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The influence of seed size and shape on their removal by water erosion

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Abstract

Under semiarid environments where surface runoff takes place, the role of water erosion in the removal of seeds and then in the plant establishment and distribution is unknown. Within the scientific literature, data about the size and shape of seeds exist, but little information can be found about the susceptibility of seeds to be removed by water erosion processes. These data are important not only from an eco-geomorphological point of view, but also for afforestation strategies in order to improve the selection of species to develop the recovery of vegetation on degraded environments. Eighty-three seed species were selected from Southeastern Spain. Variables related to size, such as weight (M), length (L), width (W) and height (H) of these seeds, were measured. From this information, other variables such as the surface (S), volume (V), density (D) and the ratio S/M were calculated. Seed shape was characterised by the Flatness Index (F.I. $= L + W/2H$) and the Eccentricity Index (E.I. $= L/W$). Laboratory rainfall simulation experiments at 55 mm h^{-1} during 25 min on 26×26 cm plots with slope angle equal to 11° were performed with five lots of 50 seeds of each species. Results demonstrated that size is the main factor explaining seed removal, whereas the shape becomes important only when the seeds are larger than 50 mg. Seeds for vegetation recovery planning should have a mass between 10 and 50 mg to avoid removal by water erosion. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Erosion; Seed losses; Seed size; Seed shape; Laboratory

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1. Introduction

Soil is a mixture of air, water, mineral matter and organic matter. During the last decades, a growing interest in the biotic part of the soil has been widely recognised due to its importance in the functioning of the soil ecosystem. Nevertheless, soil erosion studies have focussed mainly on the removal of the mineral particles, and very few researches took into account the behaviour of nutrients and organic matter losses. Seeds were ignored, although they are the base of the vegetation processes of colonisation and recovery after disturbance (Harper, 1977), and thus indirectly control soil erosion rates (Thornes, 1985).

After dispersal, seeds form soil seed banks in the upper part of the soil profile, and they remain on soil until they germinate (Chambers and MacMahom, 1994). Splash and overland flow can carry away the seeds that arrive at the surface of the soil and those that remain in the seed bank. This mechanism could explain the low vegetation cover in areas affected by severe erosion processes, but it remains untested, although some researches have been carried out during the 1990s (García-Fayos et al., 1995, 2000). In the present paper, we study under laboratory condition the seed susceptibility to surface wash removal. Our objective was to model the relation between seed variables of size and shape with seed removal.

Quick overland flow usually occurs under semiarid conditions where soils are crusted, vegetation is sparse and rainfall intensities are very high. Soils developed on road embankments (Estalrich et al., 1997), badlands (Cerdà, 1999), mine spoils (Porta et al., 1999), ploughed soils (de Alba, 1998), immediately after a forest fire (Cerdà, 1998), or after land abandonment (García Ruiz et al., 1996) are prone to generate surface runoff, and thus, seeds are threatened by water erosion.

Previous researches on seed removal by water erosion were performed with a limited number of seeds because of the difficulties of working in the field (García-Fayos et al., 1995; Cerdà and García-Fayos, 1997; García-Fayos and Cerdà, 1997). These works suggested a possible influence of the form and size of seeds on their removal. Moreover, many factors can influence the seed removal under field conditions. Laboratory rainfall simulation experiments were conducted in order to determine the influence of size and shape of seeds on their removal. Under laboratory conditions, measurements are more accurate and a greater number of experiments can be done. This is due to the small size of the seeds and to undetected previous presence of seeds in the soil, which would make it difficult to calculate seed removal balance within the field experimental plots.

Although there is a lot of information about the seed size and shape in relation to seed ecology (see Fenner and Kitajima, 1999; Harper et al., 1979; Westoby et al., 1996), there is a lack of information about these seed variables and the seed susceptibility to water erosion processes. This is why we conducted experiments in order to determine the influence of size and shape of seeds on their removal. We did not distinguish between the splash removal rate and the surface wash rate, although the research done on mineral particles shows the importance of splash (Poesen and Savat, 1980, 1981). This is a scientific challenge for future research.

