Original Research

The Influence of Microtopographies on Seed Removal by Water Erosion on Loess Slope

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Abstract

We tested the seed loss of five dominant species in the Loess Plateau region under varied rainfall intensity and soil surface conditions. The runoff rate, sediment yield, seed loss rate, and seed displacement distance were investigated. The result indicated that the seed loss rate increases with rain intensity enhanced, or the rainfall duration prolonged even with low intensity. The grass, and grass and hoof prints on the slope can reduce seed loss under high rainfall intensity. The spotted individual grass and the hoof prints can enhance soil erosion by changing the path of overland flow and increasing seed loss at the low rainfall intensity compared with the bare slope.

Keywords: seed loss, soil erosion, simulating rainfall, Loess Plateau, runoff

Introduction

Soil erosion is one of the global environmental problems that causes land degradation and ecosystem disequilibrium [1]. It also is a physical stress that affects vegetation development [2]. It acts on living habitat and the whole plant recruitment process and vegetation community assembly. The soil nutrients and water lost during soil erosion affect seed production [3] and seed viability [4]. And the overland flow removes soil as well as the seed distributed on the soil and in the upper soil layer [5, 6]. The redistribution of soil nutrient and soil seed bank would affect the seedling germination and colonization [3, 7], and then the species composition and its spatial distribution will be influenced [5, 8].

The seed is the prerequisite for plant recruitment, especially at the disturbed habitat [9]. The seed faces many different fates during the period from seeds dispersed on the soil to seed germination [10]. Many factors influence the post-dispersal movement of seeds in the disturbed ecosystems [11]. Under rainfall erosion conditions, the seeds on the surface of the soil and even in the soil profile are threatened by splash and overland flow [3, 5, 12]. It is considered that the influence of soil erosion on seed removal and redistribution may be a factor in low vegetation cover in regions with high soil erosion activity [13]. Thus, in the past decades, several studies have focused on seed loss during the soil erosion process [5], and several influence factors have been considered and studied, such as seed size and shape [5, 14], slope angle [15], bioengineering works [16], vegetation cover, and hoof prints [17, 18].

The morphology of the vegetation patch and the vegetation-driven spatial heterogeneity play important roles in structuring runoff and sediment fluxes, particularly in the regions with sparse vegetation cover [19-21]. Increasing plant cover can efficaciously reduce the overland flow and sediment yield [21, 22]. However, low patch density patterns or high vegetation-driven spatial heterogeneity will

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lead to significantly greater erosion rates [21]. Additionally, microtopographic variation in soil surface elevation also affects concentrated flow path formation and erosion [23, 24]. For example, trampling during grazing can influence the microtopography on the slope and then change erosion rates [17]. And these factors can also influence seed removal during the erosion process. For example, vegetation bands are effective at trapping seeds in runoff [16, 25]. However, the individual shrubs do not trap seeds transported by overland flow because microtopographic structures under the shrubs can influence the overland flow [12]. On the other hand, depression topography, such as hoof prints, can trap seeds removed by runoff and greatly reduce the travelled distance of post-dispersal seeds [18, 26].

The Chinese Loess Plateau is well-known for its severe soil erosion and degraded ecosystem [27], and where vegetation is sparse and forms a mosaic with the bare soil on the slope. So the tussock, vegetation patch, and microtopography caused by tramping will affect the path of overland flow and its ability to transfer the sediment and the seed. While there is little knowledge about seed removal during runoff erosion, although the seed removal of 16 species with various morphology on bare loess slope under different rainfall intensity and slope angle conditions was reported [28]. The results only reflect the seed removal susceptibility among species, but cannot reflect the seed removal on the slope with different microtopographies. Therefore, the objectives of this study were to investigate the seed removal (include seed loss and seed displacement) on loess slopes with tussock and hoof prints in simulated rainfall events, and to identify the seed interception efficiency of tussock and hoof prints by using the easily removed seeds from local species and loess soil in the hill-gully Loess Plateau region.

Material and Methods

We implemented the rainfall simulation experiment in the Rainfall Simulation Hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau. And we selected the lateral sprinkling automatic rainfall simulation system to simulate the rainfall. The height of the spray nozzle was 14.5 m, which is high enough to make the raindrop composition close to natural rainfall. And the rainfall was evenly distributed during the experiment.

