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The effects of ryegrass roots and shoots on loess erosion under simulated rainfall

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Abstract

Numerous studies have demonstrated that vegetation coverage is very important to control soil erosion by water. However, the combined impacts of plant roots and shoots on soil erosion by water and the relative contributions of the roots and shoots are not clearly understood. Four rainfall simulation experiments with the rainfall intensity at 1.5 mm min^{-1} were conducted at an interval of 5 weeks to investigate the effects of ryegrass (*Lolium perenne* L.) shoots and roots on soil erosion and runoff reductions. Ten ryegrass planted pans and four fallow pans were prepared for the experiments. The first rainfall simulation experiment was conducted after ryegrass had been planted for 12 weeks. It showed that compared with the runoffs in the fallow pans, the runoff in the planted pans decreased 25% and 70% in the 12th week and the 27th week, respectively; and the sediment decrements amounted up to 95% in the 27th week. The results also indicated that the shoot effect on runoff reduction, accounting for over 50% except in the 27th week when the shoot affect also accounted for 44%, was relatively greater than the root effect. However, the roots contributed more to soil loss reduction than the shoots, and in particular accounted for 90% of soil loss reduction at the 27th week. Both the soil erosion rate and average infiltration rate were linearly correlated with root surface area density in cm^2 root surface area per unit soil volume. Ryegrass planting could improve soil physical properties, especially soil aggregate stability, which increased from 33.1% in the 12th week to 38.5% in the 27th week. The study results are probably useful in evaluating the effects of plant shoots and roots on soil erosion control.

Keywords: Ryegrass; Roots and shoots; Soil infiltration; Soil erosion; Soil properties

1. Introduction

Soil erosion is a severe problem for most farming lands in the world and particularly in the Loess Plateau of China. Soil erosion by water has been the major cause for the losses of land nutrients and productivity. In recent years, off-site problems such as river/channel and reservoir sedimentation and waters pollution by sediment-borne chemicals have also become a concern (Poesen et al., 2003; Wu et al., 2003; Ranjith et al., 2004). Erosion control measures have been taken to reduce runoff and sediment yield. The vegetative measure is an effective way to control soil erosion by water (Gabet et al., 2003; Zhang et al., 2003, 2004).

Studies have been done to evaluate vegetation effects on soil erosion (Hou and Du, 1985; Luo et al., 1990; Jin et al., 1992; Achmad et al., 2003). The importance of vegetative coverage in reducing soil erosion by water was detailed in the literature (Gyssels et al., 2002). However, reports on relative contributions of the shoots and roots to soil erosion and runoff reduction are limited.

The effects of plant roots on soil erosion are not fully understood. Soil root systems contribute to soil strength (Li

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et al., 1991; Ghidey and Alberts, 1997; Mamo and Bubenzer, 2001a,b), soil structural stability (Márquez et al., 2004), soil infiltration (Li and Xu, 1992; Wu et al., 2000; Joseph et al., 2003) and soil aggregate stability (Monroe and Kladivko, 1987; Ghidey and Alberts, 1997; Martens, 2002) and thus are probably a key factor in the control of soil erosion by water.

The major objective of this study was to evaluate the relative contributions of shoots and roots to sediment and runoff the reduction.

2. Materials and methods

2.1. Soil properties and plant characteristics

A silty clay loam soil used in the experiments was collected from top 25 cm soil in a crop field at Yangling, Shaanxi Province, China and its sand, silt and clay contents were 13%, 58% and 29%, respectively. Wheat-maize rotation had been practiced in the field for at least 6 years. The field was moldboard ploughed and plant residues were removed. The soil was air-dried before they were sieved with 5 mm sieve to remove the residues and gravels.

Fourteen soil-erosion pans, 2.0 m long, 0.28 m wide and 0.35 m deep, were used in the experiments. 210 kg soil was filled into each erosion pan at 1.2 g cm^{-3}, the typical soil bulk density in farming field. To minimize uneven filling, the soil was filled in 3-cm layers. The bottom of the pans was porous so that excessive infiltration could leave the pans, and 2-cm deep gravel was placed on the bottom of the pans before soil was filled.

