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THE CONTRIBUTION OF *ASTRAGALUS ADSURGENS* ROOTS AND CANOPY TO WATER EROSION CONTROL IN THE WATER–WIND CRISSCROSSED EROSION REGION OF THE LOESS PLATEAU, CHINA

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ABSTRACT

Simulated rainfall experiments were conducted to investigate the effect of *Astragalus adsurgens* roots and canopy on water erosion yield, erosion processes and soil resistance to erosion. Experiments were conducted on grass, root and bare slopes, with sandy soil from a water–wind crisscrossed erosion region of the Loess Plateau, China. *A. adsurgens* coverage on grass slopes was approximately 40%. There were three rainfall intensities of 30, 60 and 90 mm h^{-1} and four slope gradients of 3, 6, 9 and 12°. *A. adsurgens* had a significant effect on soil erosion control; soil loss was reduced by ~70% on slopes with the grass compared with bare slopes. The grass roots reduced soil loss more than its canopy, particularly in high-intensity rainfall, which reduced soil loss by 82%. The presence of the grass and its roots changed the soil erosion process, reducing soil erodibility (K_r) and increasing the critical shear stress (τ_c). The soil erosion rate on the bare slope increased steadily over time; on the grass and root slopes, its rate initially increased, then decreased and then finally stabilized. K_r on the grass and root slopes was reduced by 96% and 89%, respectively, compared with the bare slope, while the corresponding τ_c increased by 92% and 195% respectively. These results provide insights into the mechanisms of grass on soil and water conservation and may help to improve vegetation construction in water–wind crisscrossed erosion regions of the Loess Plateau. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: root and canopy; soil erosion; soil resistance to erosion; water–wind crisscrossed erosion region; *Astragalus adsurgens*

INTRODUCTION

Soil erosion is a major environmental and land degradation problem worldwide. Serious soil erosion can cause the loss of topsoil, accompanied by the loss of nutrients and plant seeds, which can significantly reduce land productivity and destroy local restoration of natural vegetation (Beyene, 2015; Bochet, 2015; Dai *et al.*, 2015). Increased sediment and other pollution loads in stream waters because of soil erosion can also affect stream habitat and water quality and can cause a decline in fish species and other aquatic animals (Kreutzweiser *et al.*, 2009). The Loess Plateau of China is well known across the world for its devastating erosion rates, which can be 15,000–20,000 Mg km^{-2} annually (Xiao *et al.*, 2012). This region discharges large amounts of transported sediment into the Yellow River (Wang *et al.*, 2016). Almost 90% of the sediment in the Yellow River comes from the Loess Plateau (Tian *et al.*, 2015). The most severe soil erosion in the Loess Plateau occurs in the water–wind erosion crisscross region, where water and wind work separately or together (Fan *et al.*, 2010). Thus, management practices are needed in this region to control soil and water loss and protect the fragile ecological environment.

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Vegetation has long been recognized as an efficient way to prevent soil erosion and is used in soil and water conservation efforts in many countries, such as France (Morvan *et al.*, 2014), Spain (Moreno-Ramón *et al.*, 2014), Italy (Biddoccu *et al.*, 2016) and China (Chen *et al.*, 2016). Yuksek & Yuksek (2015) studied the effects of sainfoin on the runoff and soil loss under natural rainfall conditions in Turkey and found that its presence led to a decrease in runoff by 73% and soil loss by 81% compared with bare soil. Feng *et al.* (2015) found that rapid revegetation could be obtained in the North China Plain by sowing seed mixtures of shrub and herbaceous species, and it is a useful measure to protect soil from wind and water erosion. Tian *et al.* (2015) showed that the soil erosion in hilly and gully areas of the Loess Plateau was clearly controlled by implementation of the "Grain for Green" programme, which transformed cultivated land into forests and grasslands (Deng *et al.*, 2012; Zhou *et al.*, 2016). Numerous studies have been conducted on the influence of vegetation on soil erosion as mentioned in the preceding texts, but little information is available concerning the impact of grass on water erosion in the water–wind crisscrossed erosion zone of the Loess Plateau.

Vegetation controls soil erosion mainly through the combined effects of the plant canopy and its roots. The canopy can intercept rainfall and increase soil surface roughness and runoff infiltration (Cerdà, 1998, 1999; Zhao *et al.*, 2015a), and the roots can contribute to soil shear strength (Li *et al*., 2015; Ola *et al*., 2015), soil infiltration (Yu *et al*., 2015; Zhao *et al*., 2015b) and soil structure and aggregate stability (Ni *et al*., 2015; Vannoppen *et al*., 2015). Zhou & Shangguan (2008) showed that ryegrass roots could reduce sediment yields in silt–loam soil by up to 96%. Zhang *et al*. (2014) concluded that the canopy and roots of grasses contribute almost equally towards soil loss in a loamy loess soil. Gyssels *et al*. (2005) reported that vegetation cover was the most important parameter for splash and inter-rill erosion, whereas plant roots were at least as important as vegetation cover for rill and ephemeral gully erosion. The effect of vegetation cover and roots on soil erosion clearly varies as the plant and soil conditions vary, and it is necessary to quantify this effect in the waterswind crisscrossed erosion zone to guide future ecological environment construction of this region.

