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EFFECT OF RAINFALL EROSION: SEEDLING DAMAGE AND ESTABLISHMENT PROBLEMS

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ABSTRACT

Physical damage is one of the main factors that cause seedling mortality in many ecosystems. However, the impact of physical damage due to rainfall erosion on seedling mortality is seldom investigated. In this study, we ask the following question: how does rainfall erosion influence seedling damage and establishment in the Loess Plateau region of China? Seedling damage and establishment experiments under different patterns of simulated rainfall were conducted. The seedling damage rate, damage type and growth status were investigated. The seedling damage rate was influenced by rainfall intensity and duration and by the runoff volume. The mean damage rate of all three studied species did not exceed 15 per cent, and the highest damage rate of individual species under special rainfall events was approximately 30 per cent. The type of damage suffered by the seedlings of *Sophora viciifolia* (which produces large seeds) mainly took the form of striking down, whereas seedlings of *Artemisia scoparia* (which produces small seeds) suffered the highest rates of washing away among the three studied species. In the seedling establishment experiment, after 120 days with six rainfall events, *S. viciifolia* had the highest seedling establishment rate (80·1 2·5 per cent), followed by *Bothriochloa ischaemun* (67·2 ± 2·2 per cent), and *A. scoparia* (28·1 ± 2·5 per cent). The seedling damage rate, damage type and establishment rate were also related to seed size. Whether physical damage to seedlings is a major factor limiting vegetation restoration in eroded environments requires further research. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS: physical damage; rainfall simulation; seed size; Loess Plateau; vegetation restoration

INTRODUCTION

The restoration of fragmented habitats and degraded ecosystems is often a focus of current ecological research (Saunders *et al*., 1991; Eriksson, 1996; Bakker and Berendse, 1999). However, seedling recruitment is often a key limitation to plant community restoration on degraded land (Bakker *et al*., 1996; Seabloom *et al*., 2003). Especially in arid and semi-arid zones, seedling establishment is considered to be a problematic and sporadic process (Flores *et al*., 2004). The period between seed germination and seedling establishment is considered to be one of the most vulnerable transitions in the life cycle of plants (Harper 1977), and it affects the structure features of plant population and community and the effectiveness of vegetation restoration (Garrido *et al*., 2005; Gómez-Aparicio 2008). Thus, success during germination and seedling establishment are keys to the determination of plant distribution at both local and wider geographical levels (Flores *et al*., 2004).

The successful restoration of plant communities depends on the availability of seed resources and the presence of safe sites that allow the species to germinate and establish (Duncan *et al*., 2009; García-Camacho *et al*., 2010). Although seeds on the soil surface and in the soil profile are threatened by raindrop splash and overland flow in habitats with soil erosion (Cerdà and García-Fayos, 2002; García-Fayos *et al*., 2010), previous studies indicate that seed removal by erosion is not the key factor that explains the lack of vegetation on eroded badlands (García-Fayos *et al*., 1995; García-Fayos *et al*., 2000; Jiao *et al*., 2011). Many other studies indicate that drought is a major cause of damage in natural seedling populations (Veenendaal *et al*., 1996; García-Fayos *et al*., 2000) in arid and semi-arid ecosystems. In addition to drought stress, physical damage is another major factor that causes seedling mortality in many ecosystems (Clark and Clark 1989; Nagamatsu *et al*., 2002; de Luís *et al*., 2005). Seedlings whose roots are entirely exposed by soil erosion or killed by fallen materials such as leaves, branches or gravel are categorised as physically damaged (Nagamatsu *et al*., 2002).

Studies examining the impact of physical damage on seedling mortality commonly focus on litterfall in the forest ecosystem (see, e.g. Clark and Clark, 1989; Scariot, 2000; Gillman *et al*., 2003). On slope land, however, physical

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damage caused by surface material movement is an important factor that threatens seedling survival (Yoshida and Ohsawa, 1999; Nagamatsu *et al*., 2002; Tsuyuzaki and Haruki, 2008). The serious soil erosion caused by extreme precipitation can reduce seedling survival; seedlings may be buried by sediment, or they may be totally or partially unearthed (de Luís *et al*., 2005; Gómez-Aparicio, 2008). The kinetic energy of falling raindrops, like that of litterfall, may damage seedlings, and raindrops also can cause the soil to crust, thereby reducing seedling emergence (Sheldon, 1974; Baumhardt *et al*., 2004).