Soil Bin

The experimental soil bin (2 m × 0.5 m × 0.5 m) is able to adjust the slope gradient to 0-30º. A defined number of holes are equally distributed at the bottom of the cell for water draining. The loess soil used in the experiments was collected from the typical hilly-gulled Loess Plateau region. The soils have developed on wind-deposited loessic parent material and are classified as Calcic Cambisols [29]. Clay-sized particle content is 8-30%, $CaCO_3$ content is 10-16%, and organic content is 0.5-1.5% [30]. In the bottom, a layer (10 cm) of sand was added covered with gauze. Then the loess soil was added up to 30 cm with the soil bulk density adjusted to 1.10-1.15 g/cm^3 (based on the 0-10 cm soil bulk density of the 75 sampling plots in An'sai) [28].

Microtopographies of Soil Surface

Three kinds of microtopography of soil surface were designed for the rainfall experiments: bare slope, slope with tussock, and slope with tussock and hoof prints (Fig. 1). The plant is *Bothriochloa ischaemum,* which is the dominant species in the perennial herb and subshrub community during the middle and late stages of vegetation restoration in this region. The vegetation cover of slope was controlled about 30%. The hoof prints were set up by the cow hoof mould, and the density was five hoof prints per square meter. The angle of slopes was designed at 20º according to the results (maximum soil loss amount on 20º slope) obtained by Han et al. [28].

Seeds Placed on Slopes

According to the study by Han et al. [28] and Jiao et al. [31], species whose seeds are sensitive to water erosion were selected: *Heteropappus altaicus*, *Lespedeza davurica*, *Bothriochloa ischaemun*, *Periploca sepium*, and *Sophora viciifolia*. For the big seeds from *P. sepium* and *S. viciifolia*, 10 seeds of each species were placed on the slopes, for the small seeds from *H. altaicus*, *L. davurica*, and *B. ischaemun*, 20 seeds of each species were placed on the slopes; and totally 80 seeds were on each slope. These 80 seeds were divided into two equal groups, species by species, one group (40 seeds, dyed with fast green for easy identification and discrimination against the seeds in the other group) was placed on 100-120 cm (from the upside of the slope) of soil surface, and another (40 seeds, not dyed) was placed on 130-150 cm (from the upside of the slope) of soil surface. Seeds from each species were placed individually, non-overlapping, and spacing between species in the same line in one group, and the 80 seeds were arranged in four lines (Fig. 1). This seed configuration is designed to simplify seed displacement distance measurements.

Fig. 1. Photos of three kinds of microtopography of soil surface and experimental seed distribution (H1-5 shows the position of the hoof prints).

Rainfall Experiment

The intensity in simulated rainfall experiments on loess slopes usually is within the range of 30-200 mm/h [32]. Thus, the rainfall intensities used in these experiments were 25 mm/h, 50 mm/h, 75 mm/h, 100 mm/h, 125 mm/h, and 150 mm/h, with rainfall duration of 30 min. For the rainfall events with intensity 25 mm/h, 50 mm/h, and 75 mm/h, the rainfall duration was prolongated to 60 min to detect the effect of rainfall duration on seed removal. Two replications were designed for each experiment.

Before each rainfall simulation experiment, the seeds were placed on soil surface as described above, and the seed amount and position were recorded. The rainfall intensity was calibrated for 6 min in order to reach the request of homogeneity (> 80%) and intensity of rainfall. During the rainfall experiment, runoff samples were collected at three-minute intervals. After rainfall, the soil bins were placed outdoors (escaping the rain) for one week before the next rainfall experiment.

Data Collection and Analysis

After rainfall, the collected runoff samples were weighed and the sediment from these samples was separated, in order to calculate the runoff rate and amount and soil loss rate and amount. And the seeds from each species in these runoff and sediment samples were counted to measure the seed loss amount. The seeds in the runoff samples, the sediment samples, and the outlet of the V-shaped collecting device in each experiment were counted to calculate the total seed loss ratio. The distance of each seed traveled from its original position after each rainfall event was measured to obtain the seed displacement distance and ratio. The seed displacement distance of seeds lost out of soil bin was calculated as the distance from its original position to the end of the outlet of the soil bin. Differences in the values of these parameters between different experiments were tested using one-way ANOVA analysis. And data sets were either square-root transformed or log-transformed in order to achieve normality and homogeneity of variances. Pearson correlation was used to verify the relationship between seed loss rate and rainfall pattern on different kinds of slope.