Perennial ryegrass (*Lolium perenne* L.) was planted in 10 of the fourteen pans in March 2004. To ensure that there were same ryegrass populations in each of the pans, same numbers of seeds (3 g $pans^{-1}$) were seeded in each of the pans. No seeds were sown in the 4 control pans (fallow), which were managed in weed control and irrigation during the growing period as the planted pans were managed. In particular, all the pans were irrigated before each experiment day to ensure that nearly the water contents were the same on the day.

2.2. Soil erosion

Four rainfall simulation experiments, beginning 12 weeks after ryegrass planting, were conducted at an interval of 5 weeks from June to October. Six pans, two fallow pans, two planted pans and two canopy-removed pans in which the grass shoots were cut and entirely removed before the experiments (these two pans are called root pans in following text), were used in each experiment. 1.5 mm min^{-1} rainfall in the form of tap water was applied to the six pans for an hour. The simulator was programmed and equipped with 120 spray nozzles. The simulator consisted of two troughs each of which had three nozzles that were 1.1 m apart. The simulator nozzles were 15 m above soil surface and this height ensured that the droplets had the same kinetic energy as natural raindrops did. After each experiment, the other two fallow pans (used to collect soil samples) and other planted pans were also exposed to a rainfall with the same intensity for 1 h. The soil pans were placed on a slope of 15°. The outflow from the pans was collected every 4 min with buckets. After the simulated rainfall, all the buckets were weighed and the sediment-laden water was allowed to stand until suspended sediments settled in them. Clear water was siphoned off, and the sediments were transferred to iron basins and oven-dried at 105 °C for 8 h and weighed.

2.3. Root sampling

After each erosion experiment, six samples were randomly taken in 0–10 cm soil on the root pans (three soil samples for each root pan) with a specially designed iron box, 20 cm long, 15 cm wide and 10 cm high. The roots were separated from the soil samples by washing and dried with filter papers. The roots were then spread on a rectangular transparent plastic sheet one by one. Precautions were taken to avoid root overlapping and abutting so as to minimize error. The roots on the plastic sheet were scanned at a resolution of 300 dpi for their images. The area of the root longitudinal section was determined with the CIAS V2.0 image analysis software developed by CID Company, USA. It was assumed in the study that the cross-section of the plant roots was circular and consequently the root surface area was calculated by the root longitudinal section areas times $\prod$.

Before the root surface area was measured, the scanner and software were calibrated by measuring various areas of rectangular paper. A 9 cm^2 paper was cut into 30 pieces of different shapes. These paper pieces successively increased in area and their areas totaled 9 cm^2. The root surface area density in soil, RSAD (cm^2 cm^{-3}) was calculated with the root surface area and the sampled soil volume.

2.4. Soil aggregate and soil organic matter

Three repeated soil samples were taken from the fallow pans and the root pans after each experiment to work over the soil physical properties. The samples (≈ 1 kg) were spread <1 cm thick, air dried, and then sieved to remove the 1- to 2-mm aggregates. The aggregate stability was tested with 4 g 1–2-mm sampled aggregate soil 2 weeks after soil sampling. The sampled aggregate soils were pre-wetted with deionized water through capillary action for 10 min and agitated on 0.25-mm sieves in deionized water for 5 min with the wet-sieving apparatus described by Kemper and Rosenau (1986). The soil aggregate stability is reported as the percentage of aggregate soil remaining on the sieve after being dried at 105 °C. The initial weight of aggregate soil was corrected by means of the weight of particles >0.25 mm. The soil organic matter was determined with soil samples that were sieved with 2 mm sieve after their root fragments were removed by the modified Walkey–Black wet oxidation procedure (Nelson and Sommers, 1996).

2.5. Data analysis

In this study it was presumed that soil loss and runoff reduction by plant were only a result of the combined effects of roots and shoot. Thus, the shoot effect on control of soil loss and runoff can be calculated from the effect of total plants less the root effects.

The total plant effect on sediment and runoff reductions can be calculated by the following formulae:

$$\begin{cases} \mathrm{CS_p} = \dfrac{S_\mathrm{f} - S_\mathrm{p}}{S_\mathrm{f}} \times 100\% \\ \mathrm{CR_p} = \dfrac{R_\mathrm{f} - R_\mathrm{p}}{R_\mathrm{f}} \times 100\% \end{cases} \tag{1}$$

where $\mathrm{CS_p}$ and $\mathrm{CR_p}$ are the plant contribution to sediment and runoff reduction, respectively; S_f and R_f are the sediment and runoff in the fallow pans (g), respectively; S_p and R_p are the sediment and runoff in the planted pan (g), respectively.

