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# Runoff maintenance and sediment reduction of different grasslands based on simulated rainfall experiments

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ABSTRACT

Large-scale vegetation restoration generally reduces local water yield and influences river ecosystem health. Thus, scientific evaluation of vegetation restoration consequences is necessary for maintaining the stability of the surface water system and water cycle in semi-arid regions. In this study, we compared the efficiencies of different typical grasslands in regulating runoff and sediment yields and proposed feasible suggestions suiting for local environments. Four grasslands, including two Gramineae species (*Elymus dahuricus* and *Bromus inermis*) and two legume species (*Medicago sativa* and *Trifolium repens*), were tested during a two-year period with simulated rainfall experiments, and using bare land as control. Three replicates were done for each treatment, and fifteen plots with a slope of 20° were constructed. Three indices were used to assess the runoff and sediment yields reduction capacity of the grasslands, including runoff reduction benefit (RRB), sediment reduction benefit (SRB), and soil infiltration rate (SIR). The results showed that RRB and SRB were significantly different ($P < 0.05$) among treatments across the two-year experiments. The values of SRB increased considerably in the second year. In particular, the values of SRB for *E. dahuricus* and *B. inermis* was 98.79% and 98.07%, respectively, while that of RRB was −11.84% and 4.01%, respectively. The two Gramineae grasslands showed greater effectiveness in sediment reduction and runoff maintenance than the two legume species owing to the dense fibrous roots and higher biological soil crust coverage. Therefore, Gramineae grasslands can be considered as a suitable management practice to achieve the socio-ecological sustainability of the semi-arid areas during vegetation restoration.

## 1. Introduction

Due to low vegetation cover, harsh winters and extreme rainfall events, soil erosion has become a severe problem in semi-arid areas worldwide (Wei et al., 2007). Soil erosion leads to the deterioration of soil physical, chemical and biological properties, loss of nutrients, and even loss of cropland. Soil erosion also brings about fluvial sediment deposition (Kinnell, 2012; Rienzi, 2013). Heavy sedimentation can lead to flood risks, frequent sandstorm events with declining air quality, deterioration of water quality and landscapes, and loss of biodiversity (Li and Fang, 2016).

Vegetation restoration has been considered as one of the key strategies for soil erosion control due to its effects on the improvement of soil properties and microenvironment, and the consequent effects on the reduction of runoff and sediment yields (Cao et al., 2011; Fiener et al., 2011; García-Ruiz, 2010; Wei et al., 2007). However, precipitation is the main source of water supply in semi-arid areas (Leung et al., 2015). The surface flow after rainfall events generally forms river base flow, and is critical to ensure the sustainability of socio-ecological systems in semi-arid areas with limited water resources (Cao et al., 2010; Li et al., 2017; Robinson et al., 2003). Previous studies have reported that changes in river stream-flow are mainly affected by precipitation, temperature and land use (Johnson et al., 2009; Palmer et al., 2009). Over the past half century (1950–2000), large-scale vegetation restoration reduces the conversion of rainfall to runoff (Cao et al., 2011; Farley et al., 2005; Gao et al., 2015; López-Vicente et al., 2017), thus leading to the lower river flow and even influencing river ecosystems health (Cao et al., 2010; Li et al., 2017; Lana-Renault et al., 2018). Therefore, there is a scientific and practical need to maintain surface runoff while controlling soil loss to achieve the sustainability of

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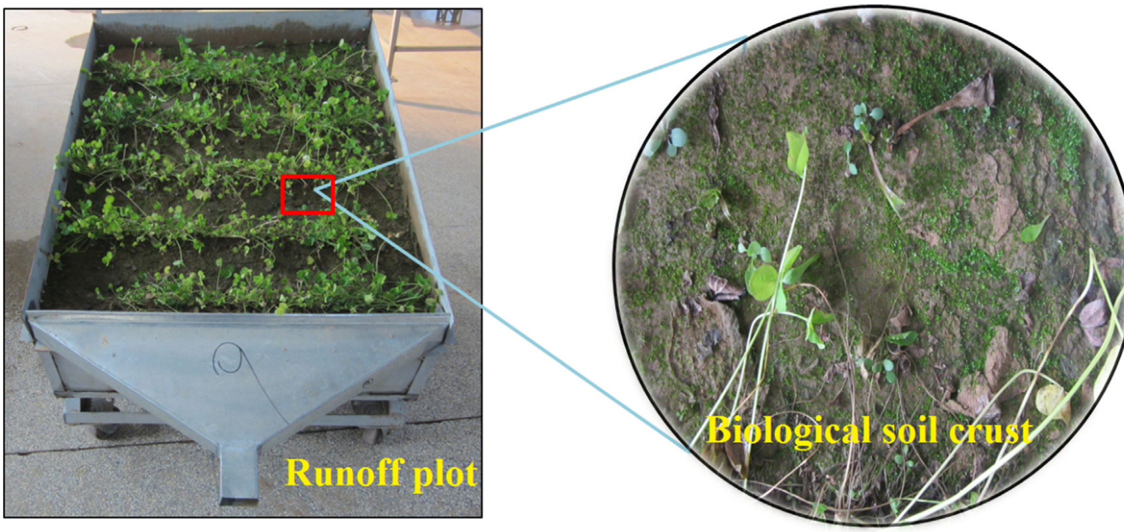