Results

Runoff Rate and Sediment Yield Rate

The runoff rate increases with enhanced rainfall intensity over different microtopographies (Fig. 2). During the simulated rainfall, the runoff rate increased quickly in several minutes after the beginning of rain and then stabilized. For simulated rainfall events of 25 mm/h, the average runoff rate was 0.04, 0.05, and 0.09 mm/min for bare slope, slope with grass, and with grass and hoof prints, respectively, and the runoff rate on slope with grass and hoof prints was significantly higher than the other two treatments ($P<0.001$). For simulated rainfall events of 50 mm/h, the average runoff rate was 0.38, 0.57, and 0.43 mm/min, respectively, and the runoff rate on slope with grass was significantly higher than the other two treatments ($P<0.001$). For simulated rainfall events of 75 mm/h, the average runoff rate was 0.56, 0.773, and 0.64 mm/min, respectively, and the runoff rate on bare slope was significantly lower than the other two treatments ($P<0.001$). For simulated rainfall events of 100 mm/h, the average runoff rate was 0.98, 0.86, and 0.93 mm/min, respectively; for 125 mm/h events the average runoff rate was 1.43 1.26, and 1.48 mm/min, respectively; for 150 mm/h events the average runoff rate was 1.95, 2.03, and 1.68 mm/min, respectively, and there was no significant difference over the three

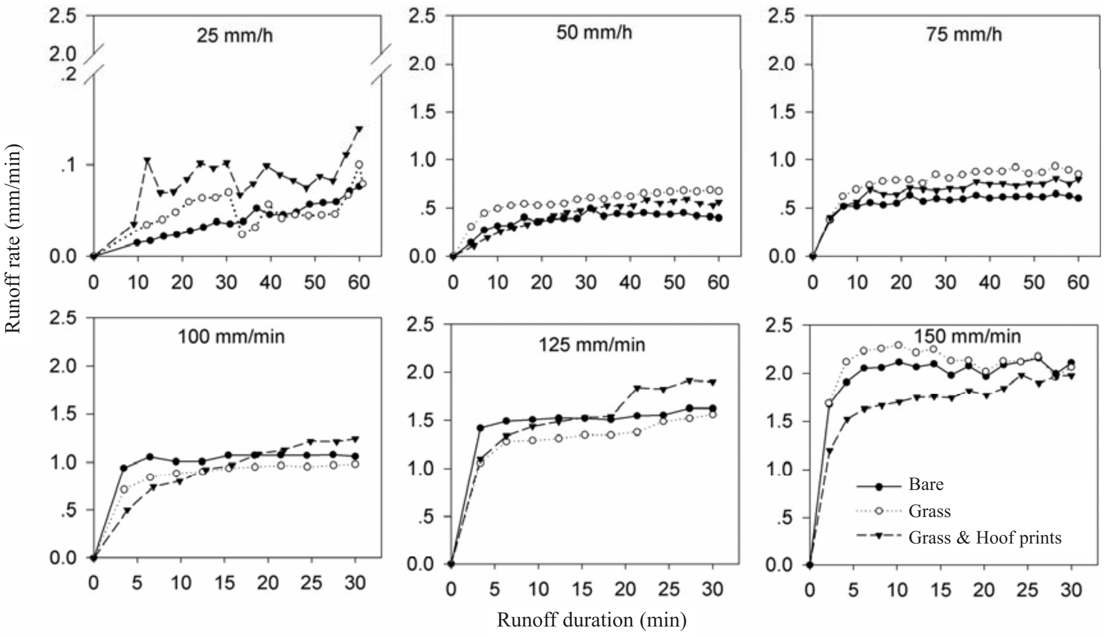

Fig. 2. Changes in runoff rates under different rainfall intensities on the different slope conditions.