2. Materials and methods

Eighty-three plant species were selected from wild and cultivated plants living in SE Spain. For each species, we collected seeds from different individuals within a population that bore mature seeds at the time of collection. We avoided seeds with appendixes and with mucilage. For seeds heavier than 2 mg, 20 seeds were weighed individually in a laboratory balance. Due to the balance accuracy, for the smallest seeds (0.2–2 mg), 10 groups of 3, 5, or 10 seeds were weighed, but when seeds were extremely small (< 0.2 mg), 10 groups of 100 seeds were weighed in order to know the mean seed mass (M).

To determine the length (L, longest axis), width (W, intermediate axis) and height (H, shortest axis) of each seed species, we calculated the average for 20 representative seeds. From this data, parameters related to size, such as surface ($S = L \times W$), volume ($V = L \times W \times H$), density ($D = M/V$) and ratio S/M (Surface/Mass), were calculated. From now on, we will quantify surface, density and volume of the seeds with these approximations.

To characterise the seed shape, two indexes were used. The Flatness Index, F.I.=$(L+W)/2H$, was used by Poesen (1987) for rock fragments. It ranged from a value of 1 for spherical seeds, to greater values for plane or spindle seed shapes. The Eccentricity Index (E.I. $= L/W$) ranges from 1 for spheres, circles and ellipsoids to values greater than 2 for spindle seed shapes.

Five rainfall simulation experiments were performed for each species. At each experiment, 50 seeds were located at the top of the 26 × 26 cm plot (11°) and simulated rainfall lasted 25 min. At the end of the experiment, the total number of seeds coming out of the plot were counted and the seed removal index of each species calculated as an average of the seed losses of five experiments. The rainfall and runoff were replicated with the rainfall simulator designed by Kamphorst (1987). This apparatus consists in a sprinkler with a built-in pressure regulator based on the Mariotte bottle principle and a support frame for the sprinkler, which is also a wind protector. The original stainless steel frame was substituted by a square (26 × 26 cm) plate covered by sandpaper with a roughness of 320 μm in order to simulate a minimum surface roughness and to avoid rolling of the spherical seeds. The sprinkler consisted of a calibrated cylindrical water reservoir (1200 ml), which is in open connection with a sprinkling head (625 cm^2). Water is discharged from the sprinkling head through 49 capillaries. The aeration tube controls the pressure head on the capillaries and the rainfall intensity. A total of 49-drop formers perform rainfall with distilled water from a 40-cm height. Mean drop size (D_{50}) reached 5.9 mm and the terminal velocity was 2.8 $\mathrm{m\ s^{-1}}$, with mean rainfall intensities of 54.73 $\mathrm{mm\ h^{-1}}$ (Var. 5.13) in this study.

Correlation analysis among variables was performed prior to this to explore their relationships with the seed loss index in order to simplify the variable matrix. Only the variable with the lower measurement error of a set of highly correlated variables was selected (Pearson correlation index ≥ 0.5). The relations between the selected variables and the seed loss index were explored with regression analysis. Comparison of variables between groups of species was performed with a nonparametric test because they did not fit with the assumption of the parametric test even after transformation. All the statistical analyses were performed with the SPSS v. 9.0 statistical package.

3. Seed size and shape

Values of seed size and shape were very variable. The mean seed mass of the species was 35.28 mg, ranging from *Sedum sediforme* (0.04 mg) and *Erica multiflora* (0.07 mg) to *Pinus pinea* (443 mg). The length of seeds (4.26 mm in average) was even more variable than the mass. The longest seed was *P. pinea*, with 15.3 mm, while *Cistus ladanifer* and *Papaver pinnatifidum* were the shortest (0.8 mm). The width ranged from 0.4 mm (*S. sediforme*) to 9.35 mm (*P. pinea)* with an average value of 2.82 mm. The height of the seed varied from 0.27 mm (*E. multiflora*) to 7.46 mm (*Chamaerops humilis*) with an average of 2.77 mm.