In addition to abiotic factors, seed traits such as size also influence seedling emergence, survival and establishment. Many previous studies show that initial seedling size and seedling survival are both positively related to seed size (see, e.g. Moles and Westoby, 2004a; Benard and Toft, 2008). The seedlings produced from large seeds are potentially more robust and possess deeper roots, and they are more likely to survive dry spells (Lloret *et al*., 1999; Padilla and Pugnaire, 2007); they are also likely to be better anchored, allowing them to resist disturbances (Coomes and Grubb, 2003; Moles and Westoby, 2004a). Seedlings derived from seeds of different sizes may therefore exhibit different tolerances for physical damage under conditions of erosion.

On the Chinese Loess Plateau, rainfall is characterised by high intensity, and the land surface is fragmented by deeply incised and densely distributed gullies. Rapid overland flow usually occurs on the slopes where vegetation is sparse and rainfall intensities are very high (Shi and Shao, 2000). Soil erosion is still one of the major challenges contributing to land degradation and limiting ecological restoration in this region. Previous studies indicate that soil erosion has a great impact on seed yield and seed germination rate; that is, more serious states of soil erosion lead to lower yields and germination rates of seeds (Zhang *et al*., 2010). However, soil erosion cannot cause seeds on the soil surface or in the soil to decrease in abundance significantly (Jiao *et al*., 2011). However, the harsh environment on the eroded slope may be the dominant limitation on seedling survival, growth and vegetation recovery. In the study region, the average annual precipitation is 504 mm, and more than 70 per cent of the precipitation falls during the rainy season (July–September), usually in the form of storms. Seeds always germinate during the rainy season, especially in August, as a result of the lack of available water in the surface soil layer on the slope outside of the rainy season. Thus, small seedlings are threatened by storms during the rainy season.

However, the impact of physical damage caused by extreme precipitation and serious soil erosion on seedling mortality is unknown. Therefore, the aim of this study was to determine the effect of rainfall erosion on seedling damage to three dominant native species with different seed sizes in the hilly and gullied Loess Plateau region using simulated rainfall experiments. The objectives were to detect seedling damage rate, seedling damage types and seedling growth status under various rainfall erosion conditions.

MATERIALS AND METHODS

Rainfall Simulation Facilities

Rainfall simulation experiments were carried out in the Rainfall Simulation Hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau. A lateral-sprinkling automatic rainfall simulation system was adopted for use in this study. The systems possess four groups of nozzles with different pore sizes, and the rainfall intensities are regulated with a pneumatic diaphragm control valve. The rainfall intensities can be varied from 20 mm h^{-1} to 260 mm h^{-1}. The height of the spray nozzle was 14·5 m; most raindrops reach their terminal velocity within 10 m after starting to fall (Zhou *et al*., 1981), so the ejective experimental raindrops could reach a terminal velocity representative of what they would achieve in nature. The raindrop sizes were close to those of natural rainfall with matching intensity, and the rainfall was evenly distributed (>80 per cent). The raindrop size and velocity are difficult to measure accurately, so the raindrop kinetic energy was calculated by an empirical equation used in the study region (Zhou *et al*., 1981).

The size of the experimental soil bin was 2 m × 0·5 m × 0·5 m (length × width × height). The soil bin had an adjustable slope within a range of 0–30 degrees, and 76 holes (diameter 0·5 cm, interval 10 cm) were equally distributed in the bottom of the bin. Loess soil from An'sai County, a typical hill-and-gully region of the Loess Plateau, was used in all experiments. Before the bin was filled with loess soil, sand was added to a depth of 10 cm, and this layer was covered with gauze. Then, 30 cm of loess soil was added, and the soil bulk density was maintained at 1·10–1·15 g cm^{-3} (a value chosen based on measurements of soil bulk density at depths of 0–10 cm for 75 sampling plots in An'sai).