The root contribution to sediment and runoff reductions can be calculated by the following formulae:

$$\begin{cases} \mathrm{CS_r} = \dfrac{S_\mathrm{f} - S_\mathrm{r}}{S_\mathrm{f}} \times 100\% \\ \mathrm{CR_r} = \dfrac{R_\mathrm{f} - R_\mathrm{r}}{R_\mathrm{f}} \times 100\% \end{cases} \tag{2}$$

where CS_r and CR_r are the root contribution to sediment and runoff reductions (%), respectively; S_r and R_r are the sediment and runoff in the root pan (g), respectively.

The shoot contribution to sediment and runoff reduction can be calculated by the following formulae:

$$\begin{cases} \mathrm{CS_s} = \mathrm{CS_p} - \mathrm{CS_r} \\ \mathrm{CR_s} = \mathrm{CR_p} - \mathrm{CR_r} \end{cases} \tag{3}$$

where $\mathrm{CS_s}$ and $\mathrm{CR_s}$ are the shoot contribution to sediment and runoff reductions, respectively.

In order to determine the correlation of plant roots to soil erosion and infiltration rate, the soil erosion rate and infiltration rate in the root pans were calculated.

The soil erosion rate is computed by the following formula:

$$E_\mathrm{r} = \frac{\Sigma Q_\mathrm{i}}{t \times A} \tag{4}$$

in which

E_r is the soil erosion rate (kg $\mathrm{h^{-1}m^{-2}}$)
Q_i is the sediments in each bucket (kg)
t is the sampling time (h)
A is the area of the soil flume ($\mathrm{m^2}$)

The infiltration rate is calculated by the following formula:

$$i = I \times \cos\theta - \frac{10R}{A \times t} \tag{5}$$

in which

i is the infiltration rate (mm $\mathrm{min^{-1}}$)
I is the rainfall density (mm $\mathrm{min^{-1}}$)
θ is the slope (°)
R_i is the collected runoff in the ith bucket (ml)
t is the sampling time (min)

One-way ANOVAs were carried out with the SAS statistical software (SAS Institute, USA) to test the differences between the soil organic matter contents and aggregate stabilities in fallow and planted pans and the different stages.

3. Results and discussion

3.1. Relative shoot and root contributions to runoff and soil loss reductions

Soil loss reduction by vegetation is a result of the combined roots and shoot effects. The reduced runoff and sediment yields at different stages of ryegrass growth are presented in Fig. 1. Compared with fallow pans, the runoff in the planted pans decreased 25% and 70% in the 12th week and the 27th week, respectively; meantime, the soil loss decreased by up to 95% in the 27th week. This indicated that plants played a very important role in soil erosion control. As the grass roots and shoots increase in quantity and size, the sediment loss and runoff decreased rapidly. Similar results have been proved by the field measurements of concentrated flow channel cross-sections with different root densities of cereals and grasses in the loess Belt of Central Belgium (Gyssels and Poesen, 2003), which indicated that rill and ephemeral gully erosion decreased exponentially with increased root densities. And the authors highlighted that the exponential decline in soil erosion as was found in different erosion studies was probably the result of the combined roots and shoot effect on soil erosion.

The difference between sediment yield and runoff reductions due to plants was also showed in Fig. 1. Namely, the decrease in runoff was smaller than that in sediment loss, which indicated that the plant effect on sediment yield reduction was greater than that on runoff reduction.