The average surface of the seeds was 17.31 mm^2 and ranged from 0.4 mm^2 of *C. ladanifer* to 143 mm^2 of *P. pinea*. The seed volume ranged from 0.16 mm^3 of *E. multiflora* to 1067 mm^3 of *P. pinea*, with an average value for the 83 measured seeds of 67.91 mm^3. *Hedysarum confertum* has a seed density of 0.15 mg mm^{-3}, and *Brachypodium retusum* is the densest seed with 2.92 mg mm^{-3}. The average value of the seed density was 0.55 mg mm^{-3}. The ratio *S*/*M* showed very variable values. The greater value was 12 (*S. sediforme*) and the lower value was 0.24 of *Avena sativa*. The average value was 2.08.

As regards the shape of the seeds, *Osyris quadripartita* had a Flatness Index of 1, which was the minimum value and indicated that the seed is completely spherical. *Dipcadi serotinum*, with a Flatness Index of 14.8, is a very planar seed such as a lentil. The whole seed set had an F.I. of 2.10 on average. The Eccentricity Index ranged from 1 in *O. quadripartita*, which is a sphere, 1.01 in *Lavatera arborea* and 1.02 in *D. serotinum*, which are very close to a circle, to 4.82 for *A. sativa* with a spindle form. The average value of the Eccentricity Index for the whole set of measurements was 1.68.

4. Seed removal

For the 415 experiments performed (83 species by 5 experiments), the mean seed loss percentage was 11%, but seed losses varied highly among species. The greater erosion rates were found for *E. multiflora* (93%), *S. sediforme* (68%) and *P. pinnatifidum* (56%), which have the smallest seeds. The lower seed losses were found for 10 species that had no losses. The distribution of frequencies of the seed losses showed that close to 50% of

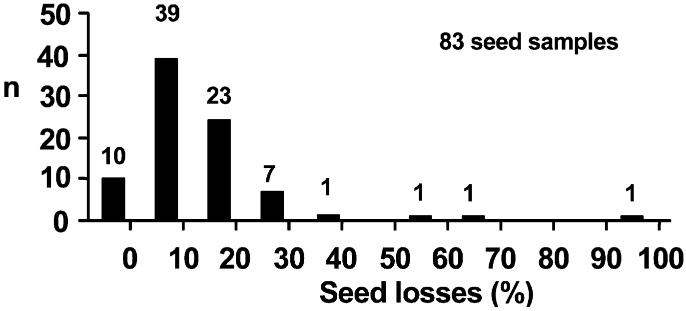

Fig. 1. Frequency distribution of the seed losses (*n* = number of seed losses).

Table 1
Correlation (Pearson) between the different seed variables

	Mass	Length	Width	Height	Surface	Volume	Density	Ratio *S*/*M*	Flatness
Length	0.782**								
Width	0.805**	0.858**							
Height	0.727**	0.730**	0.849**						
Surface	0.923**	0.901**	0.928**	0.771**					
Volume	0.886**	0.749**	0.801**	0.825**	0.906**				
Density	0.177	− 0.014	− 0.029	− 0.101	0.028	− 0.032			
Ratio *S*/*M*	− 0.325**	− 0.349**	− 0.329**	− 0.509**	− 0.264**	− 0.294**	− 0.313**		
F.I.	− 0.031	0.167	0.147	− 0.287**	0.143	− 0.100	0.011	0.554**	
E.I.	− 0.115	0.178	− 0.269*	− 0.210	− 0.110	− 0.131	− 0.080	0.230	0.155

Significance level notations are *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

the seeds had a seed loss rate between 0% and 10%. A total of 23 seed samples had losses between 10% and 20%, while losses greater than 20% were only found for 11 cases, 7 of them between 20% and 30% of seed losses (Fig. 1).

5. Correlation between seed variables

High correlation values between seed variables were found among weight, length, width, height, surface and volume (Table 1). As seed mass was the variable with lesser measurement error and was also easy to measure for future works, we selected it. Ratio *S*/*M* and Flatness Index were also highly correlated (0.554), and therefore, the latter was the selected variable as indicator of the seed shape because of the same reasons. Nevertheless, the Eccentricity Index (E.I.) and the seed density are not correlated to any other seed attribute, and the E.I. was also selected for comparison with seed losses.

6. Relationship between the seed removal and the selected seed variables

We used linear, inverse and logarithmic models to explore the relation between the selected variables and seed removal. In all the cases, the inverse model ($y = a + b/x$) fitted better with the data than the other ones (Table 2). Only the weight of seed had a considerable prediction value on seed removal, with more than 68% of the variance explained.

