

SEED REMOVAL DUE TO OVERLAND FLOW ON ABANDONED SLOPES IN THE CHINESE HILLY GULLIED LOESS PLATEAU REGION

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ABSTRACT

Theories and empirical evidences suggest that seed removal due to overland flow can result two main spatial outcomes, seed redistribution and seed loss. However, it is not fully understood in some sensitive habitats, such as in abandoned cropland of the Chinese hilly gullied Loess Plateau region. This study evaluates seed redistribution patterns in major micro-sites including eroded, deposited and trap micro-sites, characterizes seed loss by using runoff plot, and explores the effect of vegetation coverage and rainfall on seed loss along three abandoned slopes in the Zhifanggou watershed. Soil seed bank densities in eroded, deposited and trap micro-sites were recorded at 4,482, 7,697 and 5,649 seeds m^{-2} , respectively. Seed density of loss due to overland flow in 2011 and 2012 were recorded at 52 and 27 seeds m^{-2} , respectively. Seed loss rate, which was the ratio of seed loss density to the mean density of soil seed banks in the three micro-sites due to soil erosion during the study period was 0.6%. Seed densities of loss exhibited an exponent relationship with natural erosive rainfalls, and significant correlations were not found between seed loss and vegetation coverage. Therefore, soil erosion resulted in seed redistribution and caused seeds to concentrate in soils or on soil surfaces in trap or deposited micro-sites. Seed loss was affected by erosive rainfall significantly, but it could not cause the loss of large quantities of seeds. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: erosive rainfall; seed loss; seed redistribution; soil erosion; vegetation cover

INTRODUCTION

The Loess Plateau of PR China has suffered from serious soil erosion for a long time due to both natural and human-induced factors (Wang *et al.*, 2011a). Natural recovery of vegetation is an effective approach to control soil erosion in this situation, and thus, vast swathes of arable lands have been abandoned to natural succession since the beginning of the “Grain for Green” programme in 1999. However, soil erosion in turn interferes with natural recovery of vegetation by impacting the whole growth stages of plant for the degradation of ecosystems (Espigares *et al.*, 2011; Jiao *et al.*, 2009; Tsuyuzaki & Haruki, 2008). Within the life cycle of plants, the seed stage is particularly vulnerable to environmental conditions (Harper, 1977; Jiao *et al.*, 2009), especially in arid and semi-arid regions where rainfall mostly occurs in a small number of high intensity events with the potential to trigger strong soil erosion processes (Poesen & Hooke, 1997; Rodriguez-Iturbe & Porporato, 2004), consequently resulting in seed removal in soils and on soil surfaces (García-Fayos *et al.*, 1995).

Given the scale of seed removal processes, two main spatial outcomes can be resulted: seed redistribution and seed loss (Bochet, 2015). Because successful vegetation regeneration depends upon the seeds dispersing to safe sites where seeds can germinate and seedlings can establish (Urbanska, 1997; Wang *et al.*, 2014a), seed redistribution may be an opportunity for seeds to reach more favourable sites for seeds germination and seedlings survival (Vander Wall & Longland, 2004). As seeds are redistributed from one location to another on the surface of the soil and in the soil, it alters the primary seed-deposition pattern of soil seed bank (Cerdà & García-Fayos, 2002; García-Fayos *et al.*, 1995) and then affects the subsequent structure of plant communities (García-Fayos *et al.*, 2010; Nathan & Muller-Landau, 2000; Thompson & Katul, 2009). In general, seed redistribution is studied by measuring the transport distances of seeds, but it is, of course, not applicable on field measurements of soil seed bank. The current vegetation and ecogeomorphology of a site can influence the seed movement during the runoff process (Wang *et al.*, 2013a). For example, advection of seeds in runoff is likely to transport seeds into vegetation bands (Thompson & Katul, 2009), and depression topography can trap seeds removed by runoff and strongly reduce the travelled distance of seeds

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removal (Isselin-Nondedeu *et al.*, 2006; Isselin-Nondedeu & Bédécarrats, 2007). In short, the seed redistribution patterns on eroded slope can be evaluated through the comparison of soil seed banks in main micro-sites, such as eroded, deposited and trap micro-sites.

There have been many studies on seed loss on eroded slope in arid and semi-arid regions. At first, scholars argued seed loss due to overland flow to explain the lack or scarcity of vegetation. But it suggested that soil erosion could not lead to heavy losses of seed resource on badland slopes in southeastern Spain in the study of García-Fayos *et al.* (1995). Jiao *et al.* (2011) also inferred that seed loss due to overland flow was not the main reason for the sparse vegetation in the Loess Plateau basing the seed loss occurred at simulated rainfalls on bare loess slopes and the field research on propagule, seedling and population development of 16 species found on the Chinese hilly gullied Loess Plateau region. With the deep-going research on seed loss, it has been surveyed in relation to influential factors of seed loss and to explore seed movement models through simulation experiments (Aerts *et al.*, 2006; Cerdà & García-Fayos, 1997; Cerdà & García-Fayos, 2002; Han *et al.*, 2011; Thompson *et al.*, 2014), but such results are often influenced by seed location and species composition (Han *et al.*, 2011), and no studies have reported on relationships between seed loss, individual natural rainfall event and vegetation coverage under field condition.