Experimental Species

Three species were used in the experiments: *Artemisia scoparia*, *Bothriochloa ischaemun*, and *Sophora viciifolia*. These species were selected because of their dominance in different ecosystem restoration stages, life forms and seed sizes. *A. scoparia* is a taprooted, biennial, dicotyledonous forb, and it is the pioneer plant in the early restoration of abandoned land, reaching high cover between 4 and 6 years after abandonment (Jiao *et al*., 2007). It is a high occurrence species in the hill-and-gully Loess Plateau, and it exhibits high seed production and produces small seeds (0·020 mg per seed) (*Wang et al*., 2011). *B. ischaemun* is a perennial, monocotyledonous grass with a fibrous root system and a regeneration strategy including both lateral vegetative spread and soil seed bank. Its seed mass is 0·432 mg per seed (*Wang et al.*, 2011). It is the dominant species in the perennial herb and subshrub community during the middle and late stages of vegetation restoration (Jiao *et al.*, 2008). *S. viciifolia* is shrub with a partial and scattered distribution in the middle and late stages of succession with a seed mass of 23·769 mg per seed (*Wang et al.*, 2011). It grows in the perennial herb and subshrub community and is resistant to interspecies competition in reduced-area habitats. It relies on the rapid germination of a few seeds to occupy space quickly, and it then expands its population depending on seed recruitment and vegetative propagation (Jiao *et al.*, 2008). In the study region, the seeds of the three experimental species, similar to those of other species, always germinated during the rainy season when there was water available in the surface soil layer. The germination experiment in the laboratory showed that the germination rates of *A. scoparia*, *B. ischaemun* and *S. viciifolia* were 77·3 ± 3 per cent, 70·7 ± 2 per cent and 4·0 ± 2 per cent, respectively. The germination rate of *S. viciifolia* was low because of its hard seed coat; to alleviate this effect for this study, *S. viciifolia* seeds were treated before the experiment to increase their germination rate to 50 per cent. Approximately 90 per cent of the 'readily germinable' seeds of the three species can achieve germination within a week. The seedling survival rate of these species is high when there is no erosion or drought stress during soil seed bank germination experiment. More than 97 per cent of the seedlings of *A. scoparia* and almost all of the seedlings of *B. ischaemun* and *S. viciifolia* survive approximately 40 to 50 days before being removed during the germination experiments.

Seedling Damage Experiment

For each species, mature seeds were collected in late September and October 2009, air-dried and stored in paper bags under laboratory conditions until the experiments were carried out.

The seedling damage experiment was carried out in August 2010. In this experiment, the number of seeds was chosen according to seed production, seed germination rate and seedling density in the field. The numbers of seeds used in each experimental soil bin were 800 seeds, 300 seeds and 200 seeds of *A. scoparia*, *B. ischaemun* and *S. viciifolia*, respectively. The mixed experimental seeds were sown uniformly on the soil surface, and a thin layer soil was then uniformly scattered by using a sieve to cover the seeds, which were watered regularly. The soil bins were placed in the open air for germination. Because individual seedlings cannot emerge at the same time, rainfall simulation experiments were conducted after seedlings emerged and grew for 7 days. The slope of the soil surface was 20 degrees, and the total rainfall in the experiments was held constant at 50 mm with six different rainfall intensities (25, 50, 75, 100, 125 and 150 mm h^{-1}) and matched durations (120, 60, 40, 30, 24 and 20 min). Two replications were designed for each experiment. The experimental bin was divided into 10 subplots to count the number of seedlings for each species and mark their position by photograph before the rainfall was administered. After the rainfall treatment, normal seedlings and damaged seedling were counted. The seedling damage type (uprooting, striking down and washing away) and damage rate were investigated. Runoff samples were collected at 3-min intervals during the rainfall experiment, and the volume of runoff and soil loss amount were measured and calculated to indicate the degree of runoff and soil erosion.