Astragalus adsurgens is a common grass widely distributed in the water–wind crisscrossed erosion zone of the Loess Plateau and plays an important role in controlling sand and preventing windstorms. The objectives of this study were to (i) understand the relative contribution of *A. adsurgens* roots and canopy to water erosion control with varying rainfall intensities and slope gradients and (ii) investigate the impact of the intact grass and roots on soil erosion processes and soil resistance to erosion, reflected by soil erodibility (K_r) and critical shear stress (τ_c) in the water–wind crisscrossed erosion zone of the Loess Plateau.

MATERIALS AND METHODS

Experimental Facilities

Experiments were conducted in the Simulation Rainfall Hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Yangling, China. The experiments employed a side-sprinkle precipitation system, which could precisely regulate rainfall intensities by adjustment of nozzle sizes and water pressure. The height of the rainfall simulator extended up to 8 m and could simulate storms with a uniformity of 88%, with raindrop distribution and size similar to natural rainfall (Pan & Shangguan, 2006). Calibrations of rainfall intensity were conducted prior to the experiments.

Experimental Treatments and Measurements

The experimental plot was constructed with metal frames of 8 m (length) × 1 m (width) × 0.33 m (depth) and was divided into two narrow sub-plots, representing two replicates of equal width by a polyvinyl chloride panel. The measured values of each combination were the average of the two replicates. If the values of the two replicates varied greatly, the data were discarded and the test was repeated to ensure reliability of the data. The slope gradient of the plot was adjustable by a movable base. Sandy soils were collected from the top 20 cm of soil in Dingbian, Shaanxi Province, located in the water–wind crisscrossed erosion zone of the Loess Plateau. The particle-size distribution of the soil is shown in Figure 1, and the median diameter was about

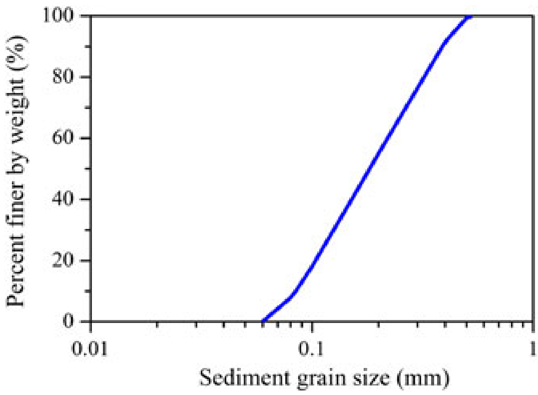

Figure 1. Particle size distribution curve of the soil in the experiment.

0.18 mm. The soil was air-dried, gently crushed and then passed through a 10-mm sieve to remove gravel and plant residue. Before packing, a layer of medical gauze was placed at the bottom of the plots to increase bed roughness and prevent soil sliding at large slope gradients. Then 20-cm-thick soil was packed in four 5-cm layers to achieve a 1.5 g cm^{-3} bulk density. Each soil layer was raked lightly before the next layer was packed to diminish discontinuity between layers. *A. adsurgens*, a common indigenous grass in the water–wind crisscrossed erosion zone, was the target species. Seeds were sown broadcast at a sowing density of 0.05 kg m^{-2}.

The rainfall simulation experiments were conducted 5 months after planting *A. adsurgens*, when the grass was in the vegetative growth stage, with a canopy height of ~20 cm and cover of 40%. The root mass density was about 1.6 kg m^{-3}. According to the rainfall characteristics and topography of the Loess Plateau, the rainfall intensities applied were 30, 60 and 90 mm h^{-1}, and slope gradients were 3, 6, 9 and 12°. One day before the experiment, a soil water instrument WET (YA1 -WET-2-K1, England) was used to determine the soil water content of the different treatments. According to the measured values, different amounts of water were sprayed with a commonly used household sprayer to ensure the same antecedent soil water content among treatments on the experiment day. The water uptake of grass roots was very small and was negligible during this period. After every rainfall test, soil erosion occurred on the plots. According to the methods used in previous studies (Zhang *et al*., 2012; Cao *et al*., 2015a), an equivalent weight of sandy soil was used to repair the eroded surface and then the repaired plots stood for 2 days before the next test, to ensure that the new soil fully integrated with the soil on the slope, so as to minimize the difference in soil surface conditions. After experiments with the intact grass (i.e. ~20 cm) were completed, *A. adsurgens* was cut to ground level with a pruner. The plots were treated as in the preceding texts, this time to investigate the effect of the roots on soil erosion control. Hereafter, we refer to the plots with intact grass and roots as grass and root slopes respectively. A bare slope with the same soil but no grass seeds sown was used as the control. A total of 36 rain events were performed. The duration of all simulated rainfall was 1 h from runoff initiation. Because the rainfall tests on grass and root slopes were completed within 2 months, the effect of grass growth during this time on soil erosion was ignored.