Thus, this study examines soil seed bank in major micro-sites (i.e., eroded, deposited and trap micro-sites) and characteristics of seed loss, vegetation coverage and rainfall throughout abandoned slopes of the Chinese hilly gullied Loess Plateau region. The objectives of this study were to identify the two outcomes on the eroded slopes, seed redistribution and seed loss, caused by overland flow and explore the effect of vegetation coverage and rainfall on seed loss. We posit the following: (i) compared with eroded micro-site, deposited or trap micro-sites would retain more species and higher densities of seeds; (ii) overland flow would cause a great loss of seed resource; and (iii) as rainfall increase or vegetation cover decrease, seed densities of loss due to overland flow would increase.

MATERIALS AND METHODS

Study Site

The study was conducted in the 8.27 km² Zhifanggou watershed in the hilly gullied Loess Plateau region (105°51'4"–109°26'18"E, 36°22'40"–36°32'16"N), situated at 1.010–1.431 m above sea level (Figure 1). The watershed is characterized by a warm, temperate-continental monsoon climate with a mean temperature of 8.8 °C. Average annual precipitation in the area is recorded at 505 mm. More than 70% of all precipitation in the area falls during the summer (June–September), and rainfall largely occurs during a small number of high intensity events. Loessial soils constitute the main soil type in the watershed, and they are composed of 65% sand, 24% silt and 11% clay (Li *et al.*, 2013). The watershed is located in the forest-

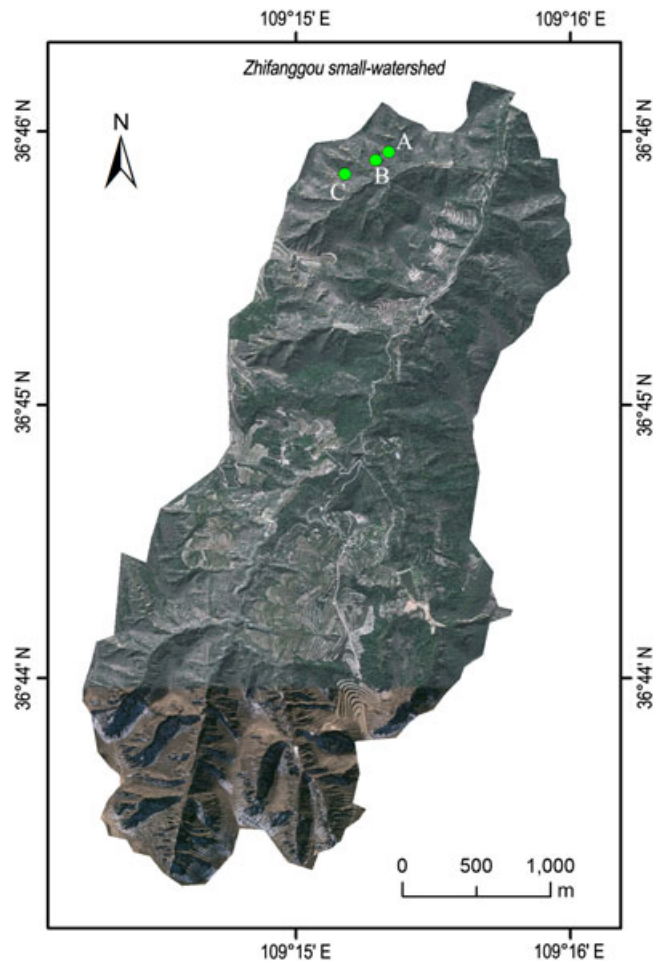


Figure 1. Location of the study site. The letters, A, B and C, stand for the study slopes.

steppe region. While human activities have completely destroyed original vegetation in the area, local vegetation is now changing considerably because croplands were converted or abandoned into woodlands or grasslands to restore vegetation and control soil erosion.

Three typical southern-aspect abandoned croplands with similar vegetation composition and periods of time because agricultural abandonment were selected in 2000 (Figure 1). Their slope angles were 28.7°, 29.4° and 25.2°, and their vegetation covers were 29.0%, 29.0% and 25.0%, respectively.