Seedling Establishment Experiment

To investigate the effect of rainfall erosion on seedling establishment, seeds of the three study species were sown in soil bins on 25 May 2010, with appropriate rainfall to aid seed germination. The rainfall simulation experiments were carried out after seeds had been grown for 20 days outside of the rainfall-simulating hall. The whole experiment lasted 120 days, and the rainfall interval was 20 days, which provided a simulation of the entire process of seedling establishment, from seedling germination to stable plant growth. Before each rainfall event, the number and height of the individual seedlings belonging to each species were measured, and the coverage of the soil surface was estimated. The experiment design is shown in Table I, and two replications were designed for each experiment with a slope of 20 degrees.

Data Analysis

The seedling damage rate was calculated as the proportion of seedlings damaged after rainfall, accounting for the total survival of seedlings before rainfall. The difference of the seedling damage rate and damage types of the individual species under the different rainfall treatments were analysed by analysis of variance (ANOVA) [the least significant difference (LSD) test was used in the post hoc analysis]. The influences of species, rainfall treatments and their interaction (species × treatment) were analysed by two-way ANOVA. The survival curves of different species were compared by using log-rank tests. The seedling growth rate was described as the increase of seedling height over the duration of the

Table I. Schedule of experiments for seedling establishment

Date of rainfall	Rainfall intensity (mm/h)	Rainfall duration (min)
15 June	25	60
05 July	75	60
25 July	125	30
15 August	100	30
05 September	50	60
25 September	150	30

experiment. The seedling growth rate was calculated according to the equation $Gr = (H_{n+1} - H_n)/H_n$ (Gr represents growth rate, H_n/H_{n+1} represents the height of the seedling at the n/n + 1 time points). The relationships between the seedling damage rate and rainfall duration, rainfall intensities were analysed by using partial correlation, and the relationships between the seedling damage rate and runoff, soil loss amount were analysed by using Pearson correlation coefficients.

RESULTS

Seedling Damage Rate

The seedling damage rate under different rainfall events were significantly different (Table II). The seedling damage rate of *A. scoparia* varied from 8·5 ± 1·4 to 29·5 ± 6·6 per cent, with an average of 14·2 ± 3·3 per cent. The maximum damage rate appeared under the rainfall event with 25 mm h^{-1} intensity and a duration of 120 min, whereas the minimum damage rate appeared under the rainfall event with 100 mm h^{-1} intensity and a duration of 30 min. The maximum damage rate of *B. ischaemun* (16·7 ± 2·1 per cent) also appeared under the rainfall treatment with a minimum intensity of 25 mm h^{-1} and maximum duration of 120 min; the next highest damage rate (11·9 ± 3·8 per cent) appeared under the rainfall treatment with a maximum intensity of 150 mm h^{-1} and a minimum duration of 20 min. The seedling damage rates under the other four rainfall events fell within the range of 4·1 ± 1·5–9·0 ± 2·1 per cent. For *S. viciifolia*, the seedling damage rate varied from 5·6 ± 5·6 to 29·2 ± 7·0 per cent with an average of 14·2 ± 3·4 per cent, and the highest damage rate occurred under the rainfall events with 75 mm h^{-1} intensity and a duration of 40 min (29·2 ± 7·0 per cent) and 100 mm h^{-1} intensity and a duration of 30 min (17·2 ± 5·6 per cent). The results of the two-way ANOVA showed that the rainfall treatments did not significantly influence the seedling damage rate ($F = 2{\cdot}026$, $p = 0{\cdot}075$), whereas the species and the interaction of species and rainfall treatment influenced the seedling damage rate significantly ($F = 14{\cdot}844$, $p < 0{\cdot}001$; $F = 5{\cdot}866$, $p < 0{\cdot}001$, respectively). The seedling damage rate of *A. scoparia* was significantly higher than that of the other two species, and there was no significant difference between the damage rates of *B. ischaemun* and *S. viciifolia*.

