Relative contribution of root physical enlacing and biochemistrical exudates to soil erosion resistance in the Loess soil

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A R T I C L E   I N F O

Article history:
Received 7 April 2016
Received in revised form 29 December 2016
Accepted 30 January 2017
Available online xxxx

Keywords:
Root
Physical enlacing effect
Biochemistrical exudates
Soil erosion resistance
Loess soil

A B S T R A C T

Plant roots significantly affect soil erosion, while few works have pursued why root-penetrated soil obtained higher soil erosion resistance as compared with plain soil. For the purpose to investigate the relative contribution of root physical enlacing (root net-link and root-soil bond functions) and root biochemistrical exudates to soil erosion resistance. This study selected Purple alfalfa root- and designed root-penetrated Loess soil as study object, and subjected to flow scouring. The results showed that roots could significantly ameliorate soil properties, especially for soil enzymes. Root physical enlacing is the main reason, accounting for 77.7–82.0% of the root total effect in strengthening soil erosion resistance. And of this total, the relative contribution ratio of net-link and soil-root bond functions to soil erosion resistance was 0.71:0.29, averagely. Root surface area density could effectively reflect root physical enlacing effect. This kind of study may provide theoretical explanations for the root reinforcement in the flow-induced erosion regions.

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1. Introduction

Soil erosion is a process, in which soil and other ground substance were destroyed, denudation, transport and deposition induced by water, wind, freeze-thaw and gravity acts in the land surface. In semiarid areas, soil erosion is a serious threat to land productivity and sustainability for natural and human-managed ecosystems (Su et al., 2010; Fu et al., 2011). Traditional vegetation techniques are recognized as effectively in reducing soil erosion, whereas the most evident vegetation source that protects soil against erosion is root wedging, which is an important mechanism where roots can bind soil together and tie weak surface soil layers into strong and stable subsurface layers (Zhang et al., 2011; Reinhart et al., 2012; Adili et al., 2012). Specifically, root-permeated soils are generally more capable of withstanding soil erosion than plain soils mainly because of the physical enlacing (root length, root surface area density, etc.) and root biochemistrical effect of roots (Liu, 1998; Li et al., 2015a, 2015b). For example, Gyssels and Poesen (2003) and Gyssels et al. (2005) pointed out that plant (Beet, Maize and Endive) roots could reduce sediment loss by 20%, averagely, in silt loam soils, Zhou and Shangguan (2005) found that soil loss could be cut as much as 96% in the Ryegrass root-penetrated soils, and such effect can be well explained by the root features like root biomass, root surface area density, etc. (Li et al., 2015a, 2015b). Even though, the relative contribution of root physical enlacing and biochemistry effect to soil reinforcement is still not clear recently, which hinders constructing a database to test newly developed erosion models, especially in the flow-induced erosion regions.

This study was performed to investigate the relative contribution of root physical enlacing and biochemistry effect to soil erosion resistance. In general, root total effect includes root net-link and soil-root bond functions, and root biochemistry effect (Liu, 1998; Li et al., 2015a, 2015b, 2016). As such, four treatments were designed: 1) root-penetrated soil samples, represents root total effect on soil erosion resistance, 2) Loess parent material, represents soil samples without root effect, 3) tillage soil, represents soil samples with only root biochemistrical effect, and 4) designed root-penetrated soil, represents soil samples with root net-link function alone. Such kind of study could strengthen the mechanism of roots to soil erosion resistance in the root-penetrated soil.

