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Aggregate enrichment ratios for splash and wash transported sediment from an Oxisol

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Abstract

Interrill wash and splash enrichment ratios (ER) and their temporal variation are poorly documented in the literature. Laboratory rainfall simulation experiments were conducted on a clay-rich kaolinitic Oxisol from Hawai'i. Three-hour storm events were replicated on slopes of 5, 10, and 20° at a constant rainfall intensity, and interrill erosion was partitioned into wash and splash components. Results indicate that both processes preferentially transport aggregates < 63 μm in diameter since ER-values were significantly greater than 1.0. In addition, splash preferentially transported 500–1000 μm aggregates. Average time-integrated wash ER-values were < 1.0 for all aggregates > 63 μm for all slopes, and these values were significantly lower than those for splash. Wash on slopes $\leq 10°$ was not energetic enough to entrain or transport splash detached granule-size aggregates, i.e., 2000–4000 μm. With a slope increase to 20° flow became competent enough to transport granule-sized aggregates but ER-values were significantly less than 1.0, and lower than those associated with splash. Splash detached all aggregate sizes, but the most easily transported fraction was < 63 μm followed by 500–1000 μm. Time-trend ER plots indicated significant temporal differences between splash and wash for the same aggregate size fractions. Nonparametric correlation and scatterplots, for selected aggregate size fractions, indicated a variety of linear and non-linear monotonic relationships with interrill sediment flux. Implications of this study are that with time preferential removal of fine material will likely produce a coarser, nutrient-depleted interrill soil matrix. These chemical and physical changes have the potential of limiting soil productivity and reducing the resilience of the soil.

1. Introduction

Over the last decade there has been a significant increase in research on the relationship between water erosion processes and particle size selectivity. This research

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has been driven by a need to better understand and predict sediment and chemical transport. To date, most research has focused on agricultural soils in an attempt to determine the degree of selectivity of interrill (unconcentrated overland flow or wash) and rill (concentrated overland flow) erosion processes. This research has generally shown that sediment transported by interrill flow is finer than the original soil matrix, as a result of selective removal of silt and clay-sized particles and aggregates or preferential deposition of coarse particles (Young, 1980; Alberts et al., 1983). Rill erosion is considered to be aselective, or at least less selective than interrill erosion (Govers, 1985; Meyer et al., 1986). The reasons given to explain selectivity of interrill erosion and aselectivity of rill erosion commonly relate to energy availability. Interrill selectivity generally results from limited stream power, due to thin flow depths, high frictional resistance and low flow velocities. Thus, interrill flow is not able to entrain, re-entrain, or to transport coarse material detached by raindrop activity. Rill aselectivity generally results from significant stream power increases as flow becomes concentrated into more hydraulically efficient channels, with higher velocities and greater flow depths. Therefore, rill erosion has the ability to transport a wider range of material, that is sediment conveyed to the rill system by interrill flow, splash input, and direct entrainment or re-entrainment of rill bed and bank material.

The relative importance of rill and interrill processes to total sediment output from fields or drainage basins has significant practical implications. If interrill flow dominates sediment transport from a given area there will be selective transport of fines (silt and clay-sized primary particles and aggregates) which are commonly the major transport pathway for plant-associated nutrients, and toxic contaminants, such as radionuclides, trace metals, pesticides, and polychlorinated biphenyls (Hart, 1982; Watters et al., 1983; Allan, 1986). Thus, given two systems with similar erosion rates, but one dominated by rill and the other by interrill processes, the latter with time will likely exhibit greater on-site nutrient depletion and a concomitant decrease in productivity. Off-site or downstream water quality will be degraded due to nutrient-rich interrill runoff, and potential for eutrophication would increase. Therefore, process research on particle and aggregate size selectivity is critical for successful on- and off-site land management.

Information on interrill selectivity is generally from a lumped-process perspective, i.e., Alberts et al. (1983) and Meyer et al. (1992). Temporal patterns and slope influences are rarely considered. However, this information is critical to our understanding of the dynamic process mechanics operating in the interrill system. Only limited data are available on the selectivity of the two dominant interrill components, splash and wash. Data in Ellison (1944) were some of the first to be published which allowed for the determination of splash and wash aggregate size selectivity. Splash and wash enrichment ratios were calculated for individual wet-sieved aggregate size fractions, with the enrichment ratio defined as:

$$\mathrm{ER} = \frac{\text{wet} - \text{sieved aggregate fraction (\%) in transported sediment}}{\text{wet} - \text{sieved aggregate fraction (\%) in original soil matrix}} \qquad (1)$$

Enrichment ratios less than one indicate aggregate size fractions in transported sediment are depleted relative to the original soil matrix, while ER > 1.0 indicate preferential or selective removal of a particular size relative to the original soil matrix. Data from the

Table 1
Splash and wash enrichment ratios for wet-sieved aggregates from an eroded Muskingum silt loam soil (data from Ellison, 1944)

Aggregate size fraction (μm)	Splash $ER_{3.5}$ [a]	Wash $ER_{3.5}$	Splash $ER_{5.1}$ [b]	Wash $ER_{5.1}$
> 2000	0.055	0.035	0.18	0.030
1000–2000	0.45	0.18	0.61	0.27
500–1000	0.78	0.30	0.76	0.36
250–500	0.83	0.27	0.65	0.36
105–250	0.90	0.50	0.94	0.44
< 105	1.38	1.65	1.34	1.63

[a] Enrichment ratios resulting from rainfall simulation using a 3.5-mm raindrop diameter.
[b] Enrichment ratios resulting from rainfall simulation using a 5.1-mm raindrop diameter.

Muskingum silt loam (Table 1) indicates ER-values < 1.0 for all aggregate fractions coarser than 105 μm (very fine sand-sized aggregates and coarser) for both splash and wash. But it is important to note that ER-values for splash were greater than those for wash. Only the < 105 μm aggregate fraction was selectively removed since ER-values > 1.0, with $ER_{wash} > ER_{splash}$. The Ellison data also indicate that ER-values generally decreased for both splash and wash as aggregate size increased. However, it is unclear from the details provided by Ellison (1944) whether wash was adequately separated from splash, or whether the wash component was actually a combination of splash plus wash. Additionally, the influence of slope angle on the partitioning of splash and wash enrichment ratios was not assessed. These data may be important in the re-design of furrow side-slopes, since these areas can be significantly influenced by interrill erosion processes.