**Fig. 1.** The runoff plots in this study and the biological soil crust on the soil surface of the soil in the studied plots.

ecological systems during vegetation restoration.

Many studies have dealt with the effectiveness of different vegetation species on soil erosion control. Sun et al. (2006) indicated that forestation notably reduced runoff by more than 50% on the Chinese Loess Plateau. Xu et al. (2009) found that two herbs (*Artemisia gmelinii* and *Pulicaria chrysantha*) had greater improvements on soil quality and reducing runoff and soil loss than a small shrub (*Ajania potaninii*), which has minimal effectiveness. In contrast, dense shrubs are the most effective land use type in reducing soil erosion in Mediterranean landscapes (Lanznaster et al., 2010; López-Vicente et al., 2011). The impacts of vegetation restoration on soil erosion control are influenced by numerous factors such as the climate, slope gradient and soil texture (Anache et al., 2018; Li and Fang, 2016). Based on this background, a systematic investigation of the efficiency of different land use types on water erosion control in global semi-arid areas has been carried out by a meta-analysis (Liu et al., unpublished results). Compared to shrublands and forestlands, grasslands generally show the greatest effectiveness for sediment control but exhibit lower runoff reduction efficiency. The dense canopies of forestlands and shrublands intercept rainfall, thus greatly reducing runoff (Pizarro et al., 2006; Wei et al., 2007). At the soil surface, plant roots physically combine with soil particles providing a mechanical barrier to soil and water movement (Gyssels et al., 2005). De Baets et al. (2007) indicated that grasslands with a shallow but dense lateral-spreading rooting pattern led to the highest potential of erosion reduction and highly increased the resistance of the topsoil against concentrated flow erosion. However, scrubland and forestland may not cover the entire soil surface, drawing a patchy distribution of vegetation, and thus leading to the occurrence of uncontrolled soil erosion in the areas without grass under the canopies of the shrubs and trees (Arnaez et al., 2015).

Furthermore, forestland with high soil moisture consumption generally lead to soil desiccation, which exacerbates environmental degradation in semi-arid areas (Cao et al., 2011). Wang et al. (2007) reported that the overall survival rate of trees in afforestation projects from 1952 to 2005 was only 24%. In contrast, Wang et al. (2012) noted that grassland was a better choice than plantations for controlling soil erosion while using minimal water. Therefore, grassland consume less water than forestland, and appears as a better choice for achieving the combined goal of soil loss control and water conservation in semi-arid areas. Previous studies mostly compared the effects of different vegetation types on soil erosion control, but the knowledge in the quantification of the performance of sediment reduction and runoff maintenance in different grasslands is lacking. Ideally, species that maintain moderate surface runoff while storing enough rainwater to meet the demands of growth can control soil loss and may contribute to the improvement of local environments ultimately.

In this study, four typical grasslands, which were the most commonly used during vegetation restoration, were selected to study the hydrological response of the soil under simulated rainfall experiments. The main objective was to evaluate the main reasons that explained the different runoff and sediment yields obtained with the four grasslands. These findings could offer a theoretical guidance to achieve the combined goal of sediment reduction and runoff maintenance during vegetation restoration in semi-arid areas.

## 2. Materials and methods

### 2.1. Experimental conditions

The simulated rainfall experiments were carried out in the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau in Yangling, Shaanxi Province, China (E 107°59′–108°08′, N 34°14′–34°20′). The climate ranges between semi-arid and semi-humid with a mean annual temperature of 12.9 °C. The annual mean precipitation and evapotranspiration is 637.6 mm and 884.0 mm, respectively (Zhao et al., 2014). Most of the precipitation occurs as short-duration and high-intensity rainstorms in the summer months between June and September.