Table 2
Coefficients of determination (R^2) and significance levels between seed losses and the three selected variables of seed size and shape in the linear, inverse and logarithmic models

	Linear	Logarithmic	Inverse
Weight (mg)	0.006	0.250***	0.682***
Density (mg mm^3)	0.004	0.003	0.001
Flatness index	0.008	0.007	0.007
Eccentricity index	0.001	0.001	0.001

Significance level notations are *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

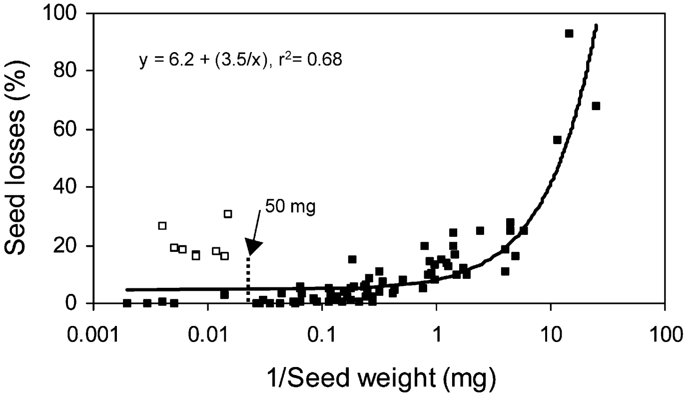

Fig. 2. Relationship between the seed mass and the seed losses for the 75 selected species. Note that the x-axis is logarithmic for better visualisation of the data. The blank dots indicate seeds greater than 50 mg and spherical shape, $p<0.0001$. If these data (blank dots) are not taken into account, the fitted equation is $y=4.5+(3.66/x)$, $r^2=0.78$, $p<0.0001$.

In Fig. 2, we present graphically the inverse model for the relation between seed weight as an index of the seed size and seed removal. For a better visualisation of the data and the relationship between seed mass and seed losses, the x-axis has been logarithmical. The model shows that the lesser the size of the seeds, the higher the seed losses are. However, it also shows an important deviation of the measured seed losses from predicted by the model in the range of seeds greater than 50 mg (more than 0.05 in the x-axis) (see Fig. 2). On the left-hand side of the graph, with seeds greater than 50 mg, we can discriminate two groups of seeds: one group with higher losses than predicted by the model (above the regression line, Group 1, blank dots) and the other group with seed loss rates near but lower than the predicted ones (below the regression line, Group 2). When the regression is carried out again without the species of Group 1, the coefficient of determination of the model increases from 68% to 78% (Fig. 2).

To explore this anomalous behaviour, we compared the value of the seed size and seed shape variables of both groups of seeds and their removal rates (Table 3). The Mann–

Table 3

Values (mean ± standard error) of the variables of seeds of Group 1 (seeds with lower losses than predicted by the model) and of Group 2 (seeds with higher losses than predicted by the model)

	Group 1	Group 2	Significance
Seed losses (%)	0.48 ± 0.29	20.27 ± 1.93	**
Flatness index	2.137 ± 0.369	1.240 ± 0.115	**
Eccentricity index	1.886 ± 0.348	1.113 ± 0.043	***
Weight (mg)	148.3 ± 48.3	136.5 ± 22.7	ns
Density (mg mm^3)	0.578 ± 0.135	0.655 ± 0.078	ns

It also shows the significance level of the U of Mann–Whitney tests for the equality of means. Significance level notations are *: $p<0.05$; **: $p<0.01$; ***: $p<0.001$.

Table 4
Coefficients of determination (R^2) and significance levels between seed losses and the three selected variables of seed size and shape in the linear, inverse and logarithmic models for seeds smaller than 50 mg

	Linear	Logarithmic	Inverse
Weight (mg)	0.165***	0.586***	0.779***
Density (mg m^3)	0.001	0.001	0.000
Flatness index	0.002	0.000	0.000
Eccentricity index	0.005	0.009	0.012

Significance level notations are *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

Whitney *U*-test showed that seed removal rates were significantly higher in Group 1 than in Group 2. Only variables related to shape (Flatness and Eccentricity Indexes) differed significantly between both groups, whereas the variables related to size did not (Table 3). The Flatness and Eccentricity Index values of the seeds of these groups indicate that round or near round shapes (values close to 1 for F.I. or E.I.) increase the seed removal rates of Group 1 in relation to Group 2, which have much flatter seeds.