Table 1. Correlation coefficient between seed loss rate and rainfall intensity.

Microtopography	Species				
	H. altaicus	B. ischaemun	*L. davurica*	*P. sepium*	*S. viciifolia*
Bare	0.865**	0.877**	0.871**	0.853**	0.889**
Grass	0.489*	0.504*	0.497*	0.705**	0.624**
Grass and Hoof prints	0.492*	0.441*	0.744**	0.614**	0.160**

**p<0.01, *p<0.05.

kinds of slopes for these three rainfall events. The grass on the slope did not reduce the runoff rate, as well as the treatment with both grass and hoof prints.

Changes in the sediment yielding rates under different rainfall events are shown in Fig. 3. The sediment yield rate on the slope with grass and hoof prints always was higher than the other two treatments, especially for the simulated rainfall events of 50, 75, and 100 mm/h. And the grass on the slope also did not reduce the sediment yield. For the simulated rainfall events of 25 mm/h, the mean sediment yielding rate was less than 1 g/(m^2 min). For the simulated rainfall events of 50, 75, and 100 mm/h, the mean sediment yield rate on the bare slope and slope with grass was less than 60 g/(m^2 min), and was significantly (P<0.001) less than on the slope with grass and hoof prints, where it ran up to more than 100 g/(m^2 min). For the simulated rainfall events of 125 and 150 mm/h, the mean sediment yield rate was always more than 100 g/(m^2 min) for each kind of slope.

Seed Loss

Seed loss rate increases with enhanced rainfall intensities and shows variance among different microtopographies (Fig. 4). According to the individual species, the seed loss rate over the three microtopographies is not significant different (P > 0.05) under the same rainfall pattern. The significantly difference (P < 0.05) is found for specific species at some rainfall pattern, such as *B. ischaemun* under a rainfall pattern of 25 mm/h, *L. davurica* under rainfall pattern of 50 mm/h and 100 m/h, *P. sepium* under rainfall pattern 100 mm/h, *S. viciifolia* under rainfall pattern of 125 mm/h and 150 mm/h, and *H. altaicus* under 150 mm/h. In general, the seed loss rate increases with the rainfall intensity enhancing, but showed different levels at different microtopographies (Table 1). With enhanced rainfall intensity, significant increases of seed loss of all the species is found on the bare slope. However, on the slope with grass and with grass and hoof prints, the seed loss rate increases lower than on the bare slope.

When the duration of 25 mm/h, 50 mm/h, and 75 mm/h rainfall events was prolonged to 60 min, the seed loss rate on the three slopes was increasing (increased 0-57.5%), especially on the bare slope under 50 mm/h (35-57.5%) and 75 mm/h rainfall (0-45%). For example, the seed loss rate of *H. altaicus* was increased 45% under 75 mm/h rainfall, and the seed loss rate of *L. davurica* and *B. ischaemun* was increased 57.5% and 40.0% under 50 mm/h rainfall on the bare slope, respectively. While the seed loss rate on the