A side-sprinkle precipitation set-up system, in which rainfall intensities can be precisely controlled by adjusting the nozzle size and water pressure, was used in the experiments (Pan and Shangguan, 2006). Deionized water, which was prepared by reverse osmosis and collected in a water tank, was used in all rainfall simulations (Bormann et al., 2010). The height of the rainfall simulator was up to 16 m, the simulated storm was of above 85% uniformity, the raindrop distribution and size could be controlled by varying the type of needles and their receptacles (Hignett et al., 1995; Wang et al., 2005). The raindrop diameter was 0.5–2 mm and the mean velocity was 4.78 m $s^{-1}$. The mean rainfall kinetic energy per unit time per unit area was 0.2193 J $m^{-2}$ $s^{-1}$. Calibrations of rainfall intensities were conducted prior to the experiments and never differed from the target intensities by more than 10%. Each experimental steel plot was 1.1 m in length, 0.8 m in width, and 0.25 m in depth (Pan and Shangguan, 2006; Zhao et al., 2014), and was fitted with four wheels for free movement (Fig. 1). A metal runoff collector was set at the bottom of the plot to direct runoff into a container. Apertures were formed at the bottom of each plot to allow soil water to freely infiltrate. The slope of each experimental plot was set at 20°, which is considered as the critical slope

 

**Table 1**
Mean values of the soil physical and chemical properties.

| Soil texture | Bulk density (g $cm^{-3}$) | pH | Total N (%) | Available N (mg $kg^{-1}$) | Available P (mg $kg^{-1}$) | Available K (mg $kg^{-1}$) | Total porosity (%) |
|---|---|---|---|---|---|---|---|
| Sandy loam | 1.35 | 8.5 | 0.03 | 37 | 2.4 | 110 | 45 |

to develop gully erosion (Tang et al., 1998). To simulate the field conditions as much as possible, the original soil used in this study was a loessial loam collected from Shenmu County, which is located in the water-wind erosion crisscross region on the Loess Plateau. The main properties of the final experimental soil were listed in Table 1.

### 2.2. Experiment setup

Soil was gently crushed before passing through a 10-mm sieve, and the sieved soil was thoroughly mixed to minimize the differences among treatments. Then, the soil was packed in each plot in two 10-cm layers at a 1.35 g $cm^{-3}$ bulk density. Additionally, each soil layer was raked lightly before the next layer was packed to diminish the discontinuity. The four selected grasslands were *Medicago sativa* (*M. sativa*), *Trifolium repens* (*T. repens*), *Elymus dahuricus* (*E. dahuricus*), and *Bromus inermis* (*B. inermis*), which are the most common grasslands during vegetation restoration in the Loess Plateau. According to the local convention, the plot grasslands were established in the spring of 2013. A total of five strips were planted with a row spacing of 20 cm. Bare land was set as the control treatment. Thus, there were five experimental treatments with three replicate plots for each treatment, yielding a total of 15 plots. All plots were placed outdoor and irrigated during the first weeks to ensure plant survival, but plants completely grew under natural conditions later and mainly depended on rainfall for growing. Compared with natural grasslands, differences in soil conditions, vegetation types, and other hydro-climatological factors were minimized in the present study. Two rainfall experiments were carried out in 2013 and 2014, respectively. One day before the rainfall experiments, a specialized soil auger of 1-cm diameter was used to determine the soil water content of different treatments. According to the measured values, different amounts of water were sprayed with a commonly used household sprayer to minimize the differences in antecedent soil water content among treatments. Soil water content was adjusted to 15% gravimetrically for all plots at the beginning of the experiments (Pan and Shangguan, 2006).