Selection of Micro-sites

Three main and widespread micro-sites on each abandoned slope were selected: tussocks as trap micro-sites (Du *et al.*, 2013), bare inter-plant areas as eroded micro-sites (Wang *et al.*, 2011b) and fish-scale pits as artificial deposited micro-sites (Figure 2). Tussock can act as physical barrier and be effective in trapping runoff sediment (Wang *et al.*, 2011b). Species, such as *Artemisia gmelinii*, *Bothriochloa ischcemum* and *Stipa bungeana*, can form tussocks and phytogenic mound often develops in different extent under the tussock in the study area (Du *et al.*, 2013; Wang *et al.*,

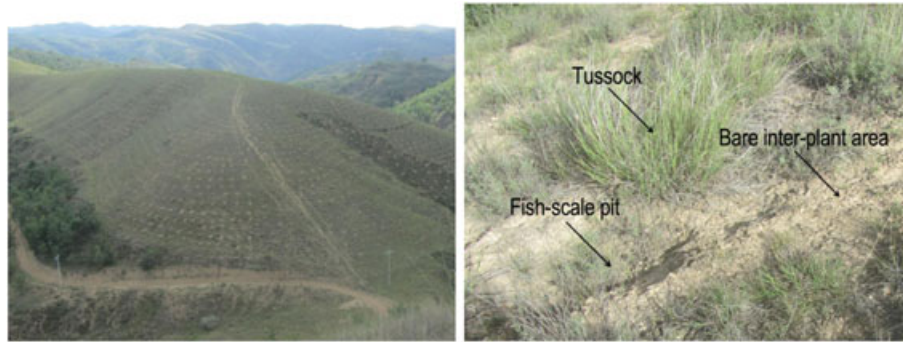


Figure 2. View of the micro-sites.

2013b). The phytogenic mound shape varies from an almost symmetrical mound-type to an asymmetrical terrace-type and its height is generally less than 15 cm (Du *et al.*, 2013). The fish-scale pit technique is an engineering measure that is commonly used for water and soil conservation. Pits are built evenly along slopes to collect runoff and sediment, thereby extending planted tree survival, and the crescent-shaped pits are built in an alternating pattern similar to the arrangement of fish scales (Figure 2), giving rise to their name (Wang *et al.*, 2014b). The size of fish-scale pits generally less than $60 \times 40 \text{ m}^2$ in the study slopes.

Soil Seed Bank Identification

Three quadrats ($20 \text{ m} \times 20 \text{ m}$) were randomly chosen on each slope before the rains came in late March of 2011. Twenty soil cores were collected using a soil auger (diameter 4.8 cm) in bare inter-plant areas in each quadrat, and samples corresponding to 0–2, 2–5 and 5–10 cm soil layers were mixed together, respectively. And similarly, the samples in trap micro-sites and deposited micro-sites were collected as described earlier in each quadrat. Seeds were identified via the seedling-emergence method. Air-dried samples were sieved to 0.15 mm, which was smaller than the diameter of the smallest seed in the study area, and the larger soil fraction was used for germination purposes to improve the germination and reduce the emergence time (Ter Heerd *et al.*, 1996; Wang *et al.*, 2011a). The samples were placed in plastic trays in a greenhouse and were watered daily with sprinklers. Seedlings were counted when identifiable and were then removed from the trays. Once the initial germination phase was complete, samples were stirred each month to expose un-germinated seeds to favourable conditions of emergence. The germination experiment was complete when no seedling emergence occurred for two consecutive weeks, and it lasted more than 6 months for full germination of seeds in soil seed banks (Wang *et al.*, 2011a).

Seed Loss Observation

Runoff plot ($1 \text{ m} \times 2 \text{ m}$) was installed to determine seed losses of abandoned slope due to overland flow. There were nine runoff plots on each slope for eliminate error. To reduce errors due to soil disturbances during experimental device installation, runoff plots were installed in October of 2010, and then seed losses due to overland flow were examined from May of

2011 to October of 2012. Runoff plots were separated by plastic plates (inserted 10 cm into the soil and extending 10 cm above the soil surface). As shown in Figure 3, a diversion device was positioned above the plots to prevent excessive runoff during storms that could have destroyed the plots; a bag with a mesh hole size of 0.15 mm, which was smaller than the diameter of the smallest seed in the study area (Wang *et al.*, 2011a) installed along the lower sides of the plots, collected seeds carried by runoff. The bag was replaced in 3 days after each erosive rainfall event, which can produce overland runoff and cause soil erosion in the hilly gullied Loess Plateau region, and its related rainfall depth and average intensity generally exceed 12 mm and 0.04 mm min^{-1} , respectively (Xie *et al.*, 2000). Rainfall data were obtained from the Ansai Ecological Experimental Station of Soil and Water Conservation of the Chinese Academy of Sciences. Bag contents were air-dried and sieved to remove litter. The number of seeds per species was counted to obtain seed density of loss due to overland flow. The vegetation coverage of runoff plots was also examined using the traditional ocular method after each erosive rainfall event. In this case, the seed density of loss in a runoff plot and its corresponding vegetation cover were obtained in each erosive rainfall event.