During each rainfall, plastic buckets were used to collect all runoff and sediment at 3-min intervals. After the rainfall, the buckets were allowed to stand until the suspended sediment settled out. The supernatant was then discarded, and the sediment was transferred to iron basins, oven dried at 105°C and weighed. Flow velocity was measured using the $KMnO_4$ dye technique, in which the velocity of the leading edge of dye (the surface flow velocity) was measured. For each test, a small amount of dye was quickly injected into the flow using a soft plastic bottle with a pipe of length 0.15 m. The travel time of the dye cloud over a distance of 1 m along the plot was recorded using a digital stopwatch, and used to estimate the surface flow velocity. For each test, four sections of 4–5, 5–6, 6–7 and 7–8 m from the upper to the lower end of the plot were designated to measure the velocity, with three replicates. The average of the three flow velocities was considered as the mean surface flow velocity of each section. The mean surface velocity was modified by a correction factor according to the flow regime to estimate the profile mean velocity of each section (Li *et al*., 1996).

Data Analysis

Soil loss reduction by plants was a result of the combined effects of roots and canopies, as the grass was in the vigorous growth stage with little litter. The canopy effect on soil erosion control was calculated from the effect of the total plant less the root effects, and the calculation accuracy was 1%.

The effects of total plant (CS_p), roots (CS_r) and canopy (CS_c) on sediment reduction were calculated using

$$\begin{aligned} CS_p &= \frac{S_b - S_p}{S_b} \times 100\% \\ CS_r &= \frac{S_b - S_r}{S_b} \times 100\% \\ CS_c &= CS_p - CS_r \end{aligned} \qquad (1)$$

Where: S_b, S_p and S_r are the erosion rates on bare, grass and root slopes respectively (kg m^{-2} min^{-1}).

The contribution rate of root (C_r) and canopy (C_c) on sediment reduction were calculated using

$$\begin{aligned} C_r &= \frac{CS_r}{CS_p} \times 100\% \\ C_c &= \frac{CS_c}{CS_p} \times 100\% \end{aligned} \qquad (2)$$

The flow shear stress τ (Pa) was calculated using

$$\tau = \rho g h S \qquad (3)$$

Where: ρ is the sediment-laden water density (kg m^{-3}), g is acceleration because of gravity (m s^{-2}), S is the slope gradient (m m^{-1}) and h is the flow depth (m). The flow depth was calculated using

$$h = \frac{Q}{VB} \qquad (4)$$

Where: Q is the average flow discharge corresponding to the erosion part of the plot (m^3 s^{-1}), V is the average flow velocity corresponding to Q (m s^{-1}) and B is the plot width (i.e. 0.5 m).

K_r and τ_c were estimated as the slope and intercept on the x-axis of the linear regression line between soil erosion rate and shear stress as described by Gilley *et al*. (1993) and Foltz *et al*. (2008). The method needs to meet two conditions. First, the method needs a short slope length. Although the slope length was 8.0 m in our experiment, the effective slope length for soil detachment was not large because of the existence of the critical slope length for erosion or rill initiation. According to the experimental observations, the critical slope lengths on grass, root and bare slopes were 6.5–7.5, 5.8–7.2 and 3.0–5.0 m, respectively, giving corresponding average effective slope lengths of 1.0, 1.5 and 4.0 m. For grass and root slopes, the effective slope lengths were sufficiently short to use the method. For the bare slope, the effective slope length of 4.0 m was a little larger. However, the estimation error caused by the slope length was small (within 15%) and could be ignored on bare slope, based on the analysis of Lei *et al*. (2005).

Second, the method needs a constant flow. The experiment in our study used constant rainfall conditions, and the discharge was not constant in space. However, as for the analysis explained in the preceding texts, for the grass and root slopes, the soil erosion mainly occurred in 6.0–8.0 m of the plot, so average shear stress only needed to be calculated between these two cross sections. The flow discharge did not vary greatly between the two sections when equilibrium was reached. The average values of Q and V between the two cross sections were used in Equation 4 to estimate the flow depth used in Equation 3. For the bare slope, the soil erosion mainly occurred in 4.0–8.0 m of the plot. The average shear stress between these two cross sections was also estimated in the same way as for the root and grass slopes. Although the simplified estimation for the shear stress may affect quantitative analysis of the result, it could still reflect the overall laws of soil erodibility on the three slopes as well as the effects of grass and grass roots on soil resistance to erosion. A one-way ANOVA and least significant difference multiple-comparison test were used to identify statistically significant soil erosion differences among treatments.

RESULTS

Sediment Yield

Sediment yields ranged between 0.001–1.374, 0.001–0.304 and 0.001–0.187 kg m^{-2} min^{-1} on bare, root and grass slopes, respectively, and the yields increased as rainfall intensity and slope gradient increased. For most tests, there were significant differences in sediment yield among the three slopes (Table I). However, in the low rainfall intensity

Table I. The sediment reduction effect of root and canopy on different slope gradients and rainfall intensities.