2. Materials and methods

2.1. Experiment design

This experiment was conducted at Ansai Field Experiment Station (36°51′ 22″N, 109° 18′ 52″E) of the Chinese Academy of Sciences in the northwest of China. The experimental treatments examined in the present study are: 1) Purple alfalfa root-penetrated soil, 2) Loess parent material, which came from soil material layer without root effect, 3) Sieved tillage soil without root available, and 4) root-texture cotton
Loess soil samples were collected from a potato-planted slope land, with aspect of N33 and slope gradient of 17°, lying in the Ansai Field Experiment Station. The soil samples were collected in two ways, one part (CK1, about 500 kg) is Loess parent material, sampled from 2.5–3 m-depth. In the sampling process, the surface contour-till-age soil was removed on one side, and then a pit was excavated using a forklift until the parent material layer appeared, where no roots existed. Such soil (bulk density of 1.28 g cm$^{-3}$, soil organic matter of 2.2 g kg$^{-1}$, sand, silt, and clay contents of 11.1%, 60.8% and 28.1%, respectively (USA classification)), represents soil samples without root biochemical effect in the present study. The other soil samples (CK2, about 700 kg) were contour-tillage soils, with depth <25 cm, 1.26 g cm$^{-3}$ soil bulk density, 3.8 g kg$^{-1}$ soil organic matter, 10.8% sand content, 57.7% silt content, and 31.5% clay contents, respectively. This kind of soil represents soil samples with root biochemical effect, but without binding effect.

2.2. Soil sample preparing

The soil samples (part1 and part2) were independently passed through a 5-mm sieve after the removal of root fragments and air-dried to a moisture content of approximately 1.3%. Then, we used metal box, with dimensions of 200 cm × 28 cm (length × width), filled with soils in every 5-cm layers to a depth of 35 cm at a bulk density of 1.28 g cm$^{-3}$. Each layer was roughened by a small rake to minimize the discontinuity between layers. Once the box was prepared, all plots were treated equally and received the same amount of simulated rainwater. To promote purple alfalfa germination, the soil surface was covered with mats, and 1.5 L regular water in a plot was sprayed. When Alfalfa grew being about 5 cm in height, watering frequency was reduced. The Purple alfalfa seeds were sown at 10 cm row spacing with plant density of 90 (R1), 180 (R2), 270 (R3) and 360 (R4) stems/m$^2$ including 4 replicates, and employed a thin layer of soil (i.e., 1.0 cm) without fertilizer applications on 6 May 2013 (Fig.1A). Similar root-texture cotton thread in a diameter of 0.4 mm was chosen as the designed roots in the present study. Cotton thread was gently worn buried in CK2 soil sample at a horizontal angle of about 10° using special designed stainless steel needle. While threading, to prevent fragmentation clods on the surface soil (natural water content of about 10%) sprinkle a little water. Soaked in water for 24 h, to make it fully saturated, and then the conventional scouring was conducted. Thus, the designed roots in the soil have net-link and soil-root bond functions, but no root biochemistry effect, to soil erosion resistance. Therefore,18 plots (4 densities × 4 replications + 2(ck1 and ck2) = 18) were prepared in the present study.

2.3. Soil sample collection for flume experiment

Laboratory-simulated flow experiments were conducted nine weeks after Purple alfalfa was planted. The above-ground biomass was chipped to be level to the soil surface, and the residues were cleared. Four special rectangular sampling metal boxes with dimensions of 20 cm × 10 cm × 10 cm (length × width × depth) were driven into the soil in each plot using a hammer. A wooden plank was placed on top of the metal box during hammering for protection. To extract the soil sample from the plot, some soil was dug out with a trowel from the area surrounding the metal box. The soil sample was then lifted in such a way that some soil was sticking out below the open bottom side of the sample. Thereafter, the sampling box was packed using a membrane with a plastic plate attached to the bottom of the metal box to prevent soil loss during transport. Prior to scouring experiment, the samples were placed in a container with a constant water level of 5 cm below the soil surface to allow 12 h for slow capillary rise. The samples were then taken out of the water and drained for 8 h to obtain the same soil moisture before the flume experiment (Fig. 1B). Total 28 samples including 4 replications, were taken from the topsoil for simulated flow experiments.