These results pointed out that seed removal rates are determined mainly by the seed size when they are lighter than 50 mg. Seed shape influences the seed loss rates when the mass surpasses 50 mg, but had no influence on the seed losses with smaller seeds (Table 4).

7. Discussion

The seed removal by the surface wash is determined by many factors. Slope angle, rainfall intensity, surface roughness and vegetation cover are some of them. However, the seed characteristics also influence the losses due to the shape and size of the seeds. The study carried out here under controlled laboratory conditions demonstrated that the influence of shape and size of seeds is rather complex. Under laboratory conditions, we found a threshold of around 50 mg of weight. Up to this threshold, the shape of the seed is the main factor determining the removal rates, while below this threshold, the size is the key factor of the seed losses. Obviously, the results presented here and the threshold found is determined by the rainfall intensity, slope angle, kinetic energy of rainfall, runoff depth, etc. Nevertheless, the laboratory experiments shed light on the complex relationship of the seed form and size with the erosion process.

In comparison to the removal of mineral soil particle (Hjulström, 1935), the behaviour of seeds is similar when weight is smaller than 50 mg. More likely, floating can be the explaining process as John Thornes (personal communication) found for organic matter with similar experiments. However, it should be highlighted that seeds greater than 50 mg have a different behaviour, and the form of the seed determines the removal rates.

The average seed losses are 11%, which is very low after showers of 5-year return periods such as the one simulated here. The soil seed bank recovery is restored yearly. With the exception of *S. sediforme* (68%), *E. multiflora* (92.8%) and *P. pinnatifidum* (56.4%), the other seed loss rates should be a tolerable loss for the soil seed bank.

Under degraded environments such as road embankments, mine spoils, burnt areas, etc., where soil seed bank is poor and damaged, sowing should take place after disturbance to restore the seed bank artificially. There, the selection of the species with the lower seed loss rates is a key for the recovery of vegetation. Seeds for vegetation recovery planning should have a mass between 10 and 50 mg to avoid removal by water erosion. Smaller seeds flow easily, and greater seeds tend to be spherical in form, which favours rolling down the slope.

The results obtained have many implications for understanding plant recovery. Although the smallest seeds should be removed easily, they are also prone to be stored in the cracks and in the hollows (Thompson et al., 1993). The seed transport and sedimentation processes should be researched under field conditions. García-Fayos et al. (1995) attempted to study the removal of seed by water erosion on badland surfaces, where seed losses decreased as the plot length increased. This means that redistribution of seeds during rainfall within the slope takes place.

What is clear from this research is that as seed size increases, the removal rate decreases. However, seeds greater than 50 mg with spherical shapes were easily removed than the plate shapes due to the influence of the shape on seed losses. The threshold is related to the laboratory conditions. Changes in rainfall intensity, slope angle, surface roughness, etc. will change the value of the threshold, or the threshold will even disappear. Then, research on the effect of such factors on the seed removal rate and the behaviour of seeds on degraded environments such as road embankments, badlands, mine spoils, fire-affected land, etc. are some of the challenges for future research.

Our results give information to plan sow works on areas degraded such as road embankments, gullies, burnt areas, mine spoils, etc. Seeds greater than 10 mg and smaller than 50 mg have the lowest removal rates. Also, greater seeds with no spherical shape have negligible losses. The predictive model on seed losses developed in the present work can aid in the selection of species to design recovery vegetation plans to be used in areas threatened by surface wash. In addition, this model permits us to understand that erosion acts on vegetation dynamics not only through the removal of sediments and litter that influences plant growth and survival (Thornes, 1985), but also through influencing plant establishment from seeds.

Poesen (1987) found similar results with rock fragments transported by rill flow. Although the experimental conditions and the subject studied were very different, the experience with the transport of rock fragments by rill flow of Poesen (1987) indicated that size plays a more important role with respect to the displacement of rock fragments than rock fragment shape.

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