Slope gradient (°)	Rainfall intensity (mm h^{-1})	Erosion rate (kg m^{-2} min^{-1})			Sediment reduction effect (%)		
		Bare slope	Root slope	Grass slope	Grass	Root	Canopy
3	30	0	0	0	—	—	—
	60	0.0014a	0.0011ab	0.0008b	39	22	17
	90	0.004a	0.003b	0.002b	54	32	22
6	30	0.012a	0.008b	0.006c	49	32	17
	60	0.051a	0.041b	0.019c	63	20	43
	90	0.144a	0.047b	0.035c	75	67	8
9	30	0.059a	0.045b	0.030c	48	23	25
	60	0.240a	0.130b	0.031c	87	46	41
	90	0.719a	0.183b	0.129c	82	75	7
12	30	0.281a	0.094b	0.051c	82	66	16
	60	0.676a	0.247b	0.041c	94	63	31
	90	1.374a	0.304b	0.187c	88	79	9

Note: Means within a row followed by the same letter are not significantly different at $P = 0.05$ level using the least significant difference method.

and small slope tests, only significant differences occurred between bare and grass slopes. Soil loss on the grass slope was reduced by 39%–94%, with an average reduction of 70%, when compared with the bare slope. The contribution of grass to soil loss reduction increased with increases in rainfall intensity and slope gradient. The reduction in the soil loss rate caused by grass increased from 49% to 75% when the rainfall intensity was increased from 30 to 90 mm h^{-1}, at a slope gradient of 6°. The effect of slope gradient on soil loss control by grass was larger than that of rainfall intensity.

The contribution rates of the grass roots and its canopy in soil loss reduction are shown in Figure 2. The soil loss reduction rate caused by the roots and canopy was in the range 20%–78% and 7%–43%, respectively, with corresponding averages of 48% and 21%. The contribution rate of roots in soil loss reduction increased from 56% to 80% when slope gradients increased from 3° to 12° (Figure 2a). There was a parabolic relationship in the contribution rate of roots with rainfall intensity, and the minimum contribution rate was at an intensity of 60 mm h^{-1} (Figure 2b). The contribution rate of the grass canopy to soil loss reduction showed an opposite trend, with increasing rainfall intensity and slope gradients. The average contribution rates of the grass roots and canopy to soil loss reduction were 66% and 34% respectively.

For the high rainfall intensity and slope gradient, rill erosion occurred on the three slopes. The appearance of the rills on the slope was the result of interaction of erosivity of rainfall and runoff and soil resistance in space and time. As rainfall continued, the runoff erosivity increased enough to scour soil clods, in particular at the point with poor soil resistance, which resulted in small waterfalls. Once small waterfalls evolved into rill headcuts, corresponding rill erosion occurred. There were marked differences in rill spatial distribution and shape between bare slope and root and grass slopes. For the bare slope, rills were mainly distributed in the middle and bottom of the plot, approximately within 3–8 m along the plot. The rills had small depths and large widths, with average depths of 0.5–1.5 cm and width nearly spreading the whole width of the plot.

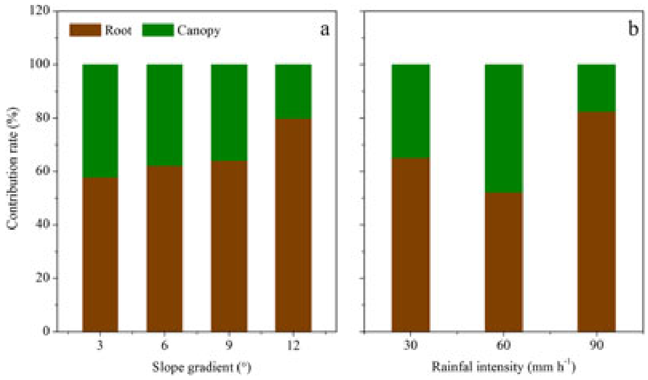

Figure 2. Contribution rate of grass root and canopy to sediment reduction under different slope gradients and rainfall intensities. (a) Different slope gradients. (b) Different rainfall intensities.

For the root and grass slopes, rills were mainly distributed in the bottom of the plot, approximately from 5.8 m on root slopes and 6.5 m on grass slopes. The rills on both slopes had large depths and small widths. The average depths and widths on root slopes varied within 1.9–4.0 cm and 8–14 cm, respectively, and the corresponding values were 1.2–3.5 cm and 6–11 cm on grass slopes.

Soil Erosion Process

The processes of soil erosion on the three slopes at different rainfall intensities (30, 60 and 90 mm h^{-1}) and slope gradients (6°, 9° and 12°) are shown in Figure 3. Because the soil loss at a slope gradient of 3° was very small or even zero, the soil erosion process is not shown. The soil erosion processes on a fixed slope at all rainfall intensities and slope gradients had similar trends. The soil erosion processes for the bare slope were significantly different from the grass and root slopes. Soil erosion rates on the bare slope fluctuated with increases in runoff duration, while on grass and root slopes, rates initially increased, then decreased and thereafter remained almost constant.