Savat (1982) suggested that minimal energy is required by runoff to erode primary particle sizes of 125 μm. Data from the literature indicate a large range in particle or aggregate sizes that are most easily transported by splash, wash, or a combination of splash and wash (Table 2). The range in size of the most easily transported interrill sediment is a function of several factors including soil texture, degree of aggregation, surface sealing and shielding, sediment availability, surface roughness, and energy conditions (slope angle, rainfall and runoff magnitude). Note from Table 2 that there is limited information available for wash in the absence of runoff. One exception to this is the data provided by Parsons et al. (1991) for a poorly aggregated soil from Walnut Gulch Experimental Watershed, Arizona. They found airsplash ER_{sand} was ≈ 1.1, ER_{silt} was ≈ 1.0, and ER_{clay} was 0.0. They suggested that the fineness of sediment in interrill flow (splash plus wash) relative to the matrix soil was not due to selective detachment of finer particles by raindrops, but to selective transport by interrill flow. Another notable investigation was by Moss (1991) who found wash was significantly finer than splash for primary particles transported from a poorly aggregated granitic soil. No selectivity data are available from clay-rich Oxisols for individual interrill erosion processes. These data are essential for the incorporation in physically-based soil erosion and chemical transport models. Thus, the objectives of this study were as follows:

Table 2
Literature summary of rainfall simulation studies documenting the most easily transported size of material by interrill flow components

Source [a]	Material used	Apparatus used and dimensions	Slopes (°)	RFI [b] (mm h^{-1})	METS-splash [c] (μm)	METS-wash (μm)	METS-wash plus splash (μm)
1	Sand-sized primary particles	Splash box, 7.62 cm (W) × 15.2 cm (L)	0–45	–	175–250	–	–
2	Loess, primary particles	Splash cup, 45.6 cm^2	0	20–120	105–210	–	–
3	Silty clay loam	Splash cup, 45.6 cm^2	0	20–120	1680–2360	–	–
4	Single grained granitic soil (23–36% G, 46–56% Sa, 12–15% Si) [d]	Soil tray, 46 cm (W) × 122 cm (L)	1.1–17.7	75–150	238–1041	–	440–1337
4	Clay soil (21% Sa, 28% Si)	Soil tray, 46 cm (W) × 122 cm (L)	1.1–17.7	75–150	122–880	–	153–1308
5+7	Sand-sized primary separates	Petri dishes, 5-cm diameter (7.7 m s^{-1} drop velocity)	0–45	6.2 mm drops	3400–4520	–	–
5+7	Sand-sized primary separates	Petri dishes, 5-cm diameter (8.7 m s^{-1} drop velocity)	0–45	6.2 mm drops	4600–5980	–	–
6	Silty clay loam (32% Cl)	Soil tray, 30 cm × 30 cm	12.5	63.5	365 (D_{50})	10 (D_{50})	–
7	Soil aggregates	Petri dishes, 5-cm diameter (7.7 m s^{-1} drop velocity)	15–45	6.2 mm drops	1900	–	–
8	Clay soil (29% Sa, 16% Si)	Flume, 100 cm (W) × 600 cm (L)	< 3.4	100	–	< 53	–
9	Granite derived soil, primary particles	Flume, 50 cm × 50 cm	0–8.5	40	200–600	< 30	–
10	Vertisol (16.3% Sa, 21.5% Si) and Andisol (46.6% Sa, 21.2% Si)	Splash cups, 8.4-cm diameter	0	56	20–2000	–	–

[a] 1 = Ekern (1950); 2 = Mazurak and Mosher (1968); 3 = Mazurak and Mosher (1970); 4 = Farmer (1973); 5 = Ghadiri and Payne (1980); 6 = Luk (1983); 7 = Ghadiri and Payne (1986); 8 = Ghadiri and Rose (1991b); 9 = Moss (1991); 10 = Proffitt et al. (1993).

[b] Represents rainfall intensity.

[c] Represents the most easily transported particle or aggregate size.

[d] G = granule; Sa = sand; Si = silt; Cl = clay.

1. To quantify wet-sieved aggregate ER-values for splash and wash transported sediment from a tropical Oxisol.
2. To assess temporal variations in aggregate ER-values for splash and wash under controlled rainfall conditions.
3. To determine the influence of slope angle on splash and wash ER-values.

2. Materials and methods

2.1. Soil selection, preparation and characteristics

The Wahiawa Oxisol, a Rhodic Eutrostox, was collected from central Oahu, Hawai'i. This soil was selected for detailed study for the following reasons: (i) preliminary research has been conducted on the splash and wash dynamics (Sutherland et al., 1996); (ii) it is an important agricultural soil in Hawai'i since it is widely used for pineapple production; and (iii) erosion of this soil has been linked to nonpoint source pollution.

The Wahiawa soil is generally considered to be well aggregated and well drained (El-Swaify, 1980). The soil used in this study was collected from the 0–10 cm depth increment, and has a pH of 5.9 and an organic carbon content of 18 g kg^{-1}. The primary particle size (after sonification) is typically 800 g kg^{-1} of clay (< 2 μm) and 160 g kg^{-1} of silt (2–63 μm). The clay fraction of this soil is dominated by kaolinite (51%) and illite (31%), and has a specific surface area of 84.2 m^2 g^{-1} (J. Jackman, pers. commun., 1994). Samples were air dried, and sieved through a 4-mm square-hole sieve.

2.2. Rainfall simulation

The laboratory drip-type simulator used by Sutherland et al. (1996) was also used in this study for detailed erosion process investigations. Raindrop fall height was 2.2 m, and uniform drops with a median diameter of 3.2 mm were produced. Domestic water supply with an average rainfall intensity for all events was 102 ± 9.0 mm h^{-1}, and this was controlled by an in-line pressure gauge. With this rainfall intensity the simulator produced an energy flux density of about 0.43 W m^{-2}, or about 72% of natural rainfall with a mean drop diameter of 2.00 mm. To approximate a random distribution of raindrops at the soil surface two opposing fans were used to generate the necessary turbulence.

The soil tray used in this study had a surface area of 0.18 m^2 [0.30 m (W) × 0.60 m (L)]. A 7-cm layer of sieved air-dry soil was gently packed to a mean bulk density of 1.02 ± 0.03 Mg m^{-3}, similar to those found in the field. Drainage from the tray was achieved without suction through a drainage outlet at the base of the tray.

2.3. Data collection

Two 3-h events were conducted on slopes of 5, 10 and 20°. Mean values are presented for each slope angle in this study. The soil tray was specially fit with two easily detachable lateral splash collectors, and one detachable front splash collector set

5-mm above the soil surface at the plot outlet. The soil surface was approximately 5-mm below the lip of the lateral splash collectors so that there was no possibility of washover. This experimental set-up does not provide for the lateral redistribution of splash from a surrounding area, which would be the case in a natural hillslope situation. Thus, this design can be viewed as a large depletion splash cup.

Wash conducted beneath the front splash collector was funneled to a beaker system. This allowed the sediment output from the erosion tray to be partitioned into that transported from the plot by airsplash and that transported from the plot by a combination of overland flow and rain-flow mechanisms (cf., Moss and Green, 1983), and this latter component will be referred to as wash in this study. Lateral side splash, front splash, and wash samples were collected at 10-min intervals throughout the run. Splash from the top end of the plot was collected at the end of each run from the surrounding 0.8 m^3 collector box that housed the soil tray, splash collectors and slope adjustment system. Runoff and percolation volumes were also measured at 10-min intervals. During each rainfall event periodic plot observations were made.

2.4. Aggregate size analysis

Following initial sieving of soil through a 4-mm screen a riffle-splitter was used to randomly select ten representative samples. These samples were wet-sieved using a procedure similar to that discussed by Gabriels and Moldenhauer (1978), and the following seven aggregate sizes were fractionated: 2000–4000 μm (granule-size aggregates); 1000–2000 μm (very coarse-sand sized aggregates); 500–1000 μm (coarse sand-sized aggregates); 250–500 μm (medium sand-sized aggregates); 125–250 μm (fine sand-sized aggregates); 63–125 μm (very fine sand-sized aggregates); and < 63 μm (silt plus clay-sized aggregates). The relative percent of each of the seven aggregate size fractions were determined for the ten samples. For each aggregate size fraction the ten values were then resampled with replacement 1000 times using a computer intensive algorithm (cf., Efron and Tibshirani, 1993). This nonparametric approach allows the researcher to draw conclusions about the population from only the small sample size at hand. The mean of the sampling distribution for each aggregate size fraction was determined, along with the 2.5 and 97.5 percentiles of the distribution (Table 3).