A concentrated flow experiment was conducted with a hydrological flume (length = 2 m, width = 0.10 m). Simulated runoff flux (4 L min$^{-1}$) was designed according to the maximum potential runoff yield caused by a typical medium storm in the hilly Loess Plateau on a standard plot (20 m × 5 m). The flume slope of 15° referred to the standard slope of conversion from farmland to forestland in China. The scouring time (15 min) referred to the maximum time frequency for rainstorms in the research region (Fig. 2). During the 15 min duration of each experiment, samples of runoff and detached soil were collected every 1 min during the first 3 min and every 2 min thereafter using 10 L buckets. After the suspended particles had settled, the clear water was drained off, and the sediments were sampled and oven-dried at 105 °C.

2.4. Soil indicator determination

Immediately after each flow experiment, all roots were separated from the soil samples by hand washing on a sieve. Each root segment...
was dried with filter paper and then was scanned at a resolution of 300 dpi to obtain the root images for calculating root surface area density (RSAD, cm² root surface-area cm⁻³ soil). Soil aggregate content was determined by a wet sieving method (Yoder, 1936), soil bulk density was determined using a soil core (stainless steel cylinders with a diameter and a height of 5 cm each) at each sampling. Soil organic matter was determined by the modified Walkley-Black method. Total nitrogen and available nitrogen were determined using the method of Kjeldahl and available potassium permanganate distillation, respectively. Total phosphorus was determined using a molybdate-based colorimetric assay and available phosphorus was determined by extracting samples with 0.5 M NaHCO₃ (Nelson and Sommers, 1982). Soil erosion resistance (SER, L g⁻¹) was expressed as soil erodibility:

\[
SER = \frac{f \times t}{W}
\]

where \( f \) is the flow rate (L min⁻¹), \( t \) is the abrasion time (minute), and \( W \) is the weight of oven-dried sediment (g). Higher SER value indicates lower erodibility.

### 2.5. Parameter calculations

Root total effect (RTE, %) on soil erosion resistance can be divided into root physical enlacing (RPE, %), including net-link and soil-root bond functions (NF and BF, %), and root biochemistry effect (RBE, %). It was calculated by the soil loss in the root-penetrated treatments as compared with that in the soil parent material treatment through the scouring experiment, and calculated as follows.

\[
RTE = \frac{y_{CK1} - y_i}{y_{CK1}} \times 100\% \quad (2)
\]

where \( y_{CK1} \) is the soil loss in CK1, \( y_i \) is the soil loss in different root density treatments (\( i = 1, 2, 3, 4 \), the same follows).

RPE denotes the soil loss in the soil samples with and without root enlacing, and was calculated by following equation:

\[
RPE = \frac{y_{CK2} - y_i}{y_{CK2}} \times 100\% \quad (3)
\]

where \( y_{CK2} \) is soil loss in CK2.

### Table 1

Soil properties in different treatments.