### 2.3. Measurements and methods

According to Tang (2004), most of the heavy rainfall intensity in the Loess Plateau ranges between 100 and 150 mm $h^{-1}$. The simulated rainfall intensity was set at 120 mm $h^{-1}$ and each simulation lasted 120 min. Such a high rainfall intensity was chosen as it is usually a typical intensity of storm that causes serious soil erosion in this region (Zhou and Wang, 1992). Some studies also selected 120 mm $h^{-1}$, which corresponds to heavy rain on the Loess Plateau (Fang et al., 2015; Lu et al., 2017; Pan and Shangguan, 2006). All rainfall events generating runoff were recorded. During each event, the runoff and sediments produced every five minutes were collected in plastic buckets. After settling of the turbid water, the volume of clear water was regarded as the runoff amount. The weight of the soil in the bucket after oven-drying was taken as the sediment yield. To calculate the vegetation coverage (VC) before each rainfall event, three to five JPG-format photos were taken using a digital camera. The lens and the plot were paralleled and the distance between the two was always the same. The vegetation cover (%) was then determined using Photoshop CS 3.0™ and Image-J™ software package (Huang et al., 2013a,b). Biological soil crusts were observed in the upper millimeters of the topsoil and were composed of bacteria, algae, fungi, lichens, and bryophytes in different proportions (Belnap et al., 2001; Swenson et al., 2018). The biological soil crust coverage (BSCC) was calculated following the same approach of the vegetation coverage.

Three metrics, i.e., runoff reduction benefit (RRB, %), sediment reduction benefit (SRB, %), and soil infiltration rate (SIR, mm $min^{-1}$) were employed to represent the capacity of the different treatments to regulate runoff and sediments, and the calculation of each metric was as follows (Zhao et al., 2014):

$$RRB = \frac{R_b - R_v}{R_b} \times 100\% \quad (1)$$

$$SRB = \frac{S_b - S_v}{S_b} \times 100\% \quad (2)$$

$$SIR = RI \times \text{Cos}(\alpha) - \frac{10 \times R_v}{s \times t} \quad (3)$$

where $R_b$ and $R_v$ are the runoff volume (ml) for the bare land and vegetated plots, respectively; $S_b$ and $S_v$ are the sediment yield (g) for the bare land and vegetated plots, respectively. $RI$ is the rainfall intensity (mm $min^{-1}$), $s$ is the plot area receiving rainfall ($cm^2$), $t$ is the rainfall duration (min), $\alpha$ is the slope gradient (°), and 10 is the coefficient for dimension conversion. In particular, Eq. (3) is based on the assumption of ignoring the evapotranspiration and interception of water by vegetation during rainfall events.

### 2.4. Data analysis

The results in this article were expressed as mean ± standard error (SE) of mean. The differences in runoff and sediment characteristics among the different treatments were compared by using one-way analysis of variance (ANOVA) procedure. All statistical analyses were performed using the software program SPSS 12.0 (SPSS Inc., Chicago, IL, USA), and figures were drawn using SIGMAPLOT 8.0 (Systat software Inc., San Jose, CA, USA). The statistical significance was evaluated at the 0.05 level.

## 3. Results

### 3.1. Runoff volume and sediment yield

The time to runoff initiation, vegetation coverage, biological soil crust coverage, runoff volume, and sediment yield for the different treatments during the two-year experiments were shown in Table 2. The BSCC and VC of all treatments clearly increased in the second year compared with the values obtained in the first year. In spite of plant ages, the values of BSCC and VC for *B. inermis* and *T. repens* were the highest, followed by *E. dahuricus*, *M. sativa,* and bare land. Moreover, the difference among the five treatments reached a significant level ($P < 0.05$). The difference in time to runoff initiation among the treatments was also statistically significant ($P < 0.05$). The time in the bare land plots was significantly higher than that observed in the plots with grasslands during the first year, but it was the lowest during the second year.

*Bromus inermis* (141.10 L) and *T. repens* (153.08 L) produced larger amounts of runoff in the first year, but lower amounts in the second year (145.03 L and 133.04 L, respectively). There were significant differences in sediment yield among treatments in both years (F = 290.69, $P < 0.05$ for the first year; F = 81.13, $P < 0.05$ for the second year). Grasslands produced significantly less sediment yield compared with bare land. Moreover, *M. sativa* produced the highest

**Table 2**
Time to runoff initiation, vegetation coverage (VC), biological soil crust coverage (BSCC), runoff volume, and sediment yield obtained for the different treatments in the two-year experiments. The experiment-1 and experiment-2 in all units represent the measurement of relevant parameters in 2013 and 2014, respectively.