Immediately after a simulated rainfall event each splash and wash sample was wet-sieved and aggregate size fractions equal to those for the original soil were

Table 3
Mean resampled wet-sieved aggregate percentages and 95% confidence intervals for the Wahiawa test soil

Aggregate size fraction (μm)	Mean (%)	2.5th Percentile (%)	97.5th Percentile (%)
2000–4000	6.55	4.76	8.23
1000–2000	14.30	12.75	16.68
500–1000	22.83	20.97	24.51
250–500	26.45	25.14	28.16
125–250	16.47	15.79	17.19
63–125	10.39	9.17	11.60
< 63	3.05	2.70	3.39

determined. Total aggregate mass for each 10-min interval was determined by summing the individual aggregate size fractions. Enrichment ratios for individual aggregate size fractions were determined using Eq. 1. Resample mean values for the original soil matrix (Table 3) were used in all ER computations.

3. Results and discussion

Data from Sutherland et al. (1996) indicated that the ratio of front splash sediment flux to wash ranged from 1.6:1.0 for 20° slopes to 7.5:1.0 for 10° slopes. Thus, these data indicate the relative importance of splash as a potential mechanism for sediment transport under the boundary conditions of this laboratory investigation, i.e., bare slopes that are both steep and short.

3.1. Time-integrated cumulative aggregate distributions

Cumulative curves for splash-transported aggregates (Fig. 1) indicated only slight differences from the control soil regardless of slope angle. Median values (D_{50}) for the airsplashed material ranged from 390 μm for the 20° slopes to 450 μm for the 5° slopes (Table 4), and this range included the D_{50} of the control soil. The D_{16}-percentiles were on average significantly finer for the splash transported sediment than that for the control soil by 230 to 360 μm. This indicates a limited ability of splash to transport the

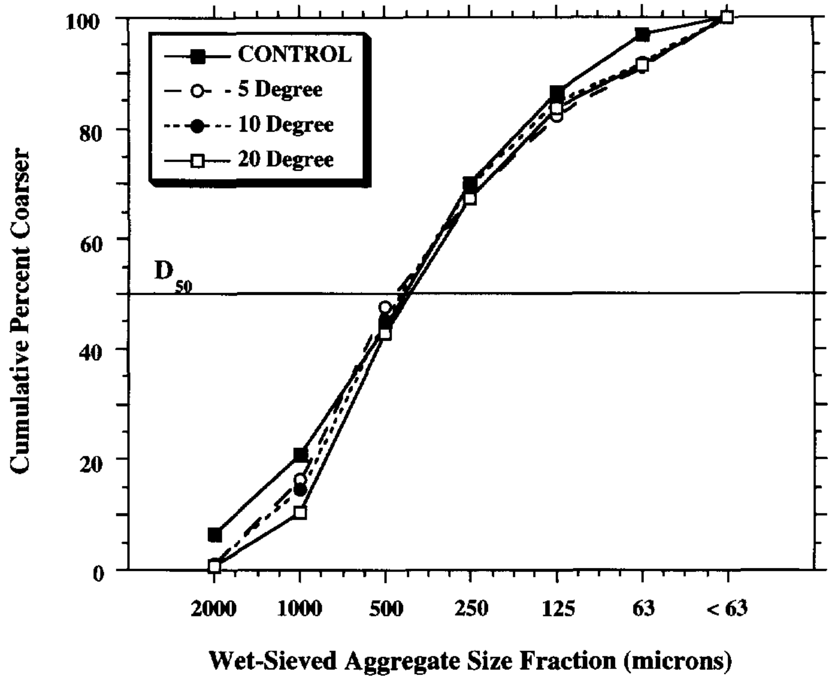

Fig. 1. Cumulative distribution curves for wet-sieved aggregates transported by splash for three slope angles relative to the control (Oxisol) soil matrix. Note that 2000 implies a size range of 2000–4000 μm; 1000, 1000–2000 μm; 500, 500–1000 μm; 250, 250–500 μm; 125, 125–250 μm; 63, 63–125 μm.

Table 4

Comparisons of percentiles of the wet-sieved aggregate size distribution for the control soil to splash sediment, wash sediment and splash plus wash sediment

Interrill process	Slope (°)	D_{16} (μm)	D_{50} (μm)	D_{84} (μm)
Control soil	–	1230	420	140
Splash	5	1000	450	110
	10	930	440	120
	20	870	390	110
Wash	5	770	260	50
	10	310	< 50 [a]	< 30 [a]
	20	140	< 50 [a]	< 30 [a]
Wash + splash	5	970	420	70
	10	900	420	100
	20	840	350	70

[a] Values represent only first-order approximations since the aggregate size fraction < 63 μm was not further fractionated, therefore values reflect a plotting bias.

available coarse aggregate fractions. Mean D_{84}-percentiles for airsplashed sediment were only 20 to 30 μm finer than the control soil.

The cumulative curves for wash transported sediment (Fig. 2) differed significantly from the control soil, and also from the curves for airsplash transported sediment (Fig.

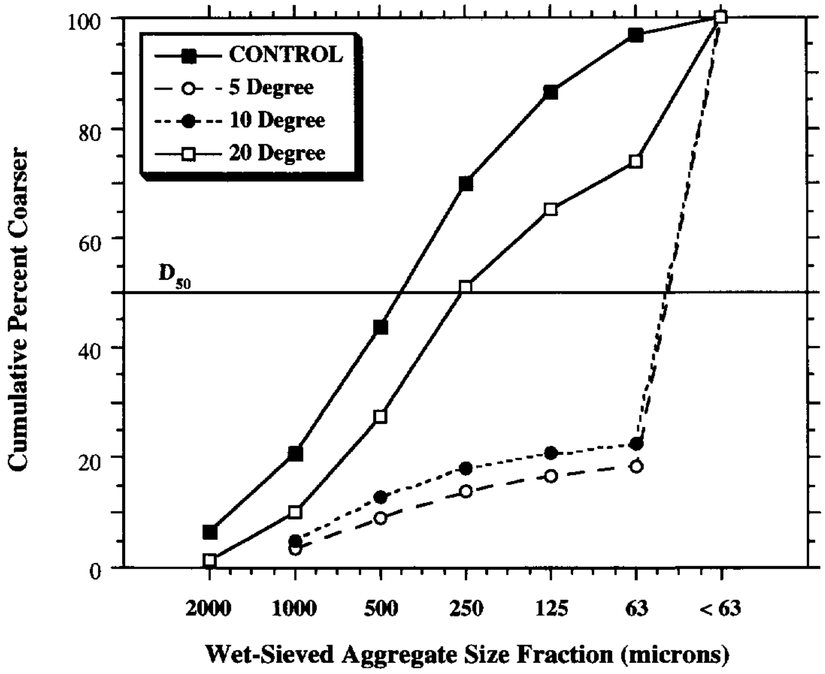

Fig. 2. Cumulative distribution curves for wet-sieved aggregates transported by wash for three slope angles relative to the control soil matrix. Note that 2000 implies a size range of 2000–4000 μm; 1000, 1000–2000 μm; 500, 500–1000 μm; 250, 250–500 μm; 125, 125–250 μm; 63, 63–125 μm.