<table>
<thead>
<tr>
<th>Soil properties</th>
<th>Treatment</th>
<th>CK1</th>
<th>CK2</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density (g cm⁻³)</td>
<td></td>
<td>1.30 ± 0.01a</td>
<td>1.28 ± 0.02ab</td>
<td>1.21 ± 0.02c</td>
<td>1.26 ± 0.02b</td>
<td>1.25 ± 0.01b</td>
<td>1.20 ± 0.02c</td>
</tr>
<tr>
<td>Aggregate content (0.25–5 mm, %) (g kg⁻¹)</td>
<td></td>
<td>42.8 ± 0.82e</td>
<td>65.5 ± 1.06d</td>
<td>133.9 ± 1.04c</td>
<td>148.5 ± 3.07a</td>
<td>140.3 ± 3.52b</td>
<td>148.8 ± 4.11a</td>
</tr>
<tr>
<td>Soil organic matter (g kg⁻¹) (g kg⁻¹)</td>
<td></td>
<td>2.32 ± 0.13e</td>
<td>3.01 ± 0.08d</td>
<td>3.73 ± 0.11c</td>
<td>4.04 ± 0.14b</td>
<td>3.81 ± 0.09bc</td>
<td>4.37 ± 0.22a</td>
</tr>
<tr>
<td>Total nitrogen (g kg⁻¹) (g kg⁻¹)</td>
<td></td>
<td>0.13 ± 0.01c</td>
<td>0.23 ± 0.01b</td>
<td>0.24 ± 0.01b</td>
<td>0.28 ± 0.01ab</td>
<td>0.26 ± 0.02b</td>
<td>0.29 ± 0.00a</td>
</tr>
<tr>
<td>Available phosphorus (mg kg⁻¹) (mg kg⁻¹)</td>
<td></td>
<td>1.63 ± 0.02f</td>
<td>2.36 ± 0.02e</td>
<td>3.99 ± 0.08d</td>
<td>5.08 ± 0.06c</td>
<td>5.27 ± 0.05b</td>
<td>8.21 ± 0.12a</td>
</tr>
<tr>
<td>Urease (NH₃-N mg g⁻¹)</td>
<td></td>
<td>0.35 ± 0.01c</td>
<td>0.49 ± 0.01b</td>
<td>0.48 ± 0.01b</td>
<td>0.47 ± 0.02b</td>
<td>0.57 ± 0.03a</td>
<td>0.63 ± 0.04a</td>
</tr>
<tr>
<td>Phosphatase (mg phenol g h⁻¹)</td>
<td></td>
<td>4.58 ± 0.17c</td>
<td>5.06 ± 0.18c</td>
<td>24.37 ± 1.72a</td>
<td>30.42 ± 1.99a</td>
<td>24.29 ± 1.42b</td>
<td>27.04 ± 1.87ab</td>
</tr>
<tr>
<td>Saccharase (mg glucose g h⁻¹)</td>
<td></td>
<td>1.02 ± 0.01e</td>
<td>1.51 ± 0.04d</td>
<td>1.45 ± 0.03d</td>
<td>6.27 ± 0.32a</td>
<td>3.87 ± 0.02c</td>
<td>4.10 ± 0.14b</td>
</tr>
<tr>
<td>Catalase (ml 0.1 N KMnO₄ g⁻¹)</td>
<td></td>
<td>2.96 ± 0.06d</td>
<td>3.58 ± 0.05bc</td>
<td>3.23 ± 0.04c</td>
<td>4.03 ± 0.10a</td>
<td>3.76 ± 0.14b</td>
<td>3.88 ± 0.09ab</td>
</tr>
</tbody>
</table>

Note: CK1, CK2 and R1 to R4 denote treatments of Loess parent soil, tillage soil and root density level 1 to 4, the same follows. Small letter in the same row means significant difference at p ≤ 0.05.
3.2. Relative contribution of roots to soil erosion resistance

Soil structural stability could be enforced by plant roots through root physical enlacing and biochemical exudates, and thus the erosion resistance of soil was improved. Table 1 indicates that soil bulk density decreased slightly in the root-penetrated soil as compared with CK2. 1.9–2.7 times were found in the aggregate content with increment of root density treatments. Compared with CK2, the soil organic matter content, total nitrogen content and available phosphorus in the root-penetrated soil were increased significantly, which demonstrates that roots can ameliorate soil structural stability, and increase soil nutrient content. On average, soil urease, phosphatase, saccharase and catalase were increased by 16.8%, 382.7%, 288.0% and 14.3%, respectively, in root-penetrated treatments as compared with those of CK2. Such results may be different in various soil types, because of the difference in soil-root-penetrated treatments as compared with CK2. Such results were increased by 16.8%, 382.7%, 288.0% and 14.3%, respectively, in root density treatments. Compared with CK2, the soil organic matter content, total nitrogen content and available phosphorus in the root-penetrated soil were increased significantly. As the root density increases, the effect of root physical enlacing increased significantly. And of this total, the relative contribution of net-link and soil-root bond functions to soil erosion resistance was 0.71:0.29, averagely. As the roots increased in quantity and size, a 18.9% percentage reduction in soil loss was observed, whereas the relative contribution of root biochemistry effect in the root total effect reduced slightly. This result indicated that root physical enlacing is the main reason, accounting for 77.7–82.0% of root total effect in strengthening soil erosion resistance. For comparison, the root physical enlacing in fibrous root-penetrated soils may play a more important role in reducing soil loss due to its larger root mass density and root surface area density (Zhou and Shangguan, 2005).