| Year | Parameter | *Bare land* | *M. sativa* | *T. repens* | *E. dahuricus* | *B. inermis* |
|---|---|---|---|---|---|---|
| 2013 | Time to runoff (s experiment-1) | 184.00 ± 6.35c | 186.00 ± 4.62c | 43.00 ± 0.58a | 49.00 ± 2.89ab | 60.50 ± 0.87b |
| | VC (% experiment-1) | — | 12.33 ± 1.45a | 33.33 ± 6.01b | 17.67 ± 1.45a | 32.67 ± 3.93b |
| | BSCC (% experiment-1) | 2.33 ± 1.45a | 5.33 ± 1.45a | 25.00 ± 2.89c | 16.67 ± 1.67b | 31.67 ± 4.41c |
| | Runoff volume (L experiment-1) | 116.74 ± 1.68a | 130.42 ± 2.82b | 153.08 ± 2.17d | 134.49 ± 2.49bc | 141.10 ± 1.25c |
| | Sediment yield (g experiment-1) | 1572.17 ± 16.25c | 490.25 ± 67.28b | 208.75 ± 25.50a | 107.26 ± 12.08a | 133.67 ± 31.00a |
| 2014 | Time to runoff (s experiment-2) | 16.50 ± 0.87a | 46.00 ± 2.31b | 85.50 ± 2.60c | 47.50 ± 2.60b | 39.00 ± 5.20b |
| | VC (% experiment-2) | — | 25.00 ± 5a | 87.50 ± 2.5b | 35.00 ± 5.00a | 82.50 ± 2.50b |
| | BSCC (% experiment-2) | 15.00 ± 5.00a | 25.00 ± 15.00a | 52.50 ± 7.50b | 32.50 ± 17.50ab | 82.50 ± 7.50c |
| | Runoff volume (L experiment-2) | 151.29 ± 6.82b | 174.40 ± 2.66c | 133.04 ± 5.35a | 168.92 ± 4.71c | 145.03 ± 4.41ab |
| | Sediment yield (g experiment-2) | 108.56 ± 11.30c | 35.01 ± 2.17b | 1.78 ± 0.11a | 1.37 ± 0.37a | 2.07 ± 0.12a |

*Note:* The values are mean ± SE. Means in a column followed by different letters are significantly different at $P < 0.05$.

sediment yields among the different grasslands, regardless of the planting ages (Table 2).

### 3.2. Runoff rate, sediment rate, and SIR

The runoff rates showed similar changing trends in all treatments during the two-year measurements (Fig. 2a; Fig. 2c). The initial runoff rate was relatively low, but increased sharply later. The initial runoff rate of *T. repens* was the highest in the first year, but the lowest in the second year. Runoff rate reached steady state conditions at 40 min in the first year, but became stable earlier, i.e., at 20–30 min, in the second year. The sediment yield rate slowed down and finally reached steady state conditions, and the stabilization time was similar with that of runoff rate. Due to rill erosion, bare land showed a slight increase in runoff rate and sediment yield rate at 95 min (Fig. 2a; b), and a similar phenomenon appeared in *M. sativa* at 55 min (Fig. 2a; b).

The dynamic process of SIR for different treatments was shown in Fig. 3. The SIRs of *T. repens*, *E. dahuricus*, and *B. inermis* were all lower than that of bare land and *M. sativa* (Fig. 3a). After slope runoff generation, SIR gently decreased. However, a different trend was observed in the second year, when SIR significantly decreased at the initial stage and then gradually became stable. *Trifolium repens* showed the lowest initial SIR among all treatments (Fig. 3b).

### 3.3. Runoff reduction benefit and sediment reduction benefit

The runoff reduction benefit (RRB) and sediment reduction benefit (SRB) for the different grasslands during the two-year experiments were shown in Fig. 4. A lower value of RRB represents a better ability of runoff maintenance for grasslands, and a higher value of SRB represents a better effectiveness of grasslands in sediment reduction. In the first year, all grasslands showed very low RRBs with the mean value ranging from −31.13% (*T. repens*) to −11.69% (*M. sativa*). In the second year, the RRBs of the different grasslands slightly increased when compared with the first year, with the mean value ranging from −15.58% (*M. sativa*) to 12.02% (*T. repens*). Overall, all grasslands showed high SRBs (greater than65%) during the two-year experiments. The SRB of *M. sativa* was significantly ($P < 0.05$) lower than those obtained in the