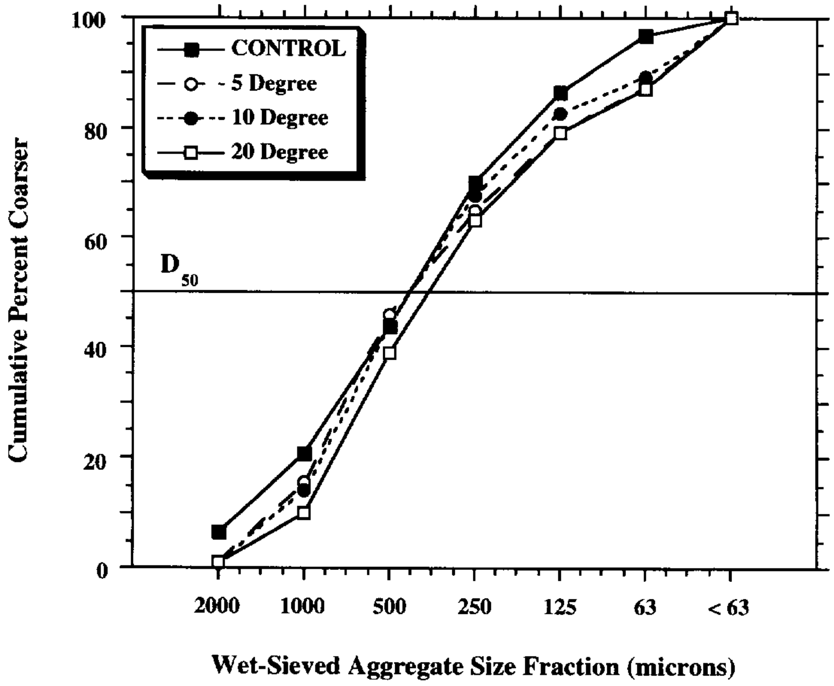

Fig. 3. Cumulative distribution curves for wet-sieved aggregates transported by splash and wash for three slope angles relative to the control soil matrix. Note that 2000 implies a size range of 2000–4000 μm; 1000, 1000–2000 μm; 500, 500–1000 μm; 250, 250–500 μm; 125, 125–250 μm; 63, 63–125 μm.

1). Additionally, wash aggregate size distributions differed significantly with slope angle. Wash associated with the 20° slope treatment had D_{16}, D_{50}, D_{84}-values 460, 160 and 90 μm finer than the control soil (Table 4). Suggesting that on steep, short interrill slopes wash will preferentially remove fine aggregates. Data from treatments with slope angles $\leq 10°$ indicated that wash transported aggregates were significantly finer than those for the 20° slope treatment, and for the control soil. The reasons for increased wash selectivity on the gentler slopes is that a slope reduction decreases shear velocity, shear stress, and stream power. Therefore, assuming wash entrainment is negligible on 5–10° slopes these data indicate that wash transport is energy limited. Sediment is available from splash redistribution, but wash is generally not energetic enough to transport the coarser aggregate size fractions, or alternatively they are preferentially deposited.

Combining all data (splash plus wash) indicates that interrill transported sediment is finer than the control soil (Fig. 3), especially for the coarser end of the aggregate size distribution (Table 4). The D_{16}-percentiles were between 260 and 390 μm finer than the control soil matrix, and D_{84}-percentiles were between 40 and 70 μm finer.

3.2. Splash and wash enrichment ratios

Individual aggregate mean ER-values were plotted for all slopes for splash (Fig. 4) and wash (Fig. 5). The ER_{splash} curves indicate that the coarsest granule-sized aggregate fraction had the lowest mean ER-value, between 0.1 and 0.2. The only fractions

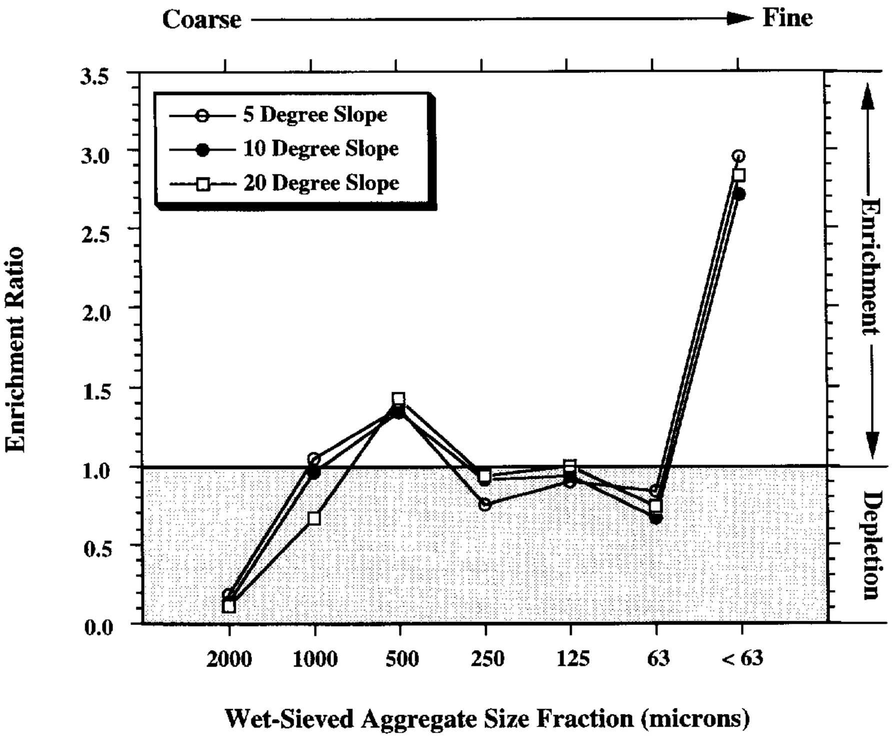

Fig. 4. Mean enrichment ratios for individual wet-sieved aggregates transported by splash and their variation with slope angle. Note that 2000 implies a size range of 2000–4000 μm; 1000, 1000–2000 μm; 500, 500–1000 μm; 250, 250–500 μm; 125, 125–250 μm; 63, 63–125 μm.

exhibiting significant enrichment in airsplashed transported material where the 500–1000 μm aggregates with mean ER-values of 1.3 to 1.5, and the < 63 μm aggregate fraction with mean ER-values of 2.7 to 3.0. Differences in ER_{splash} with slope angle were negligible. Though ER_{splash}-values differed little with slope, the mass of splash transported increased significantly as slope angle increased in the sequence 1.0, 2.5 and 6.8 for 5°, 10° and 20° slopes respectively.