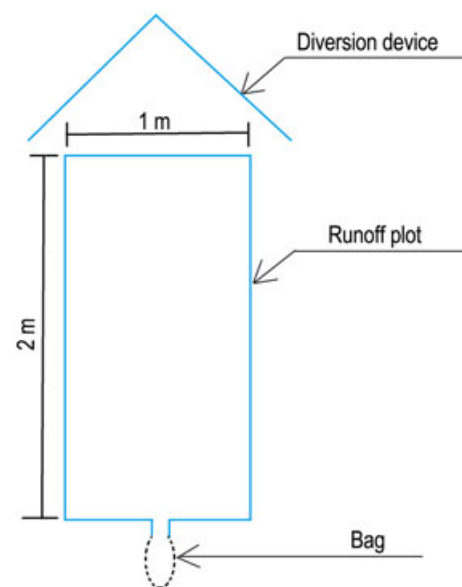


Figure 3. Runoff plot design.

Seed Rain

Seed rain was observed monthly in the study slopes from October 2010 to April 2013, and the data of seed rain was published in a Chinese Journal (Yu *et al.*, 2015). The data of seed rain was added during March of 2011 to October of 2012 as the seed's entries in the system for calculate seed loss rate, which was regarded as the ratio of seed loss density to total seed bank density including the mean density of soil seed bank in the three micro-sites before the rainy season in year 2011. According to the study of Yu *et al.* (2015), the seed rain density was 6,837 seeds m^{-2} during March of 2011 to October of 2012 (Table I). The seed rain densities were 2,352 and 1,966 seeds m^{-2} in the rainy seasons of 2011 and 2012, respectively.

Statistical Analysis

Differences in densities and species quantities of soil seed banks across the three micro-sites were examined via one-way analysis of variance. Seed densities or species were

transformed using $\log(x+1)$, thus satisfying the homogeneity of variance assumption. Correlations between seed densities of loss due to overland flow and vegetation coverage were examined using the Pearson correlation method, and relationships between seed densities of loss due to overland flow and erosive rainfall were analysed by means of exponential models.

RESULTS

Soil Seed Banks in Micro-sites

No significant differences in species richness were found in the same soil layers across the different micro-sites but significant differences in seed densities were found in the 0–2 cm soil layer (Figure 4), and thus, the effect of soil erosion on soil seed bank was mainly for top soil layers. Soil seed bank densities in bare inter-plant area, fish-scale pit and tussock were 4,482, 7,697 and 5,649 seeds m^{-2} , respectively (Table II). The total density of the soil seed bank

Table I. Seed rain density, mean soil seed bank density, total seed bank density, seed loss density and Seed loss rate during the study period

Species	Seed rain density (seeds m^{-2})	Mean soil seed bank density (seeds m^{-2})	Total seed bank density (seeds m^{-2})	Seed loss density (seeds m^{-2})	Seed loss rate (%)
<i>Artemisia giraldii</i>	1	0	1	<1	3.7
<i>Artemisia gmelinii</i>	122	173	295	1	0.4
<i>Artemisia scoparia</i>	607	4,239	4,846	28	0.6
<i>Astragalus melilotoides</i>	1,046	2	1,048	3	0.3
<i>Astragalus scaberrimus</i>	0	1	1	<1	3.7
<i>Bothriochloa ischcemum</i>	1,382	106	1,488	7	0.5
<i>Carduus nutans</i>	1	0	1	<1	7.4
<i>Cleistogenes squarrosa</i>	137	6	143	<1	0.5
<i>Clematis fruticosa</i>	1	0	1	<1	1.9
<i>Dracocephalum moldavica</i>	4	20	24	<1	0.3
<i>Heteropappus altaicus</i>	231	8	239	<1	0.3
<i>Incarvillea sinensis</i>	89	0	89	<1	0.7
<i>Ixeridium chinense</i>	4	10	14	<1	1.1
<i>Ixeris sonchifolia</i>	34	0	34	3	7.7
<i>Lespedeza davurica</i>	241	30	271	<1	0.1
<i>Polygala tenuifolia</i>	8	0	8	<1	0.7
<i>Potentilla tanacetifolia</i>	0	2	2	<1	0.9
<i>Roegneria kamoji</i>	12	0	12	<1	0.2
<i>Salsola collina</i>	12	42	54	<1	0.6
<i>Setaria viridis</i>	1,607	756	2,363	24	1.0
<i>Stipa bungeana</i>	1,254	5	1,259	8	0.6
The others	42	541	583	0	0.0
All species	6,837	5,943	12,780	79	0.6