Soil erosion and sediment processes fluctuated strongly on the bare slope. Sediment on grass and root slopes fluctuated slightly. At the rainfall intensity of 90 mm h^{-1} and slope gradient of 12°, soil erosion rates on the bare slope ranged between 0.03 and 2.25 kg m^{-2} min^{-1}, while on grass and root slopes these rates ranged between 0.06–0.46 and 0.08–0.61 kg m^{-2} min^{-1} respectively. As rainfall intensity increased, the time before erosion rates on grass and root slopes reached a stable state also increased. The erosion rate duration of grass and root slopes also showed a similar trend with increasing slope gradient at the same rainfall intensity.

The effects of intact grass, roots and canopy on soil loss reduction, with runoff duration at all rainfall intensities and three slope gradients are shown in Figure 4. The sediment reduction effects of both intact grass and roots increased with increasing rainfall intensity and slope gradient. The effects of intact grass on soil loss reduction for the three rainfall intensities were similar; there was an initial increase in soil loss reduction, which then stabilized as the rainfall continued, and the reduction rate was as high as 97% at the stable stage for high-intensity rainfall. The soil loss reduction effect of the roots and canopy differed over time for different rainfall intensities. At a rainfall intensity of 30 mm h^{-1}, the soil loss reduction rates for both the roots and canopy increased and then stabilized with time, and the effect of roots on soil loss reduction was slightly larger than that of the canopy. At rainfall intensities of 90 mm h^{-1}, the reduction rate of roots stabilized with time, whereas that for canopy initially increased, and then decreased with

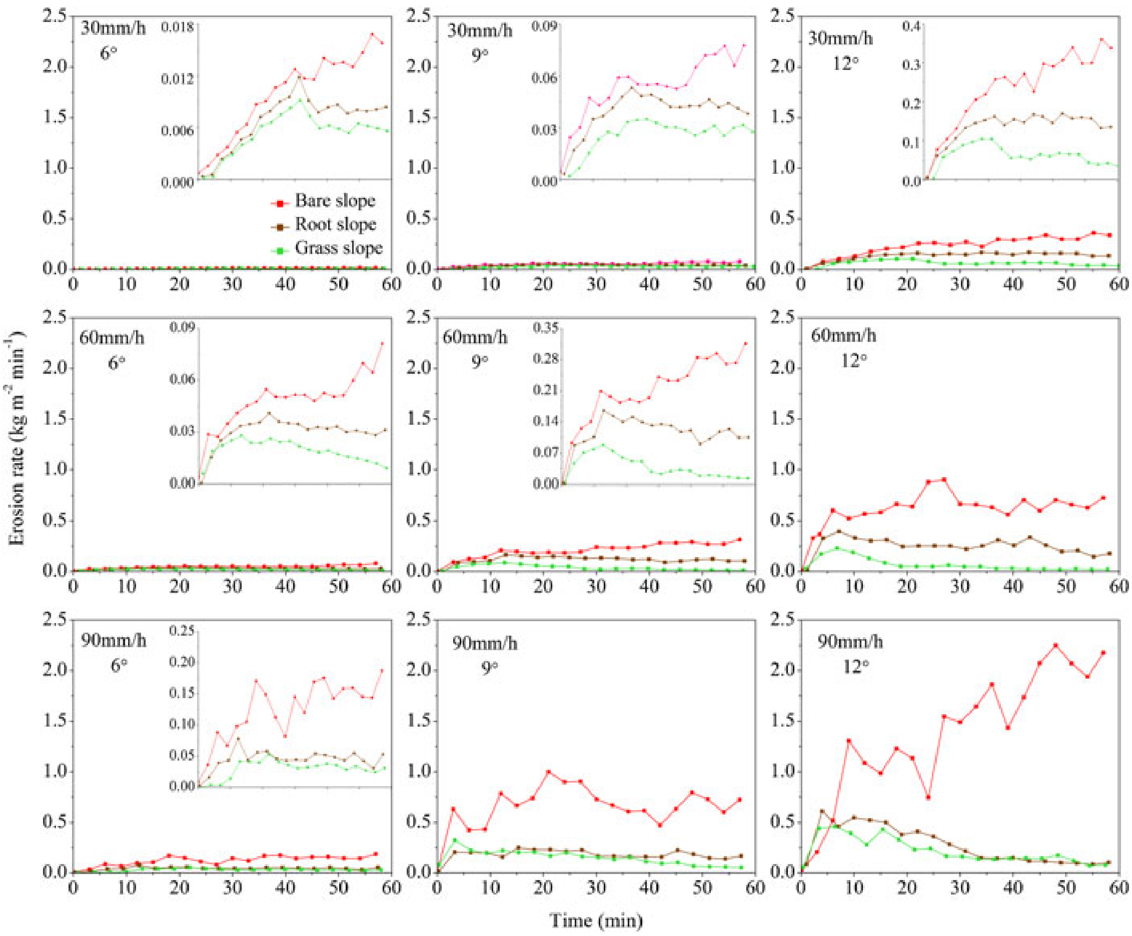

Figure 3. Soil erosion process on bare, root and grass slopes at different rainfall intensities and slope gradients except 3°.