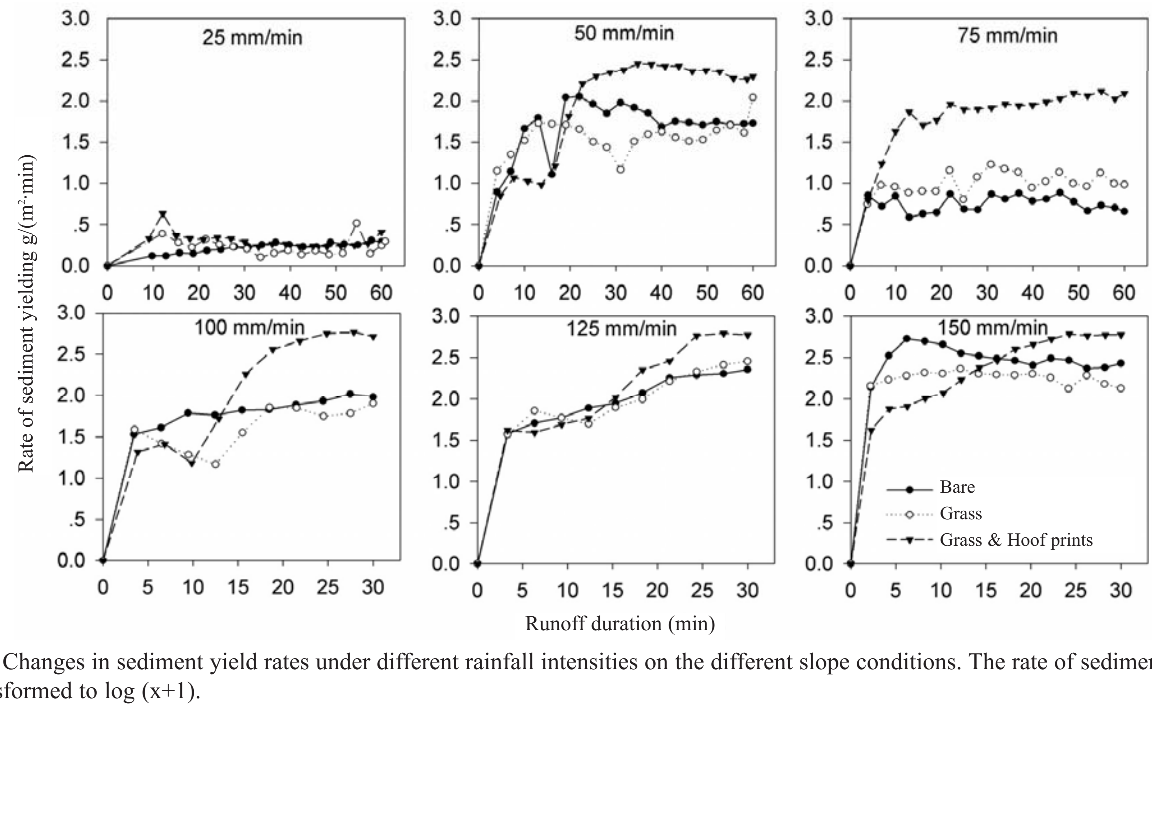

Fig. 3. Changes in sediment yield rates under different rainfall intensities on the different slope conditions. The rate of sediment yield is transformed to log (x+1).

slope with grass or with grass and hoof prints was increased 10-30% or 0-21.7%, respectively (Fig. 5).

Seed Displacement

The distances of seed displacement on the different slopes under the six rainfall intensities is shown in Fig. 6. The average displacement distance of the five species on the bare slope is always longer than on the slopes with grass or the slope with grass and hoof prints, it was 1.26 and 1.60 times (*H. altaicus*), 1.53 and 1.45 times (*B. ischaemun*), 1.34 and 1.71 times (*L. davurica*), 1.33 and 1.49 times (*P. sepium*), and 1.29 and 2.14 times (*S. viciifolia*) longer than it on the slope with grass, and on the slope with grass and hoof prints, respectively.

The seed displacement rate shows that the bare slope > the slope with grass > the slope with grass and hoof prints, except under 25 mm/h and 150 mm/h rainfall (Table 2). On the bare slope, the seed displacement rate was 60% under 25 mm/h rainfall, and above 84% under the other rainfall intensities. On the slope with grass or with grass and hoof prints, the seed displacement rate is 56-95% or 41-87%. The results indicate that the redistribution of seeds on the slopes easily occurred in the rainfall erosion process, even under low rainfall intensity or vegetation cover conditions.

Discussion

Varied microtopography is one of the main factors concentrating overland flow and increasing its eroding capability [20, 23, 31], as well as influencing seed removal on slopes. The post-dispersal seed movement is influenced by the present vegetation and ecogeomorphology on the slope during the runoff process. Vegetation bands and patches are effective at trapping seeds [15, 18, 34], like trapping