Seedling Damage Types

After rainfall, the seedlings on slopes can be classified into four types: normal, uprooting, striking down and washing away. The average status of seedlings after all the rainfall events is shown in Figure 1. After the rainfall, more than 85 per cent of the seedlings were still normal of all the three species. The proportion of damaged seedlings among different damage type had no significantly difference of *A. scoparia* and *B. ischaemun*. But the most damaged seedlings of *S. viciifolia* were striking down and only few were washing away. The results of the two-way ANOVA showed that the damage rate of uprooting was significantly affected by the rainfall treatment ($F = 2{\cdot}839$, $p = 0{\cdot}016$) and by the interaction of species and rainfall treatment ($F = 2{\cdot}555$, $p = 0{\cdot}006$) but not by the species alone ($F = 0{\cdot}853$, $p = 0{\cdot}427$). The damage rate of striking down was significantly affected by the species ($F = 6{\cdot}745$, $p = 0{\cdot}001$) and the interaction of species and rainfall treatment ($F = 2{\cdot}598$, $p = 0{\cdot}005$) but not by the rainfall

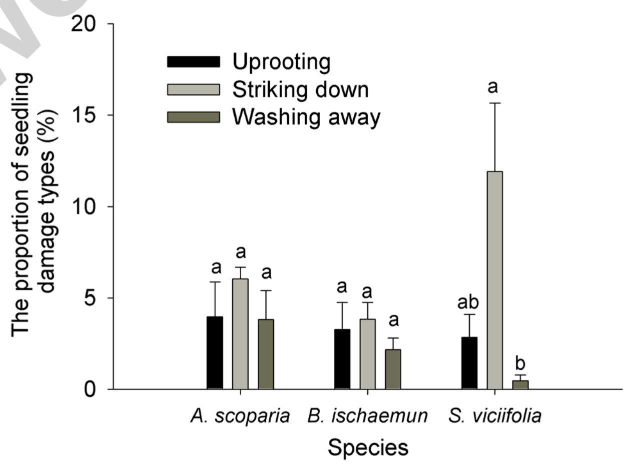

Figure 1. The proportion of seedling damage types suffered by the three studied species (the letter above each error bar indicates the level of difference across different damage types of the same species at the 0·01 confidence level).

Table II. The seedling damage rate under different rainfall events (the uppercase letters *A* and *B* indicate the level of difference across different rainfall types at the 0·01 level)

Rainfall intensity (mm/h)	Kinetic energy of raindrops (J $m^{-2}mm^{-1}$)	Rainfall duration (min)	Runoff volume (10^{-3} m³)	Erosion amount (g m^{-2})	Seedling damage rate %		
					A. scoparia	*B. ischaemun*	*S. viciifolia*
25	18·54	120	36·72	864·7	$29{\cdot}5 \pm 6{\cdot}6^{A}$	$16{\cdot}7 \pm 2{\cdot}1^{A}$	$5{\cdot}6 \pm 5{\cdot}6^{B}$
50	22·36	60	27·95	279·4	$10{\cdot}0 \pm 2{\cdot}1^{B}$	$4{\cdot}8 \pm 1{\cdot}4^{B}$	$13{\cdot}3 \pm 4{\cdot}9^{AB}$
75	24·95	40	21·72	519·8	$9{\cdot}0 \pm 2{\cdot}5^{B}$	$4{\cdot}1 \pm 1{\cdot}5^{B}$	$29{\cdot}2 \pm 7{\cdot}0^{A}$
100	26·96	30	23·71	822·1	$8{\cdot}5 \pm 1{\cdot}4^{B}$	$6{\cdot}5 \pm 2{\cdot}0^{B}$	$17{\cdot}2 \pm 5{\cdot}6^{AB}$
125	28·64	24	31·69	546·8	$12{\cdot}1 \pm 2{\cdot}2^{B}$	$9{\cdot}0 \pm 2{\cdot}1^{AB}$	$7{\cdot}7 \pm 3{\cdot}5^{B}$
150	30·08	20	25·29	2255·4	$15{\cdot}8 \pm 6{\cdot}0^{AB}$	$11{\cdot}9 \pm 3{\cdot}8^{AB}$	$12{\cdot}5 \pm 9{\cdot}0^{B}$

treatment alone ($F = 1{\cdot}731$, $p = 0{\cdot}127$). The damage rate of washing away was also significantly affected by species ($F = 7{\cdot}712$, $p = 0{\cdot}001$) and the interaction of species and rainfall treatment ($F = 3{\cdot}158$, $p = 0{\cdot}001$) but not by the rainfall treatment alone ($F = 1{\cdot}60$, $p = 0{\cdot}16$).