For airsplash the most easily transported fraction was < 63 μm, followed by the 500–1000 μm fraction. Despite energetic raindrop impacts on the soil surface, splash preferentially transported specific aggregate sizes, was aselective for other size fractions, and the coarsest fractions were left as a lag deposit. These data differ from those of Parsons et al. (1991) discussed earlier, because they found no enrichment of silt or clay fractions. However, it is difficult to make direct comparisons because they were working with very poorly aggregated soils, i.e., splash of primary particles. Work by Ellison (1944) (Table 1), Proffitt et al. (1993) and Moss (1991) (Table 2) indicate varying degrees of airsplash selectivity for fines.

ER_{wash}-values (Fig. 5) were significantly different from ER_{splash}-values (Fig. 4), and differences were also between splash and wash for individual slope angles. It is important to note that the Y-axis of Fig. 5 is logarithmic ($\log_{10}$). For slopes ≤ 10° flow was not energetic enough to transport 2000–4000 μm aggregates even though they were redistributed within the plot by splash. As the slope was increased to 20° granule-sized aggregates were transported, but ER-values were low, about 0.2. Wash transported

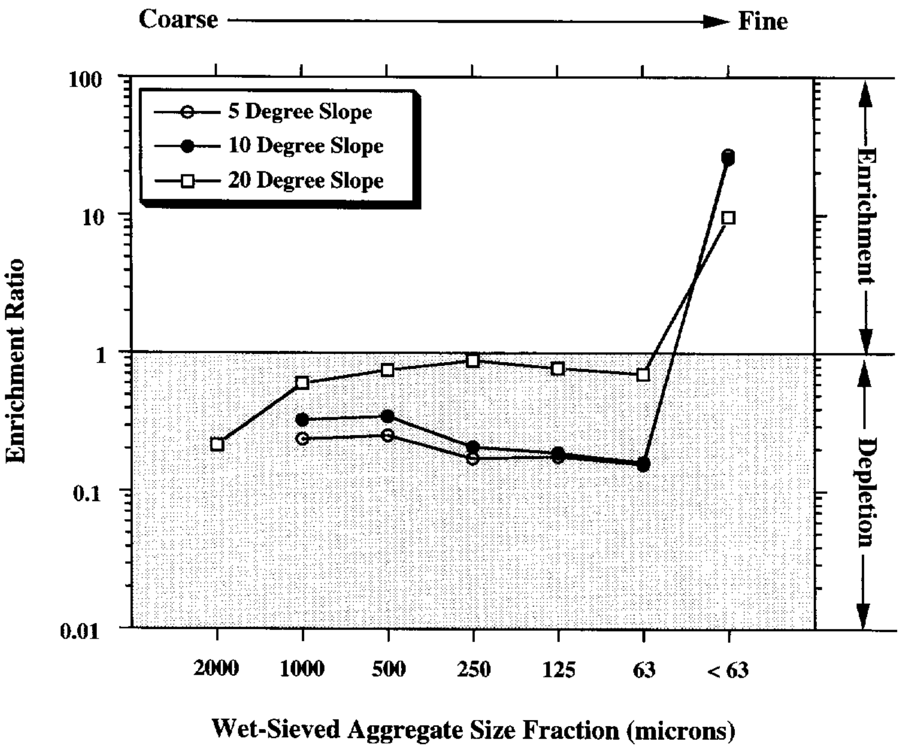

Fig. 5. Mean enrichment ratios for individual wet-sieved aggregates transported by wash and their variation with slope angle. Note that 2000 implies a size range of 2000–4000 μm; 1000, 1000–2000 μm; 500, 500–1000 μm; 250, 250–500 μm; 125, 125–250 μm; 63, 63–125 μm. Additionally, note that the enrichment ratio axis is logarithmic.

significant amounts of granule-sized aggregates during aperiodic pulses from the 20° plots, these pulses of sediment output were discussed in detail by Sutherland et al. (1996). All sand-sized aggregate fractions (63–2000 μm) were significantly depleted for slopes $\leq 10°$ relative to the test soil, with mean ER-values between 0.15 and 0.30. The sand-size ER-values for the 20° slopes were significantly greater than those for slopes $\leq 10°$, but were generally < 1.0, i.e., 0.60 to 0.85. The < 63 μm fraction showed extremely high ER-values, between 10 and 30. The < 63 μm mean ER_{wash}-values were 3 to 10 times greater than $\text{ER}_{\text{splash}}$-values. These high ER-values support earlier suggestions that wash (impacted by raindrops) is highly selective. Similar data from aggregated soils are generally not available from the literature. Only the work of Moss et al. (1979) on primary particles has indicated higher ER-values (≈ 200) for < 2 μm material when overland flow in the absence of raindrop impact occurred.

The combined interrill ER plot (splash plus wash) for the three slope treatments (Fig. 6) indicates that the two-end members of the aggregate size distribution experienced high selectivity. The granule-sized aggregate fraction was selectively depleted in interrill transported sediment, while the silt plus clay-sized fraction was selectively enriched. This would indicate that with time coarser particles would form a greater proportion of the interrill surface as fines are preferentially removed and coarse particles preferentially deposited. This scenario would eventually lead to a decreased water holding capacity of

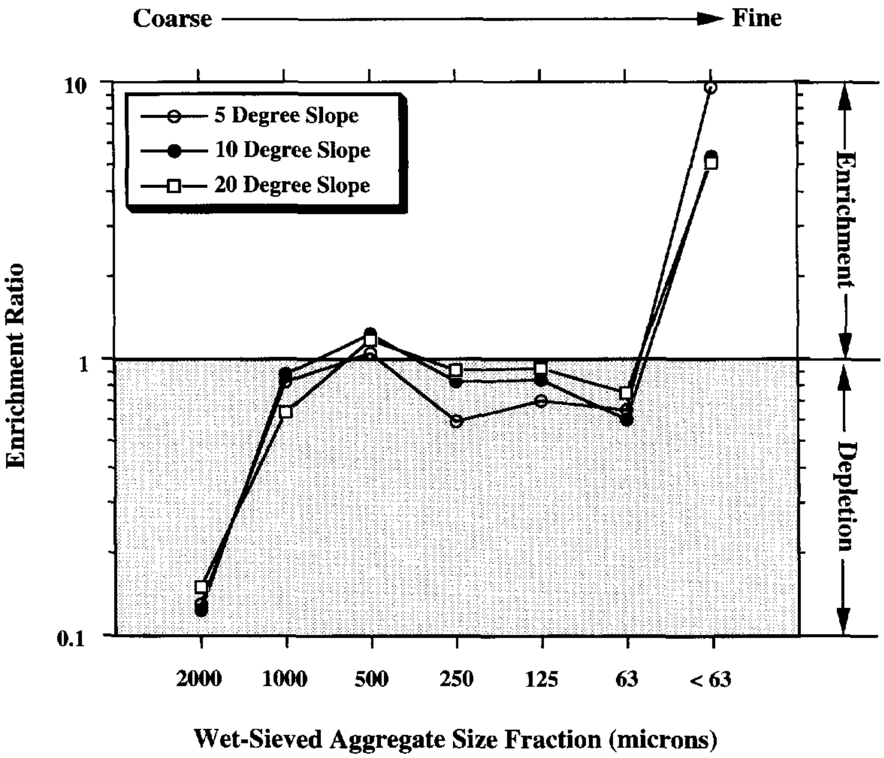

Fig. 6. Mean enrichment ratios for individual wet-sieved aggregates transported by splash and wash and their variation with slope angle. Note that 2000 implies a size range of 2000–4000 μm; 1000, 1000–2000 μm; 500, 500–1000 μm; 250, 250–500 μm; 125, 125–250 μm; 63, 63–125 μm. Additionally, note that the enrichment ratio axis is logarithmic.

the interrill area, and a concomitant decrease in nutrient inventories as fines and their associated nutrients are preferentially removed (cf. Sharpley, 1985; Palis et al., 1990; Ghadiri and Rose, 1991a, b). The management strategy to reduce selective interrill erosion of fines would require a surface contact cover. Gilley et al. (1986) found that corn residue surface cover reduced the size and mass of material transported from interrill areas. A mulch cover reduces the direct impact energy of raindrops on soil particles and the increased surface roughness would decrease flow velocity, increase the probability of deposition, decrease shear stress and stream power, thus interrill mass and nutrient flux would be significantly reduced.