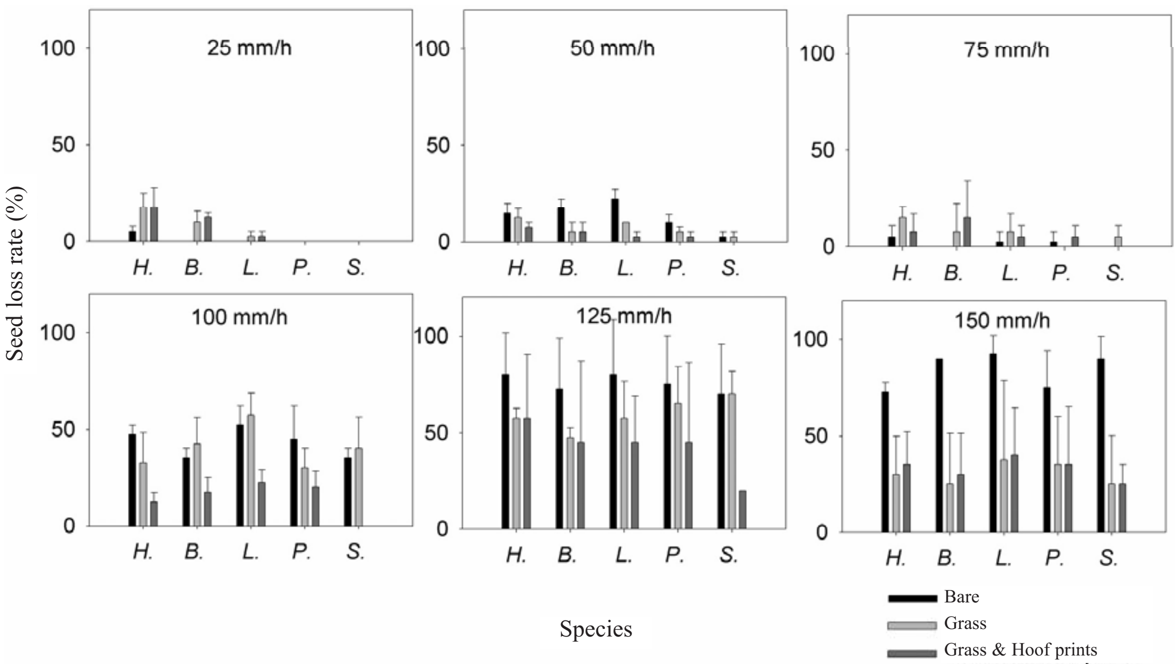

Fig. 4. Seed loss under different rainfall intensities during the 30-minute simulated rainfall with different treatments (H. – *Heteropappus altaicus*, B.– *Bothriochloa ischaemun*, L.– *Lespedeza davurica*, P.– *Periploca sepium,* and S.– *Sophora viciifolia*).

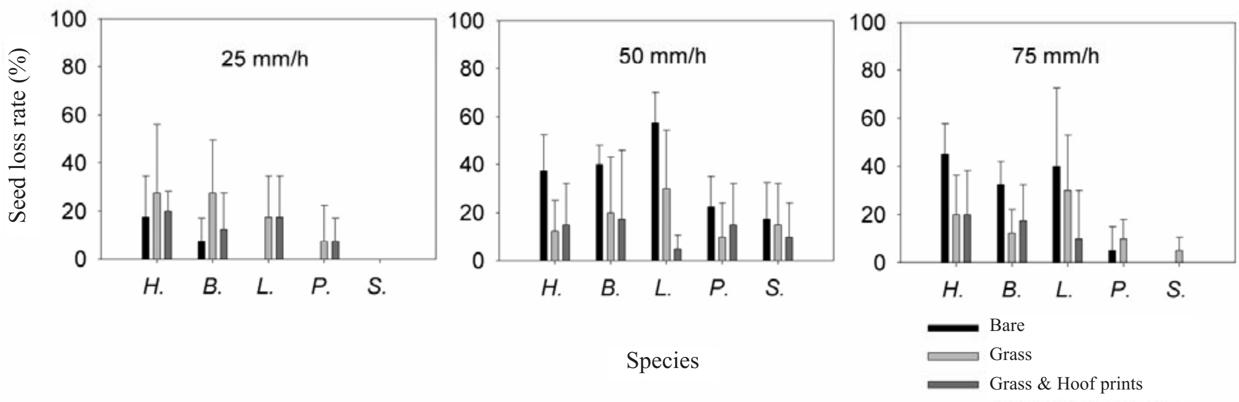

Fig. 5. Seed loss under lower rainfall intensities during the 30-60-minute simulated rainfall with different treatments (H.– *Heteropappus altaicus*, B.– *Bothriochloa ischaemun*, L.– *Lespedeza davurica*, P.– *Periploca sepium,* and S.– *Sophora viciifolia*).