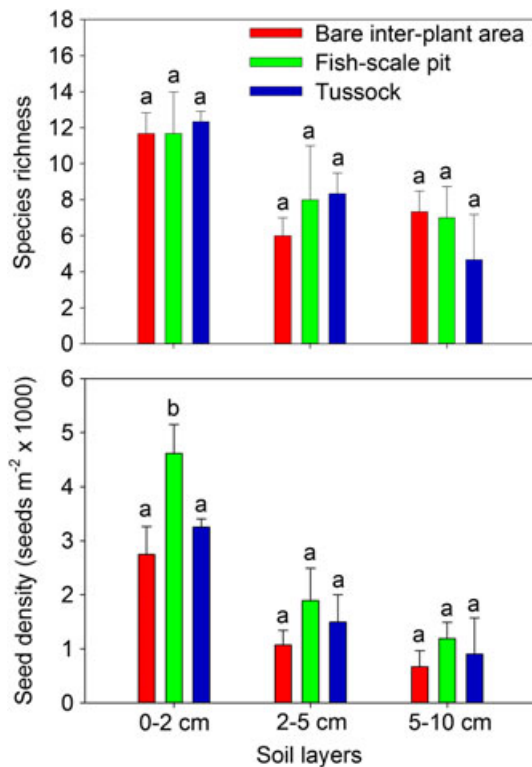


Figure 4. Soil seed bank density and species richness in different micro-sites. The presence of the same letters above the error bar in the same column denotes no significant differences among the micro-sites, and the presence of different letters denotes significant differences between the micro-sites based on the LSD test ($P < 0.05$).

in the fish-scale pit was significantly higher than the densities of the other two micro-sites, and there was no significant difference of total densities between under tussock and in bare inter-plant area.

All of the species identified in the soil seed bank can be classified into three functional groups: annual/biennial herbs, perennial forbs and shrubs/subshrubs. The annual/biennial herbs formed the largest proportion of the soil seed bank (Table II). Soil seed bank densities in the micro-sites ranked in order of higher to lower were fish-scale pit, tussock and inter-plant area for all of the functional groups.

The *Artemisia scoparia* species dominated the soil seed bank, with its seed density accounting for 79.0%, 62.7% and 77.0% of total seed density in bare inter-plant area, fish-scale pit and tussock, respectively. No significant difference was found in the densities of soil seed banks across the three micro-sites for most of species (Table II). There were four species including *Artemisia hedinii*, *Dracocephalum moldavica*, *B. ischcemum* and *Cleistogenes chinensis*, having significantly greater soil seed bank densities in fish-scale pit than that in inter-plant area. The three species, *Astragalus melilotoides*, *Kochia scoparia* and *B. ischcemum*, had a significantly greater soil seed bank densities in tussock than that in inter-plant area. There were five species including *Artemisia hedinii*, *D. moldavica*, *Kochia scoparia*, *Cleistogenes chinensis* and *S. bungeana* having a significantly difference in the densities of soil seed banks between tussock and fish-scale pit.

Table II. Mean density of soil seed banks in the three micro-sites

Species	Bare inter-plant area (seeds m ⁻²)	Fish-scale pit (seeds m ⁻²)	Tussock (seeds m ⁻²)
Annual/biennial herbs			
<i>Artemisia hedinii</i>	184 ± 46a	718 ± 445b	150 ± 89a
<i>Artemisia scoparia</i>	3,540 ± 653a	4,829 ± 968a	4,347 ± 1,082a
<i>Astragalus melilotoides</i>	0a	0a	6 ± 5b
<i>Dracocephalum moldavica</i>	15 ± 11a	40 ± 14b	6 ± 5a
<i>Kochia scoparia</i>	0a	0a	6 ± 4b
<i>Salsola collina</i>	21 ± 30a	49 ± 30a	55 ± 40a
<i>Setaria viridis</i>	439 ± 331a	1,253 ± 579a	577 ± 427a
Perennial forbs			
<i>Astragalus scaberrimus</i>	3 ± 5a	0a	0a
<i>Bothriochloa ischcemum</i>	52 ± 11a	132 ± 30b	135 ± 23b
<i>Cleistogenes chinensis</i>	31 ± 14a	246 ± 77b	111 ± 32a
<i>Cleistogenes squarrosa</i>	12 ± 21a	3 ± 5b	3 ± 5b
<i>Heteropappus altaicus</i>	9 ± 9a	12 ± 14a	3 ± 5a
<i>Ixeridium chinense</i>	12 ± 11a	12 ± 14a	6 ± 5a
<i>Potentilla tanacetifolia</i>	3 ± 5a	3 ± 5a	0a
<i>Stipa bungeana</i>	6 ± 5ab	0a	9 ± 9b
Shrubs/subshrubs			
<i>Artemisia gmelinii</i>	98 ± 46a	252 ± 96a	169 ± 111a
<i>Buddleja lindleyana</i>	0a	6 ± 10a	6 ± 5a
<i>Euphorbia humifusa</i>	34 ± 14a	89 ± 38a	40 ± 38a
<i>Lespedeza davurica</i>	12 ± 11a	52 ± 46a	25 ± 14a
Annual/biennial herbs	4,209 ± 1,001a	6,889 ± 557b	5,142 ± 1,143ab
Perennial forbs	129 ± 51a	408 ± 98b	267 ± 42c
Shrubs/subshrubs	144 ± 37a	399 ± 168b	239 ± 129ab
Total	4,482 ± 987a	7,697 ± 686b	5,649 ± 1,296a

Data are expressed as the mean ± standard deviation (SD), with different letters denoting significant differences at the 0.05 level across the different micro-sites.