Seedling Survival Rate

During seedling growth under the six rainfall events, the seedling survival rate was significantly different among the three species (log-rank test; $p < 0{\cdot}001$) (Figure 2). The seedling density of *S. viciifolia* was relatively stable during the whole growth process, and the survival rate was higher once the seedlings had emerged. The seedling density of *B. ischaemun* decreased after 40 days but remained stable after 100 days because of successful seedling establishment. The seedling density of *A. scoparia* decreased markedly, especially in the 20 to 40-day time period. The rates of seedling establishment of *S. viciifolia*, *B. ischaemun* and *A. scoparia* were $80{\cdot}1 \pm 2{\cdot}5$, $67{\cdot}2 \pm 2{\cdot}2$ and $28{\cdot}1 \pm 2{\cdot}5$ per cent, respectively.

Seedling Growth Rate

The seedling growth rates of all three study species also changed significantly with time (two-way ANOVA; $F = 144{\cdot}487$, $p < 0{\cdot}001$) and were significantly different among the three species (two-way ANOVA; $F = 43{\cdot}079$, $p < 0{\cdot}001$) (Figure 3). The seedlings of *A. scoparia* and *B. ischaemun* were small during the initial stage after germination because of their small seed size. However, these seedlings had rapid growth rates and exhibited size increases in excess of 500 per cent during the 20 to 40-day time period of the experiment. After this high-speed growth period, the seedling growth rates of these two species declined quickly to a low value. The growth rate of *S. viciifolia* was stable during the experimental process.

The dynamic change of seedling cover during the seedling establishment process is shown in Figure 4. For the first 40 days, the seedlings grow slowly; the seedling cover was consequently low and increased slowly. From 40 to 60 days, the seedlings established successfully and grew quickly, and the cover increased rapidly. From 60 to 100 days, the cover increased slowly. After 100 days, seedlings growth and cover were stable.

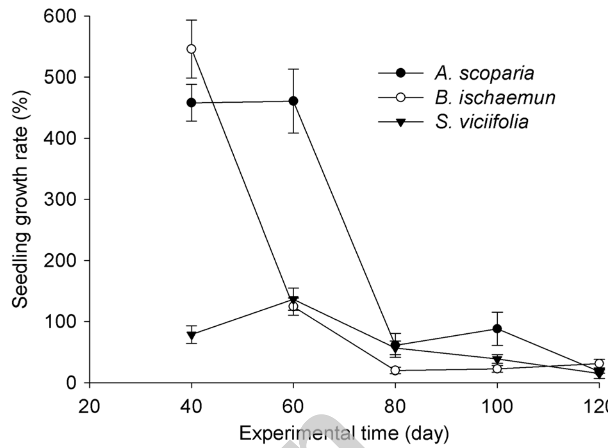

Figure 3. The seedling growth rate changes with experiment duration.

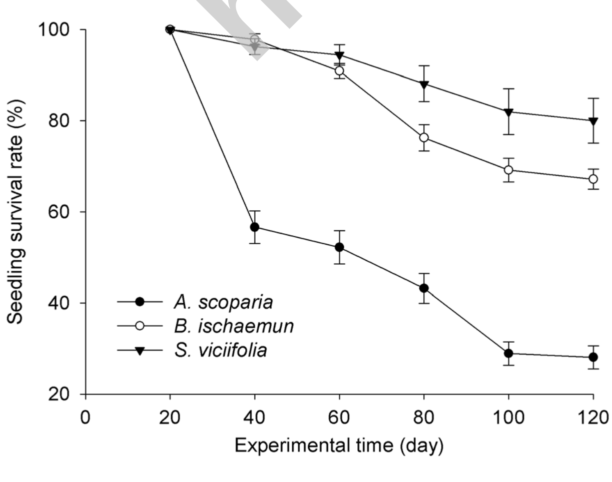

Figure 2. The seedling survival rate declines with experiment duration.