Table 2. Seed displacement rate on the slopes under different rainfall conditions.

Rainfall intensity (mm/h)	Seed displacement rate (%)		
	Bare	Grass	Grass & Hoof prints
25	60.0	73.1	65.0
50	98.8	56.3	41.3
75	98.1	79.4	71.3
100	84.4	68.8	47.5
125	100.0	94.4	86.9
150	100.0	57.5	68.1

the sediment [15, 26]. The seed loss rate in the vegetated slope was evidently lower than in the bare slope, and seeds deposited under shrubs are not likely to be lost by surface wash, even under extreme rainfall conditions[12]. Additionally, in the erosion process, seeds can be trapped by the depression topography, such as hoof prints. And the travelled distance of post-dispersal seeds is strongly reduced [17, 18].

In this study, different from the prediction, under the same rainfall pattern, the seed loss rate on the bare slope was not significant higher than in the other two conditions. And there was always no significant difference over the three conditions. In contrast, the seed loss rate on the bare slope was lower than on the other two conditions at the low rainfall intensity, such as 25 mm/h and 75 mm/h, and especially at the beginning 30 minutes (Fig. 4). This phenomenon may be caused by the grass on the slope, which distributed separately but not in band. So the spotted vegetation structure caused runoff water to be diverted to the bare area around the tussock, and increase the depth and velocity of the flow and its eroding ability [12, 19, 21, 35], causing higher runoff rate, sediment yield, and seed loss. With the rainfall intensity increasing, the depth of overland flow increased on the bare slope. Therefore, the concentration effect of spotted vegetation structure on the flow was not so obvious. On the other hand, the grass can intercept the rain drop and protect the seeds under its canopy. Therefore, with the rainfall intensity enhancing, the increasing seed loss rate was lower on the slope with grass or with grass and hoof prints than on the bare slope.

On the slope with grass and hoof prints the seed loss rate was lower, but the sediment yield rate was higher (Fig. 3). Why it expressed this phenomenon? The previous study indicated that the erosion rate is higher on the rougher slope [23, 24, 33]. Microtopographic variation in soil surface elevation, quantified as surface roughness, affects concentrated flow path formation and enhances its depth. And spatial variability in depth of overland flow will lead to a similar distribution of shear stress. In areas of greatest shear stress, rills might be expected to form preferentially. So in this study, the hoof prints may act as the point where the rill formed. After the rill formed, the flow gets into the rill and its eroded ability is declined on the other part of the slope. Therefore the seed loss rate and seed displacement rate were lower on the slope with grass and hoof prints.

Rainfall intensity is the most important factor determining the degree of water erosion and seed removal, as discussed by Han et al. [28]. In this study, it was found that rainfall duration is an important factor effecting seed removal in low intensity rainfall condition. The low intensity rainfall with long duration can also cause high seed