Seed Loss due to Overland Flow

In total, 79 seeds m^{-2} from 22 species were found during the study period. The seed densities of loss due to overland flow in 2011 and 2012 were 52 and 27 seeds m^{-2} , respectively. Seed densities of *Stipa viridis* and *A. scoparia* were 28 and 24 seeds m^{-2} , respectively, higher values than that of the other species (Table III).

We obtained a total seed density of 12,780 seeds m^{-2} including the seeds that entered the system through seed rain from March of 2011 to October of 2012 (6,837 seeds m^{-2}) and mean soil seed bank of the three micro-sites collected in late March of 2011 (5,943 seeds m^{-2}) (Table I). All of the species in seed loss could be found in the total seed bank. Seed loss rate of all species was 0.6%. The rates were various in different species, from 0% to 7.7%. The seed loss rates of *A. scoparia* and *S. viridis* were 0.6% and 1.0%, respectively. Seed loss rates of the other species, such as *Astragalus melilotoides*, *B. ischcemum* and *S. bungeana* of which total seed bank were greater than 1,000 seeds m^{-2} , were 0.3%, 0.5% and 0.6%, respectively.

Relationships between Seed Loss, Erosive Rainfall and Vegetation Coverage

As shown in Figure 5, seed densities of loss showed a significant exponent relationship with erosive rainfalls ($P < 0.05$). However, the significance of relationships between them over the 2 years was not consistent.

Seed densities of loss did not show relationship with vegetation coverage during each erosive rainfall event ($P > 0.05$). As cover increased, seed densities of loss were

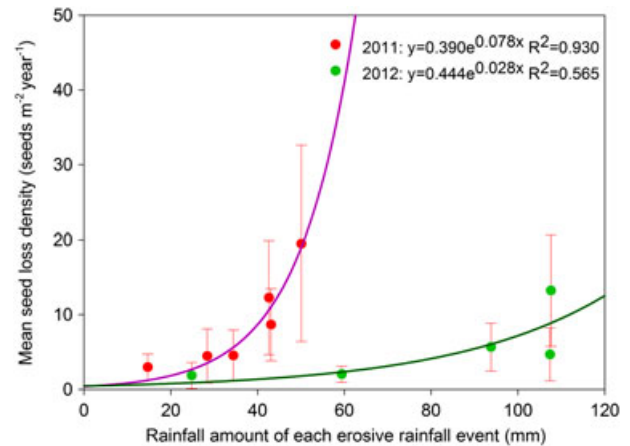


Figure 5. Corresponding relationships between seed loss density and erosive rainfall for 2011 and 2012.

variable (Figure 6). The seed amounts of loss were smaller and steady after the vegetation coverage increasing to a threshold in some rainfall events, such as the events of which the precipitations were 34.4 mm, 28.4 mm, 50.1 mm and 93.8 mm, respectively (Figure 6).

DISCUSSION

Soil Seed Banks in Micro-sites

The recovery of natural vegetation relies upon the effective dispersal of viable seeds first, followed by the development of safety sites where seeds can germinate and seedlings can establish (García-Fayos *et al.*, 2013; Harper, 1977). Vegetation influences overland flow, constrains spatial seed dispersal and can further affect seed germination and establishment (Moreno-de las Heras *et al.*, 2011). Phytogenic mounds developing under isolated plants can concentrate nutrients and litter in the study region with scattered plant distributions (Du *et al.*, 2013). Zhang *et al.* (2012) noted that vegetation canopies can effectively reduce runoff and sediment while protecting seedlings from radiation, thus improving rates of seed germination and seedling survival in the hilly gullied Loess Plateau region. Overall, tussock may serve a safe site for vegetation regeneration. Thus, according to the results of this study, species, especially *B. ischcemum* dominating the later successional stage in abandoned lands of the Loess Plateau (Jiao *et al.*, 2008), for which soil seed bank densities under tussocks are greater than those of bare inter-plant areas, may show greater capacities for vegetation regeneration.

The lack of water is the main limiting factor in terms of vegetation recovery, and fish-scale pits have been popularized as one means of runoff collection in the hilly gullied Loess Plateau region (Li *et al.*, 2011). Ma *et al.* (2006) and Wang *et al.* (2011b) found that fish-scale pits can increase species diversities of plant communities as well as soil quality. Seed densities in the fish-scale pits were significantly higher than those of inter-plant areas and tussocks in this study. This shows that