DISCUSSION

Seedling Damage versus Rainfall Patterns

The emergence and survival of seedlings, both of which are key processes for the maintenance of plant density (Lauenroth *et al.*, 1994), are mainly controlled by water availability in the surface soil layer and the micro-environment close to the soil surface (Lauenroth *et al.*, 1994; Novoplansky and Goldberg, 2001). However, in the study region, water availability is highly pulsed and dependent on precipitation, and rainfall is often characterised by high intensity, which can cause serious soil erosion (Shi and Shao, 2000). Rainfall patterns were

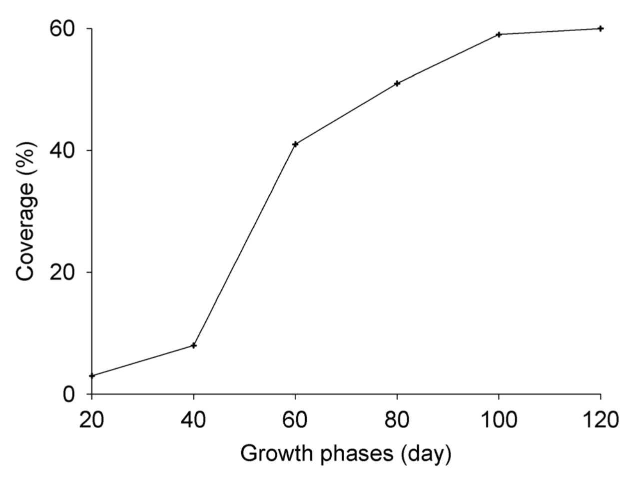

Figure 4. The degree of seedling coverage during different growth phases.

considered to be determinants of seedling damage on Mount St. Helens (Chapin and Bliss, 1989), and they affected seedling mortality through surface material movement on the slope (Yoshida and Ohsawa, 1999; Nagamatsu *et al*., 2002; Tsuyuzaki and Haruki, 2008). Seedlings die because of burial by sediment or because of being totally or partially unearthed (de Luís *et al*., 2005; Guerrero-Campo *et al*., 2008). In the eroded region, local storm patterns are important in determining the shape of the runoff hydrograph (de Lima and Singh, 2002). It was indicated that surface material movement, such as high-speed flow with sediment, was one of the major determinants of seedling mortality (de Luís *et al*., 2005; Guerrero-Campo *et al*., 2008). Thus, rainfall patterns determine the destructive force that rainfall erosion exerts on seedling damage.

The present study indicated that, in some cases, seedling damage rate increased as rainfall intensity increased, or as rainfall duration increased, particularly for *A. scoparia* and *B. ischaemun* (partial correlation, $p < 0{\cdot}05$). Both short duration high intensity rainfall and long duration low intensity rainfall can result in higher seedling damage. Rain duration and intensity could both have important effects on hydrological processes and soil erosion (Cerdà and García-Fayos, 1997). The seedling damage rate closely corresponded with runoff and erosion amount (Pearson correlation, $p < 0{\cdot}01$) in the cases of *A. scoparia* and *B. ischaemun*. However, the damage rate of *S. viciifolia* seedlings responded to rainfall patterns differently than those of *A. scoparia* and *B. ischaemun*. *S. viciifolia* seedlings were damaged by rainfall with higher intensity and sufficiently long duration. The highest damage rate occurred under moderate-intensity rainfall conditions (75 mm h^{-1} and 40 min, 100 mm h^{-1} and 30 min). The damage type of *S. viciifolia* seedlings was mainly striking down (11·9 per cent), and few of seedlings were washed away (0·5 per cent); for *A. scoparia*, the rate of seedling damaged by washing away was highest among the three study species. The maximum seedling damage rate reached 30·6 per cent for *A. scoparia*, 28·5 per cent for *S. viciifolia*, and 16·8 per cent for *B. ischaemun*, with averages of 13·8 per cent, 14·9 per cent and 9·3 per cent, respectively. The seedlings belonging to different species exhibited different damage rates and damage types over different rainfall treatments, which may have been caused by differences of traits for each species.