3.3. Temporal variation in aggregate size enrichment ratios

Data presented in Figs. 3–6 were mean values for individual aggregate fractions for 3-h runs. Moss (1991) developed detailed ER-time plots which included all aggregate size data, and this approach was adopted here because it provided a useful visualization tool. ER-time plots for each slope treatment and for each interrill process were constructed. Enrichment ratio isolines were plotted using Surface III + (Kansas Geological Survey, 1992). Only plots for splash at a 5° slope angle (Fig. 7) and wash at a 5° slope angle (Fig. 8) are presented. It is important to note that there were no 2000–4000

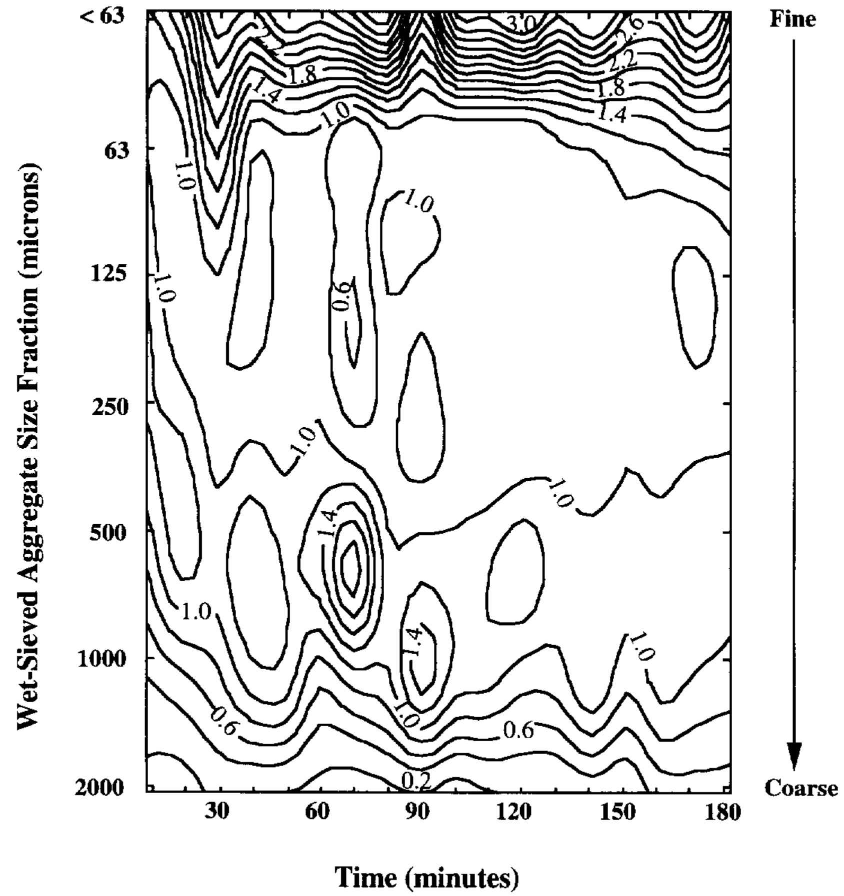

Fig. 7. Enrichment ratio plots of all wet-sieved aggregates transported by splash from 5° slope treatments. Note that 2000 implies a size range of 2000–4000 μm; 1000, 1000–2000 μm; 500, 500–1000 μm; 250, 250–500 μm; 125, 125–250 μm; 63, 63–125 μm.

μm aggregates transported by wash and transport was delayed since runoff initiation occurred after about 28 min at this slope angle, thus the plot boundaries differ slightly from those used for splash. Additionally, because of the large range in ER_{wash}-values the interpolated ER isolines in Fig. 8 are logarithmic (i.e., $\log_{10}$), thus an ER_{log}-value > 0.0 represents enrichment, negative values reflect depletion.

Comparison of 5° splash (Fig. 7) and 5° wash (Fig. 8) plots indicates that the individual interrill processes have distinct temporal patterns. ER_{wash}-values for all aggregates > 63 μm were extremely low with highest values, but still < 1.0 (on a linear scale), generally in the early phases of the runoff process (Fig. 8). The splash ER plot (Fig. 7) exhibited low values for only the 2000–4000 μm fraction. Time-trends for most aggregates are more consistent throughout the 3-h events, with a notable increase with time for the < 63 μm fraction.

The 5° ER_{splash}-plot (Fig. 7) can be compared to the only other published plot for an Oxisol from Robertson, N.S.W. (Moss, 1991; p. 300). Rainfall simulation by Moss was conducted on a 1.1° slope at a rainfall intensity of 40 mm h^{-1} for a duration of 50 to 60 min. His data indicate that ER-values for aggregates 1000–2000 μm increased with