Table III. Mean density of seed loss for different species

Species	Seed density (seeds m^{-2})	
	2011	2012
<i>Ailanthus giraldii</i>	<1	<1
<i>Artemisia giraldii</i>	<1	-
<i>Artemisia gmelinii</i>	1	<1
<i>Artemisia scoparia</i>	18 ± 3	10 ± 6
<i>Astragalus melilotoides</i>	1	2 ± 2
<i>Astragalus scaberrimus</i>	-	<1
<i>Bothriochloa ischcemum</i>	5 ± 6	2 ± 1
<i>Carduus nutans</i>	<1	<1
<i>Cleistogenes squarrosa</i>	-	1 ± 1
<i>Clematis fruticosa</i>	-	<1
<i>Dracocephalum moldavica</i>	-	<1
<i>Heteropappus altaicus</i>	<1	<1
<i>Incarvillea sinensis</i>	<1	<1
<i>Ixeridium chinense</i>	1	<1
<i>Ixeris sonchifolia</i>	-	3 ± 2
<i>Lespedeza davurica</i>	<1	<1
<i>Polygala tenuifolia</i>	-	<1
<i>Potentilla tanacetifolia</i>	<1	-
<i>Roegneria kamoji</i>	-	<1
<i>Salsola collina</i>	<1	-
<i>Setaria viridis</i>	22 ± 11	2 ± 1
<i>Stipa bungeana</i>	2 ± 2	6 ± 4
Total	52 ± 9	27 ± 4

Data are expressed as the mean ± standard deviation (SD).

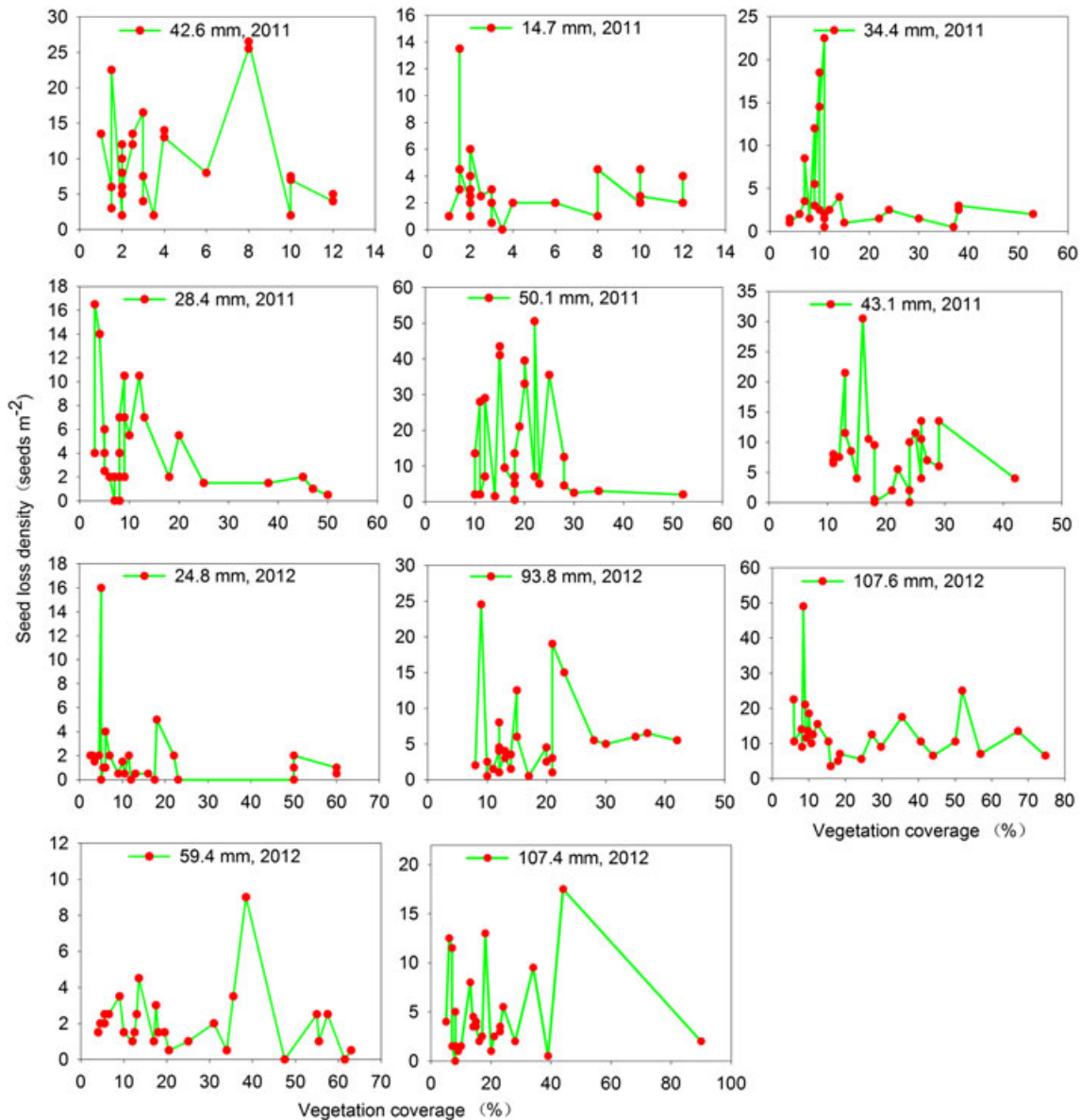


Figure 6. Relationships between seed loss density and vegetation coverage for each erosive rainfall event in 2011 and 2012.