The relative roots and shoot contributions to runoff and sediment reduction during the growing season are also showed in Fig. 1. The shoot effect on runoff reduction, amounting for over 50% except in the 27th week in which the shoot effect also accounted *t* for 44%, was relatively greater than the root effect. Whereas the shoots and roots effects on sediment reductions were opposite. The roots

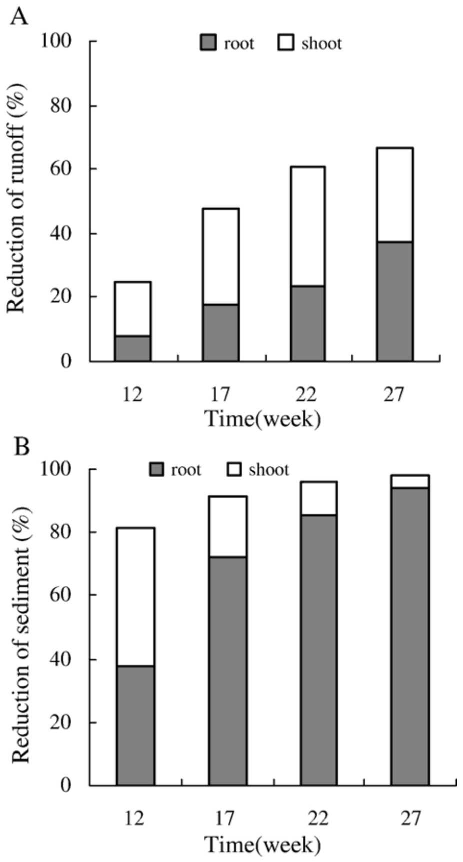

Fig. 1. Contribution of roots and shoots to the reduction of runoff (A) and sediment (B).

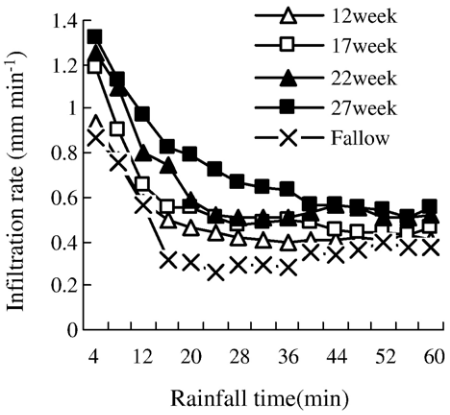

Fig. 3. Infiltration dynamics at different growing stages in the shoots removed pans and fallow pans.

reduced soil loss most, especially at the late growth stage when the roots contributed more than 90% to sediment reduction. These were probably because rainfall interception by shoot and prolonged infiltration reduced runoff, thus resulting in greater contributions to runoff reduction. And the root development could improve soil physical properties such as soil strength, shear strength, structural stability and aggregate stability, which are closely related to soil erodibility, thus resulting in greater root contribution to soil loss control (Monroe and Kladivko, 1987; Li and Xu, 1992; Ghidey and Alberts, 1997; Wu et al., 2000; Martens, 2002; Joseph et al., 2003).

3.2. Root effects on erosion

The soil loss rate decreased as the RSAD increased (Fig. 2). In contrast, Li and Xu (1992) and Wu et al. (2000) found that the density of fine roots, defined as the number of roots <1 mm in diameter per unit soil volume, has a considerable impact on the anti-scouribility of a loess soil from Loess Plateau and a red soil from granite in southern China. Mamo and Bubenzer (2001a,b) reported that the erodibility decreased sharply with increased root length density. In addition, Gyssels et al. (2002) reported that the soil erosion under intensified flow reduced with the increased root biomass density in soil. All of the study results can give us some useful information about the root effects on soil erosion control. However, little detailed and quantitative understanding of the root influences of living plants on soil erosion control is known. In Mamo and Bubenzer's research, the root

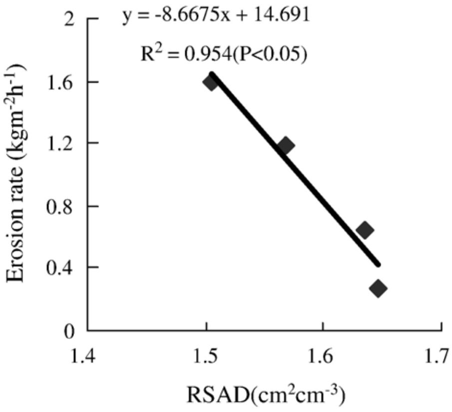

Fig. 2. The relationship between soil erosion rate and root surface area density.