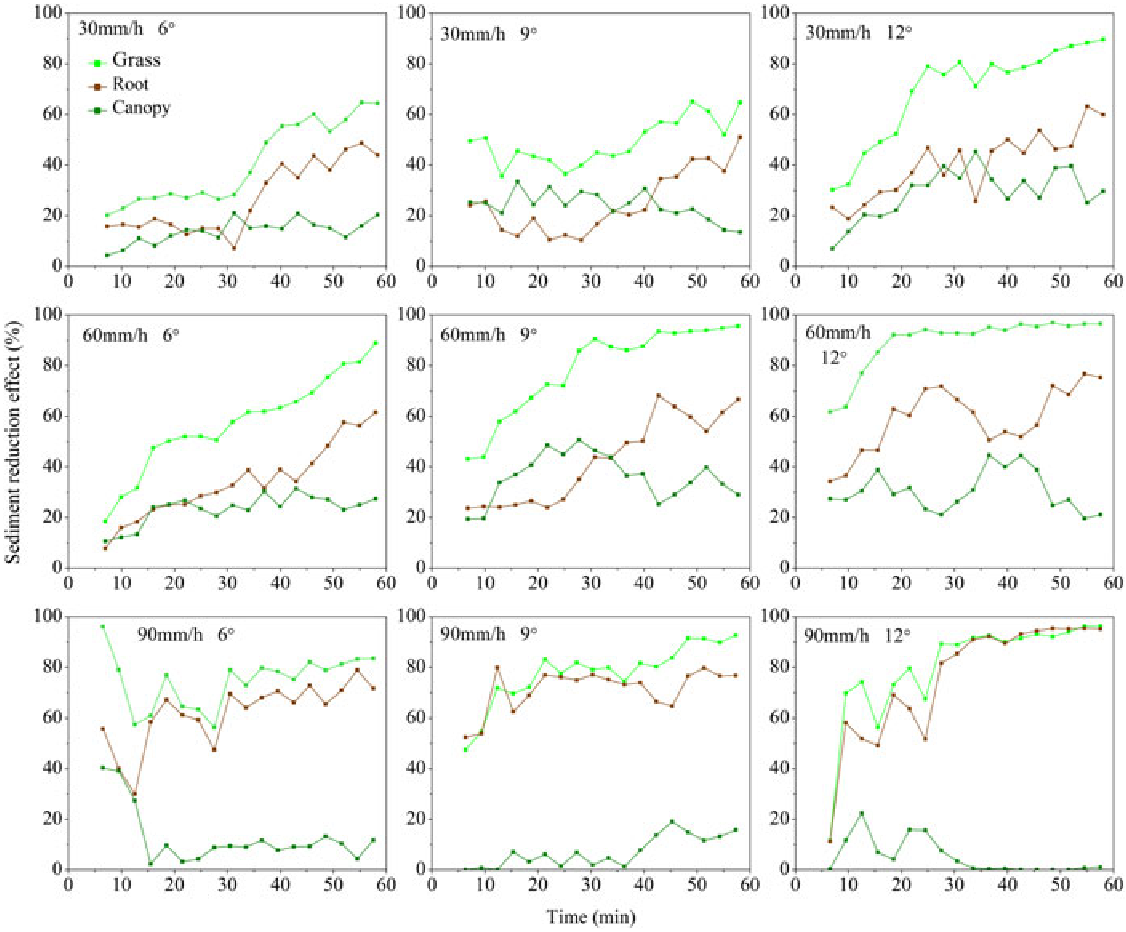

Figure 4. Sediment reduction of root and canopy with time at different rainfall intensities and slope gradients except 3°.

runoff duration. The effect of roots on soil loss reduction was much larger than that of the canopy.

Soil Erodibility and Critical Shear Stress

The K_r and τ_c for the three slopes are shown in Figure 5. The grass and roots effectively reduced K_r and increased τ_c. The K_r value of the bare slope was 1.104, which was 9 and 28 times higher than those of the root and grass slopes respectively. The contribution of roots in the reduction in K_r was much larger than that of the canopy—92% and 8% respectively. The τ_c on bare, root and grass slopes was 0.434, 0.832 and 1.282 Pa respectively. Compared with bare soil, τ_c increased by 92% and 195% for the root and grass slopes respectively.