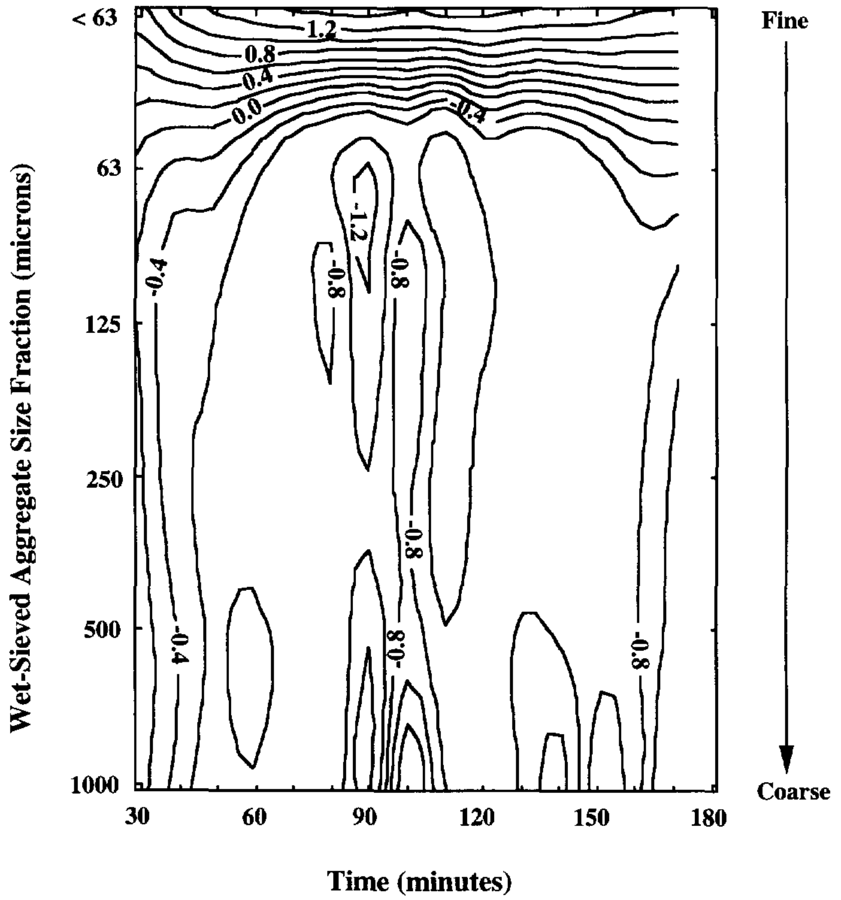

Fig. 8. Enrichment ratio plots of all wet-sieved aggregates transported by wash from 5° slope treatments. Note that 1000 implies a size range of 1000–2000 μm; 500, 500–1000 μm; 250, 250–500 μm; 125, 125–250 μm; 63, 63–125 μm. Additionally, note that the enrichment ratio isolines are logarithmic.

time from 0.25 to 1.0. ER-values for aggregates between 250 and 500 μm decreased with time from about 1.50 to 1.25. For aggregates between 60 and 125 μm little change occurred with ER-values about 1.25. Aggregates < 63 μm were fractionated with the highest ER-values for the < 10 μm fraction, which exhibited a decrease with time from about 10 to 2 at the end of the simulation run. Data from Moss (1991) and the data from the present study indicate that the enrichment ratios of individual interrill processes is a time dependent phenomenon. Time trends varied with process and aggregate size, and these trends reflect the changing nature of the chemical and physical characteristics of the surface soil as it responds to rainfall and runoff.

Temporal ER-plots similar to Figs. 7 and 8 are useful but fail to provide a linkage with the time varying output of material. Selected time varying plots of enrichment ratios with aggregate mass flux are presented (Figs. 9–12). Two aggregate size fractions were considered for detailed examination, the < 63 μm fraction and the 250–500 μm fraction. The finest fraction is environmentally significant and displays enrichment for both splash and wash. The coarser medium-sand size aggregate fraction was selected since this fraction generally exhibited mean ER-values ≤ 1.0.

Time-varying ERs were smoothed using the lowess (locally weighted regression scatterplot smoothing) algorithm in Data Desk[4] (Velleman, 1992). This technique was used to reduce the "noise" in the data so that general trends could be explored. Unsmoothed ER-values were correlated with all splash and wash sediment flux data

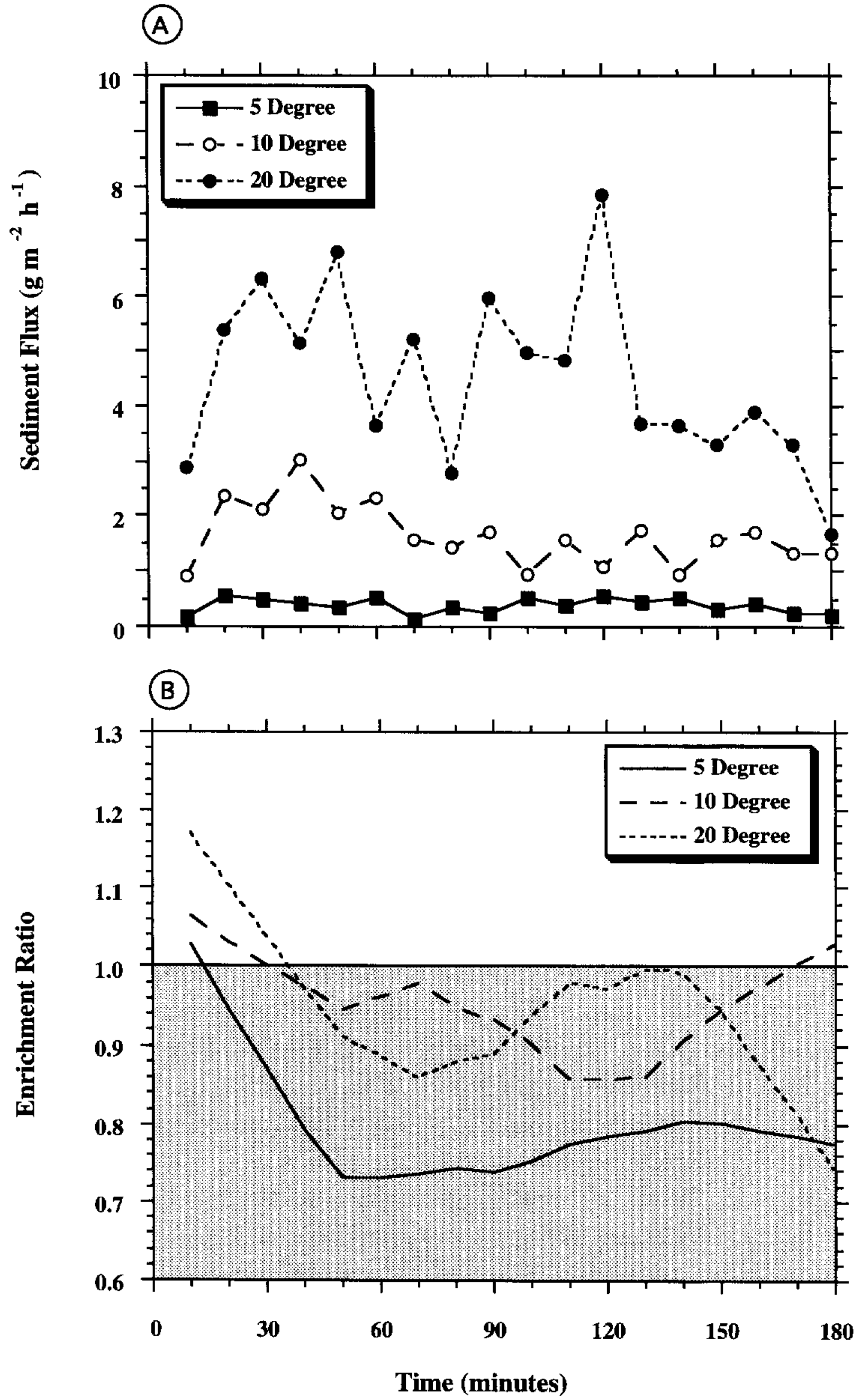

Fig. 9. (A) Temporal variation in splash flux for 250–500 μm aggregates for all slopes. (B) Temporal variation in lowess smoothed enrichment ratios for splash transported aggregates of 250–500 μm.