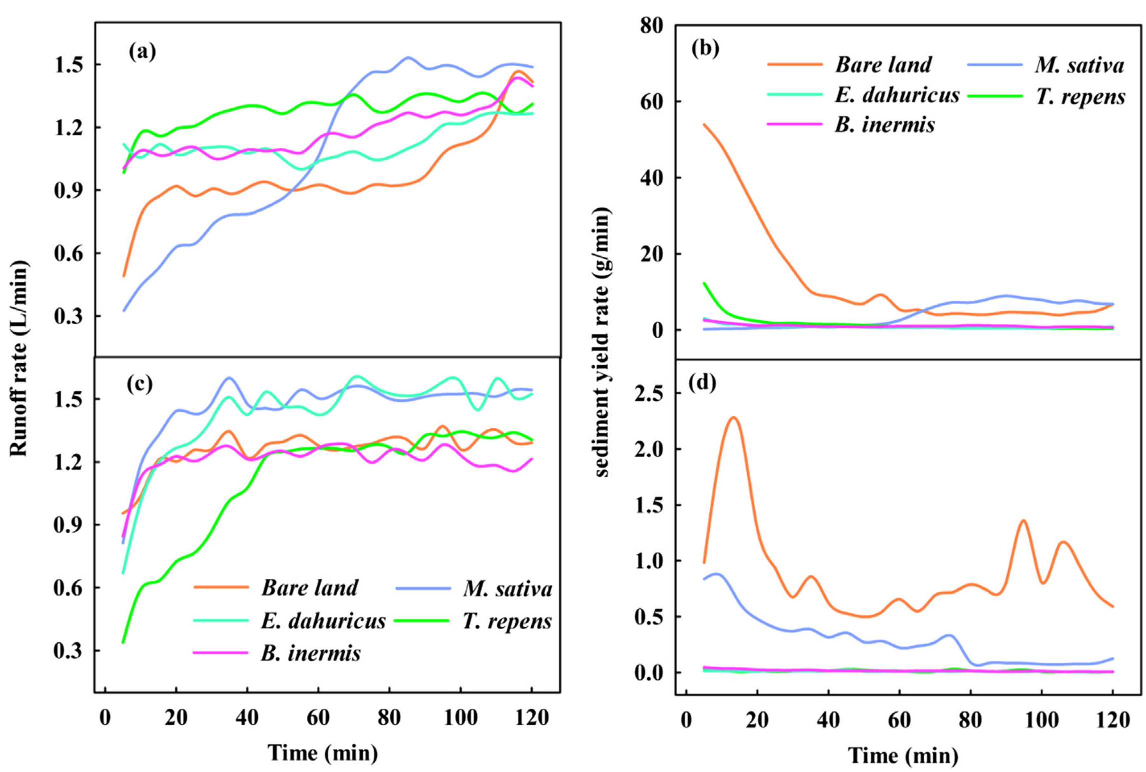


**Fig. 2.** Runoff processes (a) and sedimentation processes (b) for different plots in 2013, runoff processes (c) and sedimentation processes (d) for different plots in 2014. Each value of runoff rate and sediment rate was averaged.

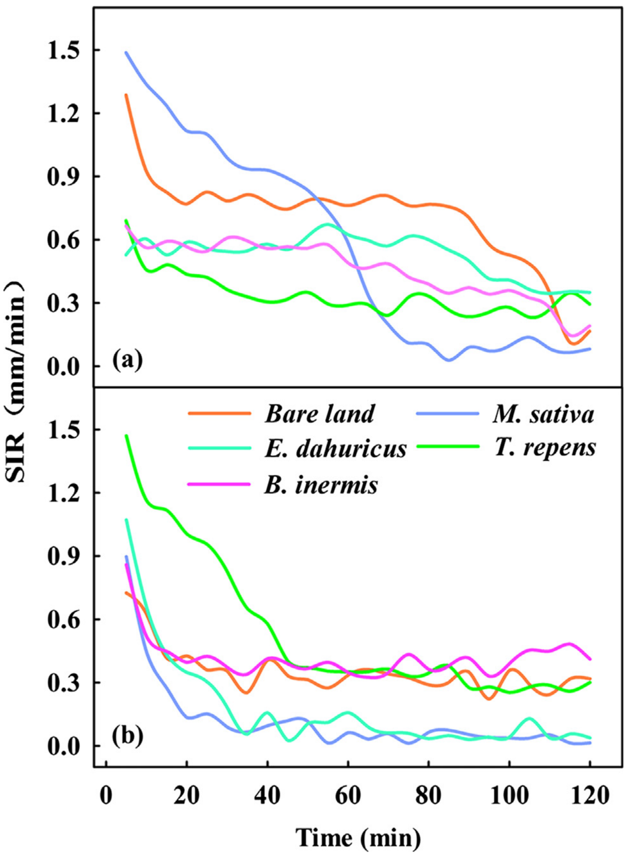


**Fig. 3.** Infiltration processes for different plots in (a) 2013 and (b) 2014. Each value of infiltration rate was averaged.

other grasslands. However, no significant difference was observed among *T. repens*, *E. dahuricus*, and *B. inermis*. Moreover, a great increase in SRB from the first year to the second year was found for all grasslands.