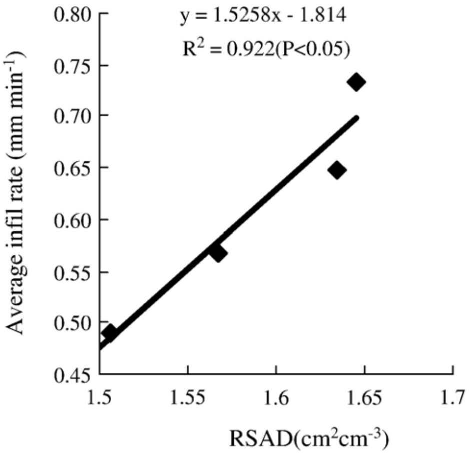

Fig. 4. Relationship between the average infiltration rate and the root surface area density in the shoots removed pans.

Table 1
Changes of soil organic matter and aggregate stability in fallow pan and planted pan in different stages

Time (week)	Organic matter (%)			Aggregate stability (%)		
	Fallow	Ryegrass	Difference	Fallow	Ryegrass	Difference
12	1.43±0.021 a	1.43±0.017 b	n.s.	31.9±2.16 a	33.1±1.98 b	**
17	1.42±0.025 a	1.46±0.019 b	n.s.	31.9±2.65 a	34.8±2.37 ab	**
22	1.42±0.016 a	1.51±0.021 a	*	31.8±1.98 a	37.6±1.88 a	**
27	1.41±0.020 a	1.52±0.018 a	*	31.8±2.09 a	38.5±2.07 a	**

Different letters indicate significant differences among time intervals in two treatments (fallow and ryegrass); the difference level between fallow and ryegrass in each stage is indicated by the following symbols: $^{**}P<0.01$, $^{*}P<0.05$, n.s $P>0.05$.

diameter impacts were not considered, while Li and Xu (1992) and Wu et al. (2000) did not consider the root length influences. The root thickness impacts in terms of root diameter and root length can be important on soil erosion control. The RSAD, which is the function of the root diameter and root length, can be a better indicator to quantify the relationship between roots and soil erosion.

3.3. Root effects on soil infiltration

Fig. 3 indicates that the initial infiltration rate increased with root growth. With infiltration going on, remarkable effect on infiltration appeared compared with the infiltration in the control at different growing stages. In addition, the average infiltration rate increased with increased RSAD during the experiment (Fig. 4).

The root role of the living plant in improving soil physical properties affecting soil infiltration has been discussed. It is known that roots release various organic and inorganic substances into soil (Hawes et al., 2000), which can improve soil physical properties around roots and thus increase soil aggregate stability and then infiltration rate (Martens, 2002). It is found that as soil water potential decreases, root exudates begin to release water into soil. When this occurs, the surface tension and viscosity of the exudates increase. As the viscosity increases, the resistance of soil particles contacting root exudates to water movement increases, and the stabilization within rhizosphere is enhanced to some extent. And this promotes soil infiltration (McCully and Boyer, 1997). Meanwhile, previous studies have reported that all plants form root channels which promote water entry as well as increase the infiltration rate (Devitt and Smith, 2002).

3.4. Root effects on soil organic and aggregate stability

Plant roots may affect soil aggregate stability and organic matter content. Increased organic matter and aggregate stability were observed in the planted pans from the 12th week to the 27th week (Table 1). In addition, the aggregate stabilities in the planted pans were significantly greater than those in the fallow pans at all the stages. And the organic matter contents in the planted pans were also significantly greater than those in the follow pans at the last two stages (Table 1). Previous study conducted by Mamo and Bubenzer's (2001a,b) also reported that the aggregate stability and organic matter increased compared with their original values after grass had been planted for three months. These indicated that plant roots could improve soil physical properties. Young (1995) found that the rhizosphere promotes water entry and soil aeration, thus resulting in increased microbial activities. Bacterial communities all contribute to good soil structure either by physically binding soil particles into aggregates, such as in the case of fungal hyphae and bacterial exudates, or by feeding other organisms that ultimately increase soil organic matter and soil aggregate stability (Ghidey and Alberts, 1997).

In a conclusion, ryegrass planting could improve soil physical properties and reduced most of the soil loss and runoff. The shoot contribution to runoff reduction was relatively greater than the root one, whereas, the shoots and roots effect on soil loss was opposite. The roots reduced soil loss most, especially at the late stage when the roots contributed more than 90% of sediment reduction. In addition, both soil erosion and infiltration rate were linearly correlated with root surface area density.

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