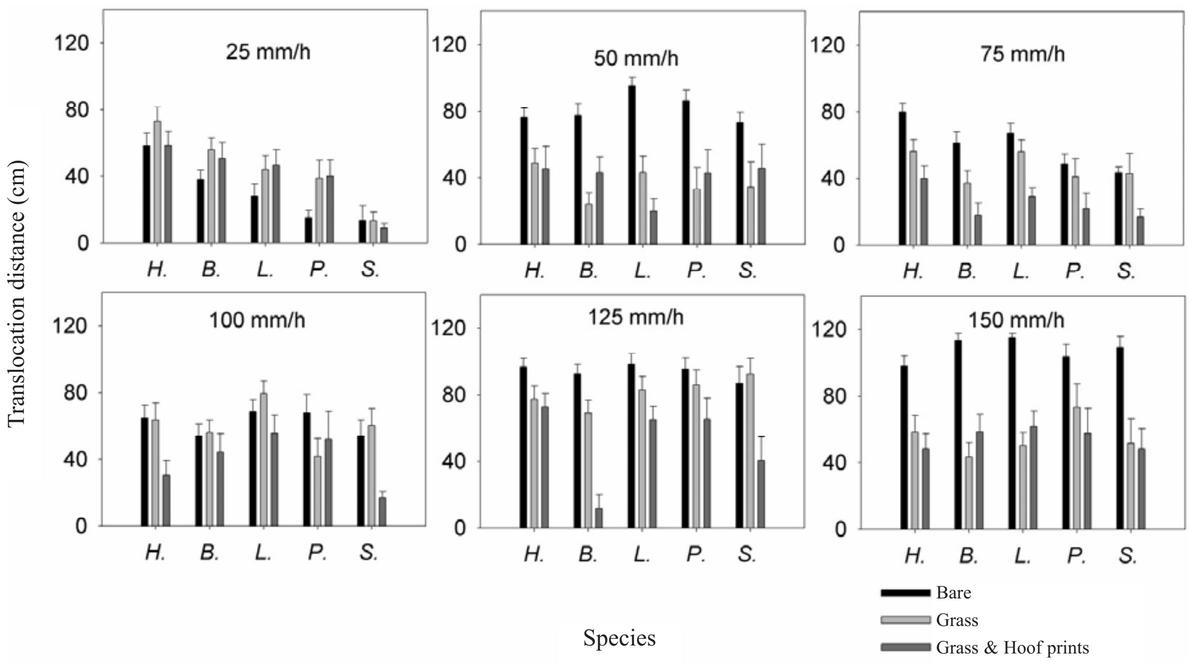

Fig. 6. Average seed translocation distance under different rainfall intensities (H.– *Heteropappus altaicus*, B.– *Bothriochloa ischaemun*, L.– *Lespedeza davurica*, P.– *Periploca sepium*, and S.– *Sophora viciifolia*).

removal. When the rainfall duration was prolonged from 30 min to 60 min, the seed loss rate at 25 mm/h, 50 mm/h, and 75 mm/h rainfall was increased evidently (Fig. 5). It may be explained that low intensity and long duration rainfall make the soil surface completely saturated and decrease the cohesion between seeds and the soil, and seeds are easily washed away. However, when rainfall intensity was more than 100 mm/h, seed loss mainly occurred within 30 min in the rainfall process. Under the intense rain, the infiltration capacity of the soil is exceeded in a moment and the flow with high velocity and eroded ability yield quickly. So the seeds are removed or washed away in a short time. Above all, both short-duration high-intensity rainfall and long-duration low-intensity rainfall can result in high seed removal, but with different mechanisms.

The results from the simulation study indicate the general trend of seed loss under different microtopographies with different rainfall intensities. However, in the field there may be some differences. First, in the field rainfall is always at low intensity, or short duration with high intensity [36]. Second, the tussocks in the field have grown for many years. During rainfall they influence erosion not only by intercepting rainfall and protecting the soil surface against the impact of rain drops and by intercepting runoff, but also influence the fluxes of water and sediments by increasing soil aggregate stability and cohesion and by improving water infiltration [37]. Third, the soil surface is rougher in the field. And it can provide more suitable microsites to trap seeds [11, 17]. Additionally, many cracks on the soil surface can trap seeds [10, 38]. Therefore, in the field, more rainfall has a chance to infiltrate soil, and the eroded ability of overland flow may not be so high. Then the seeds have more chance to retain under the tussocks or the depression topography. So in the field, although erosion is frequent on the slope land, previous studies have shown that erosion does not affect the seed reserve as much as expected. Seeds do accumulate on the slope surfaces in sufficient quantities to ensure plant recruitment [6, 15, 39]. In the study region, the previous study also indicated that tussock and depression microsites on the slope can retain more seeds in the field [40].

Conclusion

Under rain simulation the seed loss rate increases with the rain intensity enhanced or the rainfall duration prolonged, even with low intensity. The grass or grass and hoof prints on the slope can reduce seed loss on the slope under high rainfall intensity. The spotted individual grass and the hoof prints can enhance soil erosion by changing the path of overland flow and increase the seed loss at the low rainfall intensity compared with bare slope. However, in the field, the characteristics of the rainfall, vegetation pattern and soil surface microtopographies would be different, and the tussock and depression microsites can act as seed traps under some conditions.

Acknowledgements

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