## 4. Discussions

*E. dahuricus* and *B. inermis*, as Gramineae grasslands, have abundant fibrous roots. For the legume species, *T. repens* is abundant in fibrous roots, while *M. sativa* has a different root architecture with tap roots (Fan et al., 2016; Vamerali et al., 2003). Grasslands, especially *E. dahuricus*, *B. inermis*, and *T. repens*, significantly reduced sediment yield when compared with bare land in our study. These results were consistent with those reported by Wu et al. (2010), who proved that vegetation significantly decreased soil erosion and improved soil physical, chemical, and biological properties. Plant growth could improve soil conditions through fine root-network development and litter accumulation, which forms a virtuous cycle to control soil loss (Gyssels et al., 2005; Xu et al., 2009; Wu et al., 2016). Thus, grasslands with accumulated fibrous roots in shallow soil had better effects on reducing sediment yield.

The results showed that grasslands had relatively lower runoff reduction benefits compared to the superior sediment reduction benefits (Fig. 4). In particular, grasslands had higher surface runoff compared with bare land in the first year, very likely due to the presence of the root systems. Leung et al. (2015) found that roots occupied soil pores while growing initially, affecting both soil saturated hydraulic conductivity and infiltration rate, which led to increased runoff. Grassland had more abundant fine roots in the shallow soil compared with forestland, and those fine roots decreased infiltration by clogging the soil pore space (Archer et al., 2002). Additionally, roots physically combined with soil particles at the soil surface (Gyssels et al., 2005), gradually reduced the infiltration rate and increased the runoff rate due to a surface seal formation until a steady-state condition was reached (López-Vicente et al., 2016; Smets et al., 2011). Another reason might be that grassland had a significantly higher biological soil crust coverage (BSCC) than bare land (Table 2). Biological soil crusts could create an impermeable seal by swelling sheath material during imbibition, favoring soil water repellence that was markedly increased in both intensity and persistence, thus leading to more rapid ponding (López-Vicente and Navas, 2012; Zhang et al., 2014). The time to runoff and infiltration rate of bare land and *M. sativa* were obviously higher than those of the other grasslands in the initial stage of rainfall (Table 2; Fig. 3). Higher BSCC may prevent infiltration, which would lead to decreased infiltration rate and consequently increased surface runoff. Biological soil crusts modified the surface micro-topography, which reduced the speed of water flow and the connectivity of water and sediments among source areas concurrently (Rodríguez-Caballero et al., 2012; Singh and Liu, 2004). The grasslands with the higher BSCC had significantly positive effects on regulating runoff and sediment yields.

Several studies found that infiltration rates in grasslands can be either higher or lower than bare land at different stages of plant growth (Mašíček et al., 2013; Zhao et al., 2014). In this study, the runoff amounts in the plots with *B. inermis* and *T. repens* were significantly lower than those measured in the other grasslands and bare land plots in the second year (Table 2). Additionally, the initial infiltration rate was relatively higher (Fig. 3), possibly due to the particularly high vegetation coverage (VC). *Bromus inermis* and *T. repens* with higher VC correspondingly had more dense root systems, which grew maturely in the second year. Similar results were found by Meek et al. (1989), who suggested that channels or macropores formed by the decomposition of roots increased infiltration rates and decreased runoff. In addition,