It should be mentioned that the rainfall intensity used in our experiment was higher than that experienced in nature. However, the nozzles of rainfall simulators produce raindrops with low kinetic energies relative to those within natural rainfall (Madden *et al*., 1998). Thus, the intensity of simulated rainfall experiments on the loess slopes was usually within the range of 30–200 mm h^{-1} (Pan and Shangguan, 2006). In our study, the soil loss amount under the six rainfall patterns was 0·28–2·26 kg m^{-2}. These results did not reflect the seedling damage when rill or gully erosion occurs, and in this case, the seedling damage would be critical. Additionally, vegetation cover has the ability to intercept raindrops and to reduce runoff and soil erosion (Cerdà, 1998, 1999); consequently, pre-existingvegetation may reduce seedling damage during the rainfall erosion process. The present study only examined rainfall erosion on the seedlings on a bare slope, so seedling damage rates may be less on natural vegetated slopes.

Seedling Damage and Establishment versus Species Traits

Generally, seedling size and seedling survival rate are both positively correlated to seed size (Jakobsson and Eriksson, 2000; Moles and Westoby, 2004a). In this study, the seedling sizes and morphological characteristics of the three species were different and affected the seedling damage rate and damage type. *A. scoparia*, with the smallest seed size, had the highest seedling damage rate and the largest number of seedlings washed away. *S. viciifolia*, with the largest seed and large cotyledon, had the lowest mean seedling damage rate, but it had the largest proportion of seedlings struck down and few seedlings washed away. To be struck down was the main damage type suffered by *S. viciifolia* because of its large cotyledon exposed to rain drops, but it had lowest proportion of washing away because of its seedlings deep strong root. Seedling damage events always happened when there was higher intensity rainfall over enough length of time. *B. ischaemun* is a gramineae species with larger seeds and slender leaves, and it suffered a relatively low seedling damage rate.

The seedling establishment experiment yielded results similar to those of previous studies. The seedling survival rate was positively correlated to seed size (Moles and Westoby, 2004a). In the present study, seedling death because of rainfall erosion damage was more prominent in species with small seeds. In the first 40 days, the seedling coverage was low, and all of the seedlings were exposed to rainfall erosion. Additionally, previous studies indicated that, in the initial stage of growth, seedling–seedling competition is plausible only when the seedling density is very high (e.g. more than 2000 seedling s m^{-2}) (Moles and Westoby, 2004b). In this study, the seedling density was less than 1000 seedling s m^{-2}; thus, there should be no seedling–seedling competition in this period. In the first 40 days, the mortality rates of *A. scoparia* and *B. ischaemun* were obviously higher than the rates in the soil seed bank germination experiment without rainfall erosion, especially in the case of *A. scoparia*. In this period, the main factor causing seedling death was rainfall erosion. During the period from 40 to 60 days, the seedling coverage increased to more than 40 per cent, and soil erosion was reduced by vegetation coverage (Cerdà, 1998, 1999). In this period, the increase in the seedling mortality rates of *S. viciifolia* and *B. ischaemun* might be due to seedling–seedling competition. Finally, *S. viciifolia* had the highest seedling establishment rate (81·9 per cent), followed by that of *B. ischaemun* (65·3 per cent), and *A. scoparia* had the lowest seedling establishment rate (25·6 per cent). The seedling establishment rate was closely correlated with the seed sizes of the three studied species. Our results are in accordance with those of previous studies, which have also shown that seedlings grown from large seeds have higher rates of establishment than those grown from small seeds (Moles and Westoby 2004a; Benard and Toft, 2008; Metz *et al*., 2010).

CONCLUSIONS

This paper demonstrates that both rainfall intensity and rainfall duration affect seedling damage during rainfall simulation experiments. The seedling damage rate was determined by the intensity and runoff volume of the simulated rainfall. On bare slopes, the mean damage rates of all three study species did not exceed 15 per cent, and the highest damage rate of an individual species under extremely high rainfall intensities was 30 per cent. The seedling survival and growth rates exhibited differences among species with different seed sizes and morphologies. Physical damage caused by rainfall erosion play a role in the vegetation–erosion competition especially in the case of species with small seeds and under low vegetation cover and high runoff discharges. Further research should be performed to clarify the following questions: is physical damage a key factor limiting vegetation restoration and ecosystem recovery on degraded land suffering serious erosion, and can the seedling traits of different species lead to resistance against rainfall erosion?

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