root surface area density, root volume density of the total root, and the $D \leq 0.5$ mm diameter class were only second to those of the grassland due to the fine lateral roots. These results may indicate that cover crops in orchards also increase root length density, root surface area density, and root bulk density in the surface soil. However, it is worth noting that with the growth of the crop, the roots gradually extend downward and become thicker due to gradual lignification, which in turn leads to reduction in the distribution of surface roots, especially fine roots, in surface soil. Coupled with tillage, this will seriously reduce the distribution of the root system in surface soil. Duan et al. [34] also pointed out that compared with grass cover, cover crops had higher annual variations in runoff and erosion due to tillage practices. These results again confirmed that grass cover in orchards is the best choice to increase the distribution of roots in the topsoil of orchards [51,52].

Studies have shown that roots contribute greater than 50% to the soil detachment process [53]. In this study, the soil detachment capacity was significantly correlated with root surface area density, root volume density, and root mass density (Figure 4). Soil detachment capacity decreased as an exponential function with increasing root mass density (Figure 7a), which is similar to the findings by Li et al. [27]. Soil detachment capacity decreased as a linear function with the increase in root surface area density (Figure 7b) and root volume density (Figure 7c). However, root surface area density ($R^2 = 0.376$) and root volume density ($R^2 = 0.351$) were poor predictors of soil detachment capacity. Previous studies have indicated that root length density was often considered to be the best predictor of soil detachment capacity [33]. However, this study indicated (Figure 4) that there was little correlation between the effect of root length density and soil detachment capacity. In general, root length density determines the degree of root distribution, while root surface area density and root volume density affect the amount of soil bound by roots. With greater root length density, root surface area density, and root volume density, the root network is denser, the amount of bound soil is greater, and the soil is stabilized. However, due to the different vegetation types in the different land use categories, the root length density, root surface area, and root volume density of the roots in the surface soil were quite different, which affects the soil detachment capacity. Therefore, root length density, root surface area, and root volume density had limited power for predicting the soil detachment capacity for different types of land use.
Variables explaining soil detachment capacity, the agricultural land use, the soil shear strength was large, the soil stability was low. In addition, due to the different management measures, the existence of soil crusts after the agricultural land use, which improves the shear strength of the soil. Therefore, although the soil shear strength was large, the soil stability was low. In different land utilization types based on agricultural land use, some plots, such as forest, had higher soil stability although the density of fine roots in the surface soil was small. Other plots, such as farmland, had higher density of fine roots in the surface layer, but the soil stability was still low. This demonstrates that in different land utilization types based on agricultural land use, the soil shear strength and fine root length density have limited correlation with soil detachment capacity; instead, root mass density and aggregate stability can effectively explain soil detachment capacity.

### 4.4. Relative Contribution of Root System and Soil Properties to Changes in Soil Detachment Capacity

Exploring the contribution of each root characteristic and soil property to the soil detachment capacity can help to better predict the soil detachment process. The contribution of roots and soil properties (explanatory variables) to the effect of soil detachment capacity (response variables) was determined by the hierarchical division method [45,54]. The root mass density (14.49%) had the greatest contribution to the effect of soil detachment capacity among root characteristics (Figure 8). Among the soil properties, the aggregate stability (11.45%) had the greatest contribution to soil detachment capacity. Hao et al. [55] pointed out that among root characteristics and soil properties, the fine root length density and soil shear strength were the most powerful variables explaining soil detachment capacity, which was not consistent with the results of the present study. This was likely due to the existence of soil crusts after the agricultural land use, which improves the shear strength of the soil. Therefore, although the soil shear strength was large, the soil stability was low. In addition, due to the different management measures of different land use after agricultural land use, some plots, such as forest, had higher soil stability although the density of fine roots in the surface soil was small. Other plots, such as farmland, had higher density of fine roots in the surface layer, but the soil stability was still low. This demonstrates that in different land utilization types based on agricultural land use, the soil shear strength and fine root length density have limited correlation with soil detachment capacity; instead, root mass density and aggregate stability can effectively explain soil detachment capacity.
Root mass density can be increased by adding a large number of fine roots and adding a small number of coarse roots, but the coarse roots may damage the large aggregates when interspersed in the soil. Related studies have also shown that fine roots are more effective than coarse roots in reducing the soil detachment capacity [20,56]. Fine roots also had a greater role in carbon and nutrient cycling [57]. Therefore, increasing root mass density by increasing fine roots is a better choice and can effectively reduce the soil detachment capacity.

4.5. Estimation of Soil Detachment Capacity

The determination of soil detachment capacity is complex, so it is necessary to estimate the soil detachment capacity based on easily measured parameters. Surface runoff, root system, and soil properties are the main factors influencing the soil detachment capacity. The hydraulic parameters of surface runoff can be used to estimate the soil detachment capacity, so the commonly used shear stress was selected as the surface runoff parameter (Figure 5). Moreover, this study found that root mass density and aggregate stability were better indicators for predicting the soil detachment capacity of different land utilization types based on agricultural land use. The linear equation to predict soil detachment capacity based on shear stress, root mass density, and aggregate stability was established (Equation (11)):

\[
D_c = -0.928(1.405 - \tau) \exp^{-0.789RMDc} \exp^{-2.534WMDc}
\]  

(11)

Although the equation can predict the soil detachment capacity of the orchard with grass cover, orchard with no cover, farmland, and bare land, its prediction is excessive for the soil detachment capacity of grassland and forest (Figure 9). This is because the higher root density in grassland increases the roughness of the soil surface, while in the forest, despite the lower root density, the coarser root diameter also leads to increased surface roughness. The increased roughness significantly reduces the erosivity of overland flow, especially when the shear force is low [55,58].

![Figure 9. Comparison between measured and predicted soil detachment capacity by Equation (11). Note: CK, bare land; CFO, orchard with no cover; SCL, farmland; GL, grassland; GO, orchard with grass cover; FL, forest.](image-url)
5. Conclusions

Agricultural land use reduced the root system distribution and impacted the soil properties of the surface layer. The root length density, root surface area density, and root volume density of the orchard with no cover, the orchard with grass cover, and farmland were smaller than those of grassland; soil bulk density, aggregate stability, and organic matter of the orchard with no cover, the orchard with grass cover, and farmland were lower than that of the forest. The changes in root and soil properties also seriously affected soil detachment capacity. The mean soil detachment capacity of the orchard with no cover and farmland was \(20.09 - 37.46\) and \(18.70 - 34.87\) times that of grassland, orchard with grass cover, and forest, respectively.

The relationship between soil detachment capacity and soil bulk density, aggregate stability, organic matter, and root mass density can be described by an exponential function, and the relationship between soil detachment capacity, root surface area density, and root volume density is linear. In addition, shear stress, stream power, unit stream power, and flow velocity can all be used to estimate soil detachment capacity. A model based on flow shear stress, root mass density, and aggregate stability was established to estimate soil detachment capacity.

It was proposed that agricultural land use increased the risk of soil erosion, and a reasonable groundcover management strategy, such as planting grass in orchards and straw mulching, could effectively increase the fine root distribution and aggregate stability to control soil erosion. The findings from this study reveal the specific root and soil properties that affect soil detachment capacity in agricultural land use. In addition, the findings provide a quantitative evaluation of the soil and water conservation efforts in agricultural land use to optimize soil and water conservation measures.

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Data Availability Statement: The data reported in this study are available on request from the corresponding authors. The data are not yet publicly available because the authors are writing other papers that apply these data.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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