3.3. Relationship between RPE and RSAD

There is a remarkable relationship between soil erosion resistance and plant roots. Fig. 3 showed that an exponential function of $RPE = 90.67(1 - \exp(-0.037RSAD))$, $r^2 = 0.836$ could fit well the relationship between RPE effect and RSAD. This result is in accordance with the findings of Zhou and Shangguan (2005) that RSAD is an effective indicator in evaluating soil erosion resistance. Therefore, the RSAD could effectively reflect the effect of root physical enlacing, and thus could forecast the changes in soil erosion resistance.

4. Conclusions

In conclusion, our study demonstrated that root physical enlacing is the main form, accounting for 77.7–82.0%, in total root effect strengthening soil erosion resistance. As the root density increases, the effect of root physical enlacing increased significantly. And of this total, the relative contribution of net-link and soil-root bond functions to soil erosion resistance was 0.71:0.29, averagely. As the roots increased in quantity and size, a 18.9% percentage reduction in soil loss was observed, whereas the relative contribution of root biochemistry effect in the root total effect reduced slightly. This result indicated that root physical enlacing is the main reason, accounting for 77.7–82.0% of root total effect in strengthening soil erosion resistance. For comparison, the root physical enlacing in fibrous root-penetrated soils may play a more important role in reducing soil loss due to its larger root mass density and root surface area density (Zhou and Shangguan, 2005).

As depicted in Table 2, root physical enlacing effect of Purple alfalfa can reach as much as 81.95% in R4 treatment, with an average of 80.02%. A gently increasing trend was found in root physical enlacing as the root density increases from R1 to R4 treatment. This result agreed with the conclusion of previous studies that root mass density had a significant impact on soil erosion resistance in the flow-induced erosion regions (Zhang et al., 2013; Wang et al., 2014a, 2014b). In the root physical enlacing of Purple alfalfa, the relative contribution ratio of net-link and soil-root bond functions to soil erosion resistance was 0.71:0.29, averagely. As the roots increased in quantity and size, a 18.9% percentage reduction in soil loss was observed, whereas the relative contribution of root biochemistry effect in the root total effect reduced slightly. This result indicated that root physical enlacing is the main reason, accounting for 77.7–82.0% of root total effect in strengthening soil erosion resistance. For comparison, the root physical enlacing in fibrous root-penetrated soils may play a more important role in reducing soil loss due to its larger root mass density and root surface area density (Zhou and Shangguan, 2005).

### Table 2

<table>
<thead>
<tr>
<th>Root effect (%)</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root total effect (RTE)</td>
<td>100.00</td>
</tr>
<tr>
<td>Root physical enlacing (RPE)</td>
<td>77.74</td>
</tr>
<tr>
<td>Root biochemistry effect (RBE)</td>
<td>22.26</td>
</tr>
</tbody>
</table>

Note: CK1, CK2 and R1 to R4 denote treatments of Loess parent soil, tillage soil and root density level 1 to 4, the same follows.
contribution ratio of net-link and soil-root bond functions to soil erosion resistance was 0.71:0.29, averagely. Exponential function of $RPE = 90.67(1 - \exp(-0.037RSAD))$, $R^2 = 0.836$ could well express the relationship between root physical enlacing effect and root surface area density to soil erosion resistance. Therefore, the root surface area density could be regarded as the key indicator in forecasting the changes in soil erosion resistance in loam soils under the flow-induced erosion regions.

Acknowledgments

Financial assistance for this study was provided by the projects of the National Natural Science Foundation of China (Grant No. 41661101, 41471438), Doctoral research foundation of Yulin University (16GK19), the Open Program of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, CAS&MWR (A314021402-1604). We thank Zhai Lianning for her hard work on the laboratory analyses. We also express our gratitude to the anonymous reviewers and editors for their constructive comments and suggestions.

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