fish-scale pits encourage vegetation recovery. However, Zhang *et al.* (2009) noted that high evaporative capacities of fish-scales pits can exacerbate moisture loss processes, thereby limiting vegetation recovery during periods without rainfall. And Wang *et al.* (2014b) evaluated effects of fish-scale pits and found that afforestation in conjunction with the use of fish-scale pits is ineffective at controlling soil erosion and improving vegetation recovery. Furthermore, pioneer species of annual/biennial herbs such as *A. scoparia* dominate soil seed banks, and especially in fish-scale pits. Thus, we must further explore whether annual/biennial herbs can delay succession because of their ability to compete for resources with the other species in the three micro-sites.

Seed Losses

Seed loss rates were low in this study. And for dominant species during different successional stages, such as *A. scoparia*,

Lespedeza davurica, *S. bungeana*, *A. gmelinii* and *B. ischaemum* in this study, can form a persistent and stable soil seed bank in the study area (Wang *et al.*, 2011a). Thus, low seed loss rate cannot explain the reason why vegetation was sparse from a seed resource perspective on abandoned slope in the hilly gullied Loess Plateau region. The low seed loss rate was usually explored by examining mechanisms of seed removal constraints (García-Fayos *et al.*, 2013; Jiao *et al.*, 2011). For example, seed morphologies that resist soil erosion are conducive to species development on eroded slopes (Cerdà & García-Fayos, 2002). Species, such as *A. scoparia*, *A. gmelinii* and *D. moldavica* can secrete mucilage once moistened (Jiao *et al.*, 2011). When mucilage dries, it securely anchors the diaspore to the surface, reducing the probability of seed removal (García-Fayos & Cerdá, 1997). Moreover, the seeds of most dominant species appearing in this study begin to disperse after the rainy season (Yu *et al.*, 2015). For example, seeds of *A.*

scoparia, *A. gmelinii* and *S. viridis* begin to disperse after September. This reduces the risk of seed loss due to overland flow by reducing seed inputs during the rainy season.

Rainfall and Vegetation Effects on Seed Removal

Rainfall intensity and duration can affect seed loss due to overland flow. Han *et al.* (2011) and García-Fayos *et al.* (1995) showed that seed losses increase as the intensity and duration of rainfall increases. In our study, seed densities of loss due to overland flow exhibited an exponent relationship with natural erosive rainfalls. However, inconsistent relational significance between seed loss and erosive rainfall over the 2 years, and it might be caused by varied densities in seed rains during the rainy season. As the densities were 2,352 and 1,966 seeds m⁻² in the rainy seasons of 2011 and 2012 in the study slopes (Yu *et al.*, 2015), the more abundant seeds inputted the surface of slopes between the 2 years, the greater loss of seeds was caused under same rainfall condition.

The results did not show significant correlations between seed removal and vegetation coverage. Other vegetation characteristics (e.g., spatial distribution patterns of vegetation and plant shoot architectures) may play a key role. Spatial patterns of vegetation are largely identified as patches or strips of shrubs and grasses that reflect limited water and nutrient availability in arid and semi-arid regions, and they influence the regulation of surface hydrological processes (Aguiar & Sala, 1994; Cerdà, 1997; Vásquez-Méndez *et al.*, 2010). Zhang *et al.* (2014) noted that patches performed more effectively than strips in terms of increasing hydraulic roughness and then reducing soil erosion. Furthermore, plant shoots or stems can act as physical barriers while reducing the flow velocity of seeds transported through overland flows (Breshears *et al.*, 2003; Ludwig *et al.*, 2005). Therefore, a relationship between seed loss and vegetation cover might be not observed because of interference by other vegetation characteristics. Besides, the more or less presence of fish-scale pits in a runoff plot and the differences of soil seed bank densities among all plots could influence the results.

In addition, the recently listed results are limited by the scale of runoff plot used in the study. The other studies have shown that seed losses decrease as plot lengths increase along badland surfaces (García-Fayos *et al.*, 1995). Upslope runoff and sediment effects were ignored in the study and with increasing runoff and sediment rates from upper slopes, degrees of shallow flow erosion increase (Xiao *et al.*, 2001), increasing seed removal risks.

CONCLUSIONS

In this study, soil erosion caused seeds to concentrate in soils or on soil surfaces under tussocks and in fish-scale pits at varying levels. But it did not remove large quantities of seeds from the abandoned slopes. Seed loss was affected by erosive rainfall. In conclusion, soil erosion is not the limiting factor for natural vegetation recovery in the seed stage.

Other factors, such as seed germination and seedling survival capacities, must be studied further.

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