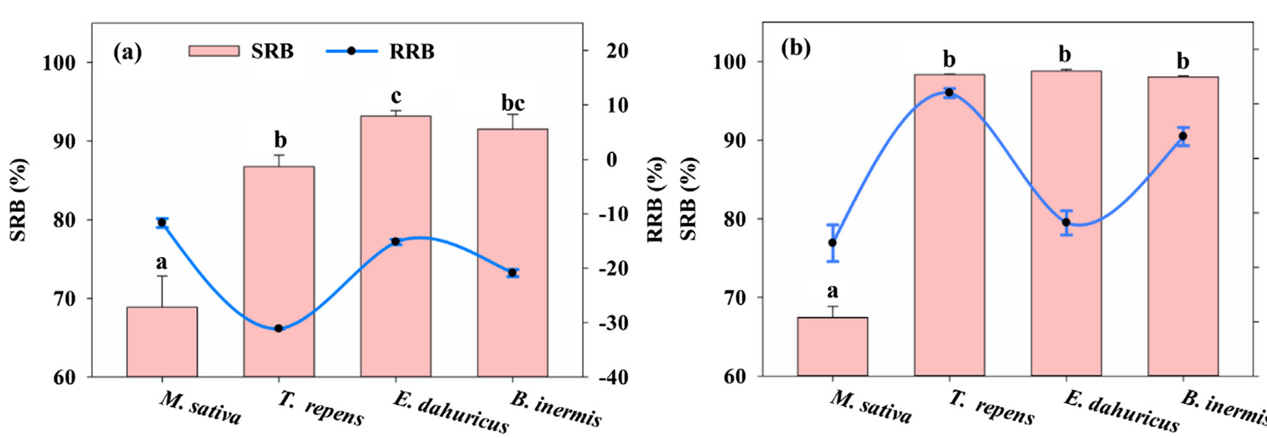


**Fig. 4.** Runoff reduction benefit (RRB) and sediment reduction benefit (SRB) for different vegetated plots in (a) 2013 and (b) 2014.

decaying roots increased soil organic matter content, which in turn influenced the infiltration capacity due to the change in the burrowing activity and biomass of earthworms (Fischer et al., 2014). Plant roots significantly affected soil hydrological processes by forming preferential pathways and increasing hydraulic conductivity, which would facilitate the storage and uptake of water and nutrient (Archer et al., 2002; Wu et al., 2017). Although the decomposition of fine roots increased the infiltration rate and decreased runoff volume in the second year, the runoff reduction benefit (RRB) of grasslands were still low. In general, grassland substantially maintained runoff while reducing sediment yield during the rainfall simulations.

In this study, the differences in erosion process among the different grasslands were attributed to the presence of biological soil crusts, vegetation cover, and root systems. In general, grasslands showed comprehensive effects on sediment reduction and runoff maintenance, especially the Gramineae grasslands with abundant fibrous roots. Therefore, Gramineae grasslands maintained moderate surface runoff while storing enough rainwater to meet the demands of growth and controlled soil loss. Thus, they contribute to the improvement of the local environment ultimately. With regard to the development of ecological environment in semi-arid areas where water is limited, Gramineae grasslands, as typical vegetation type during vegetation restoration, could be considered for soil loss control as well as water resources conservation.

Although our study determined the runoff maintenance and sediment reduction performance of different grasslands during the two-year experiments, there are still some limitations. This study was conducted by means of outdoor simulated rainfall experiments and lasted for only two years, which might mask the possible time variability in relation to runoff maintenance and sediment reduction performance of grasslands. It is unclear that whether grasslands still have great effectiveness in sediment reduction and runoff maintenance under long-term planting. Therefore, further studies should be focused on analyzing the effects of grasslands with different planted ages on regulating runoff and sediment yield based on long-term field experiments. Despite these limitations, the analysis of sediment reduction and runoff maintenance performance of different grasslands is useful and can potentially contribute to achieve the sustainability of ecological systems during vegetation restoration in semi-arid areas.

## 5. Conclusions

This study confirmed the different dynamic effects caused by four typical grasslands during vegetation restoration on runoff and sediment reduction through two-year simulated rainfall experiments. The runoff reduction benefit (RRB), sediments reduction benefit (SRB), and soil infiltration rate (SIR) significantly differed ($P < 0.05$) among the different treatments and during the two years, and the values of SRB greatly increased in the second year, indicating that grasslands contributed to greater benefits in soil loss control with increasing planting ages. Due to the presence of abundant fibrous roots and higher biological soil crust, the values of RRB were relatively lower. Grasslands generally had a greater impact on sediment yield than on runoff volume. The two Gramineae grasslands reduced sediment yield by more than 90% and showed a better effectiveness in sediment reduction and runoff maintenance, and were considered as a suitable management practice to ensure the sustainability of ecological environments during vegetation restoration in semi-arid areas.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2019.03.008.

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