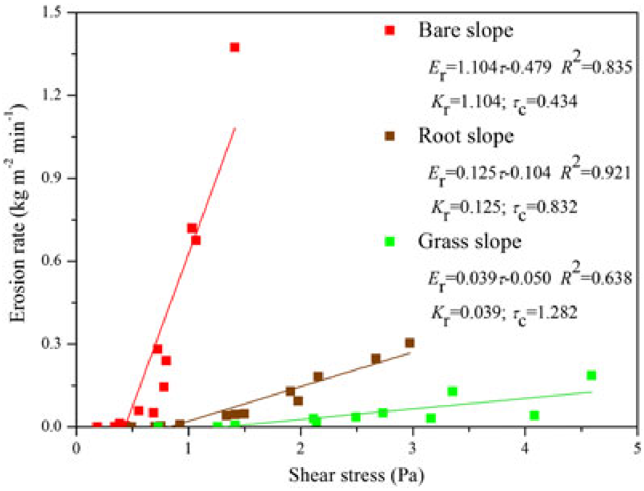

Figure 5. Erosion rate as a function of shear stress.

DISCUSSION

Effects of Grass Roots and Canopy on Soil Erosion

Soil erosion is very serious in the water–wind crisscrossed erosion zone of the Loess Plateau. In this study, the soil loss on the grass slope was reduced by ~70%, indicating that vegetation construction plays a very important role in soil erosion control in this region. Similar results were also found for other plant species, soil types and areas (Braud *et al*., 2001; Casermeiro *et al*., 2004; Mohammad & Adam, 2010; Ouvry *et al*., 2010; Fattet *et al*., 2011; Zhang *et al*., 2012). The contribution of grass to soil loss reduction increased as the rainfall intensity and slope gradient increased, implying that grass could have a much more significant effect on soil and water conservation at high-intensity rainfall and on steep slopes.

Both the roots and the plant canopy caused a reduction in soil erosion, and their respective contributions differed. The contribution rate of the plant roots to the reduction in soil erosion was much greater than that of the plant canopy: 66% and 34% on average respectively. Similar results have been found in previous studies (Zhou & Shangguan, 2008; Zhang *et al*., 2012). Our results, along with these studies, suggest that in many agroecosystems, although the above-ground component of vegetation is harvested or removed, the belowground component of vegetation is still effective and reliable for soil erosion control. However, some studies have reported that the effect of plant roots and canopy on sediment reduction are almost equivalent on grass slopes (Zhang *et al*., 2014), with some even suggesting that the effect of roots is less than the effect of the canopy (Gyssels *et al*., 2005). These conflicting results may be because of differences in the plant species and soil types used in the different studies.

The mean erosion rates for several tests of the experiment were significant, with a mean erosion rate of up to $0.3\,\mathrm{kg\,m^{-2}\,min^{-1}}$ for the root slope (Figure 1). The serious soil erosion mainly occurred on the high rainfall intensity and slope gradient conditions and seemed closely related to the formation of rills in the bottom of the plot. Rill erosion might compromise the stability of the plants in the slope and cause severe soil loss on pruned slopes. Thus, suitable plant species should be selected in the water–wind crisscrossed erosion region of the Loess Plateau for controlling the rill or gully erosion (De Baets *et al*., 2009). Meanwhile, any channels formed should be filled as soon as possible to prevent further deterioration from rill erosion.

The presence of grass or plant roots on slopes also affected the soil erosion process on sandy soil. The soil erosion rate on the bare slope tended to increase with runoff duration. On grass and root slopes, there was an initial increase in the soil erosion rate, followed by a decrease, after which it stabilized. It is possible that for the bare slope with sandy soil, the soil was loose and soil pore connectivity was better, so that cohesion between the soil particles was poor, which may have provided enough detached material for soil erosion and flow transport, because of continued raindrop impact. For the grass and root slopes, early in the rainfall, the original loose material on the soil surface flowed down the slope, which rapidly increased the initial erosion. As the rainfall continued, although the soil moisture gradually reached saturation and runoff became large, there were less detached soil particles and other loose materials present because of the protection and improvement to the sloping soil from the grass or roots. This resulted in a decrease in the soil erosion rate. Infiltration and rainfall eventually reached equilibrium, and the intensity of the erosion tended to stabilize.

The soil erosion process on the bare slope presented here also differed from that found on silt-loam soil, which showed a rapid increase–decrease–stable trend (Katuwal *et al*., 2013; Cao *et al*., 2015b). This difference can be mainly attributed to the difference in soil textures. In the early stages of rainfall, erosion was mainly caused by splashes of the raindrops. Many soil particles became detached, rapidly increasing the erosion. As rainfall continued, the mechanical action of raindrop impact, the wetting of soil and the deposition of suspended sediment on the soil surface gradually led to the formation of a restrictive sealed layer on the surface of the silt–loam soil, which did not easily form on sandy soil. The formation of a soil surface seal can increase the soil shear strength, thus decreasing the soil erodibility (Moore & Singer, 1990). The decreasing soil erodibility resulted in a decrease in erosion rate with cumulative rainfall. As the rainfall continued, the runoff rate became stable, which lead to further stabilization of the erosion rate.

The sediment transport rate on all slopes fluctuated, although to different extents. The soil erosion rate on the bare slope had the greatest fluctuation in our experiment. This is consistent with Van Oost *et al*. (2009), who reported that erosion fluctuated on a bare slope, and that more local minima and maxima occurred during erosion and sediment processes because of repeated and alternating connections of rills, collapse of side walls and blocking and breakthrough. During low-intensity rainfall, the effect of the grass roots on soil erosion control was similar to the effect of the canopy, while at greater rainfall intensity, the root effect was much larger, especially at an intensity of $90\,\mathrm{mm\,h^{-1}}$. This suggests that plant roots play the most important role in soil loss reduction during high-intensity rainfall. As such, planting vegetation with large root systems may be the most effective method for controlling soil erosion in the region.

Effects of Grass Roots and Canopy on Soil Erodibility and Critical Shear Stress

K_r and τ_c are important parameters reflecting the ability of soil to resist the dispersion of rainfall and runoff, which is closely related to soil erosion. Soil erosion occurs when flow shear stress exceeds the τ_c of soil as well as when the sediment concentration is lower than the sediment transport capacity of the flow. It is thought that grass prevents soil erosion through the direct or indirect effects of its roots and canopy on K_r and τ_c. The grass and its roots significantly decreased K_r and increased τ_c, and the contribution of roots to K_r reduction was much larger than that of the canopy. This was also why the roots had a much larger effect on soil loss reduction than the canopy.

The difference in K_r and τ_c for the grass and root slopes can be attributed to the different physical properties of the soil. The presence of the grass canopy can increase soil infiltration rate and water content, and both these parameters have a positive impact on the ability of the soil to resist scouring and a negative impact on K_r (Zhou *et al*., 2010). So the increase in soil infiltration rate and water content led to an increase in τ_c and a reduction in K_r on the grass slope. Moreover, the grass canopy could also increase the slope surface roughness and decrease the runoff velocity and erosion intensity, which had an indirect positive influence on reduction in K_r and increase in τ_c.

Soil and vegetation types also affect K_r and τ_c. By collecting available data from different studies, Knapen *et al*. (2007) reported that the K_r of silt–loam and clay–loam soils was 0.78 and 0.24 respectively, which was lower than the K_r of sandy soil, while the τ_c of sandy soil was less than silt–loam (3.4 Pa) and clay–loam (6.9 Pa) soils, indicating the greater susceptibility of sandy soil to soil erosion. The K_r of the grass slope was 0.039, which was 1 order of magnitude smaller than that reported by Wang *et al*. (2014), who used korshinsk peashrub, black locust and Chinese pine in their study. The use of different plant species may account for the difference in K_r and τ_c values.

Biological crusts are another important factor influencing soil erosion in sloping land, and they are often observed in the water–wind crisscrossed erosion zone of the Loess Plateau. Biological crusts quickly develop in the initial stage of vegetation restoration because of the vegetation and litter cover and are effective in protecting the surface soil from rainfall detachment and flow transport (Muscha & Hild, 2006; Rodriguez-Caballero *et al*., 2012). Biological crusts are mostly composed of algae and mosses. Biological crusts of a thickness of ~1.0–1.2 mm were also present on the root and grass slopes in the present study and likely had an important role in soil erosion control.

Grass can significantly control soil erosion (Pereira *et al*., 2015) and re-establishes the infiltration rate and decreases soil erodibility faster than other plant types (Cerdà & Doerr, 2005). The effect of grass on soil loss reduction is a result of the combined effects of aboveground and belowground parts. Aboveground biomass can reduce raindrop impact, increase rainfall interception and surface roughness, decrease runoff velocity and improve soil ability to absorb rain (Pan & Shangguan, 2006; Zhang *et al*., 2012). Plant roots can bind soil particles at the soil surface to reinforce the soil and increase soil strength by penetrating the soil mass (Ghidey & Alberts, 1997). Root exudates can cement soil and form a stable aggregate structure, which then strengthens soil cohesion (Martens, 2002). All of these direct or indirect actions have a positive influence on reductions in K_r and increasing τ_c and can therefore make a large contribution to soil erosion control.

CONCLUSIONS

A. adsurgens could significantly control soil erosion on sloping land in the water–wind crisscrossed erosion region of the Loess Plateau. In this study, soil loss was reduced by ~70% on slopes with the grass compared with bare slopes. *A. adsurgens* controlled soil erosion mainly through the combined effects of its roots and canopy; its roots reduced soil loss more than its canopy. Notably, during high-intensity rainfall, its roots played the most important role in sediment reduction. The grass and its roots also changed the soil erosion process. The presence of grass affects soil resistance to erosion, as reflected in K_r and τ_c. The grass and its roots effectively reduced K_r and increased τ_c, with its roots and canopy reducing K_r by 92% and 8% respectively. These results are useful in revealing the mechanism of the action of grass roots and canopy on soil and water conservation and have implications for vegetation selection and construction in the water–wind crisscrossed erosion region of the Loess Plateau.

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