Table 5
Nonparametric Spearman's rank correlations (r_s) between enrichment ratios and mass flux for splash and wash aggregates of < 63 μm and 250–500 μm

Comparisons [a]	Slope (°)	r_s	r_s^2	Description [b]
SP_{250} vs. ER_{250}	5	0.58^{***}	0.34	PNLM
	10	0.56^{***}	0.32	PLM
	20	0.62^{***}	0.39	PLM
$SP_{<63}$ vs. $ER_{<63}$	5	0.32^{NS}	0.10	C
	10	0.20^{NS}	0.04	C
	20	0.46^{**}	0.21	C/PLM
W_{250} vs. ER_{250}	5	0.85^{***}	0.73	PLM
	10	0.71^{***}	0.51	PLM
	20	0.85^{***}	0.73	PNLM
$W_{<63}$ vs. $ER_{<63}$	5	0.42^{*}	0.18	C/PNLM
	10	0.42^{*}	0.18	C/PNLM
	20	-0.54^{**}	0.30	NNLM

[a] SP and W represent splash and wash sediment flux (g m^{-2} h^{-1}) for aggregates of 250–500 μm or < 63 μm; ER represents the associated enrichment ratio for a given aggregate size fraction.

[b] PLM represents a positive linear monotonic relationship; PNLM represents a positive non-linear monotonic relationship; C represents a complex relationship; NNLM represents a negative non-linear monotonic relationship.

*, **, *** Data are statistically significant at significance levels $\alpha \leq 0.05$, 0.01, and 0.001 respectively; ^{NS} represents not significant at $\alpha = 0.05$.

using the nonparametric Spearman rank correlation coefficient. The nonparametric approach was used since data were not normally distributed and trends other than linear (i.e., non-linear monotonic) were considered to be important.

Splash flux of 250–500 μm aggregates (Fig. 9A) indicated statistically significant differences with slope angles, 20° > 10° > 5°. Splash transport was most variable for the 20° slope treatment, and the detailed pattern indicated several periods of high sediment flux. These pulses were generally associated with increased availability of material transported in wave-like fashion (visually observed) downslope by wash. Smoothed splash ER_{250}-curves for all slopes (Fig. 9B) indicate an early enrichment ($ER_{250} > 1.0$) followed by depletion ($ER_{250} < 1.0$). The 5° slope exhibited the lowest ER_{250}-values, and time trends for 10° and 20° slopes appeared to be mirror images. Splash ER_{250}-values < 1.0 cannot be explained by limited energy availability, since a reasonably high magnitude event was simulated, and since ER_{500}-values were > 1.0 (Fig. 4). Thus, this may indicate rapid in-filling of surficial void space with 250–500 μm aggregates and incorporation into a developing surface seal layer. This process would shield aggregates from splash and wash transport. The variation is splash transport of 250–500 μm aggregates may reflect a combination of surface seal breakdown that increased aggregate availability, plus the aperiodic increases in wash. Micromorphological investigations are necessary to confirm this hypothesis.

Correlations between splash mass flux (250–500 μm) and ER_{250}-values (Table 5) indicate that statistically significant positive linear monotonic (PLM; 10° and 20° slopes)

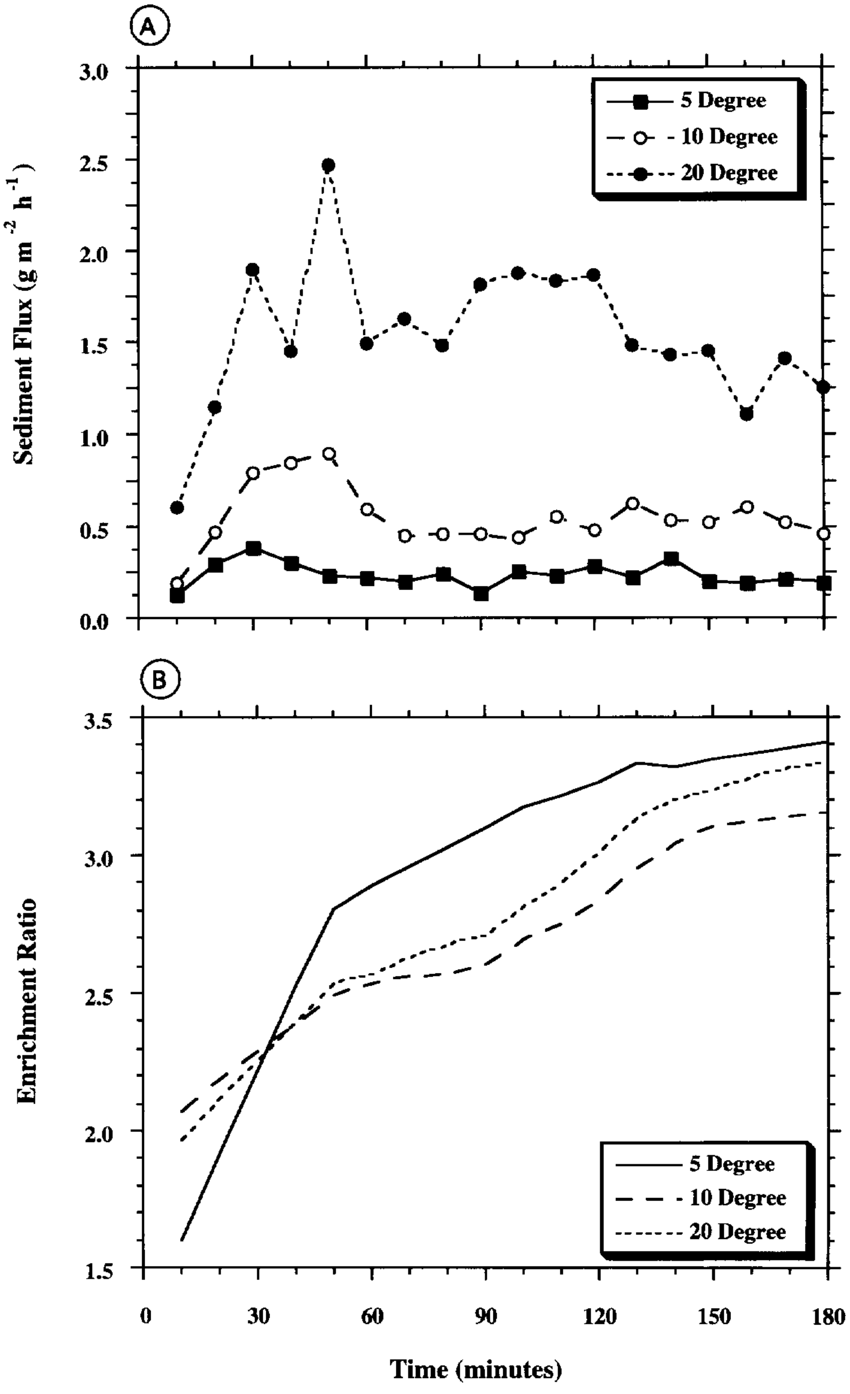

Fig. 10. (A) Temporal variation in splash flux for < 63 μm aggregates for all slopes. (B) Temporal variation in lowess smoothed enrichment ratios for splash transported aggregates of < 63 μm.

and positive non-linear monotonic (PNLM; 5° slopes) relationships were present. Nonparametric coefficients of determination (r_s^2) were between 32 and 39%, suggesting factors other than mass flux of 250–500 μm aggregates were also important in controlling splash ER_{250}-values.

Splash transport of < 63 μm aggregates indicated the dominance of 20° slopes > 10° slopes > 5° slopes. Time trends (Fig. 10A) were similar to those reported by Sutherland et al. (1996) for all aggregate data. Temporal splash $ER_{<63}$ patterns (Fig. 10B) were very different from the ER_{250} patterns (Fig. 9B). Splash $ER_{<63}$-values

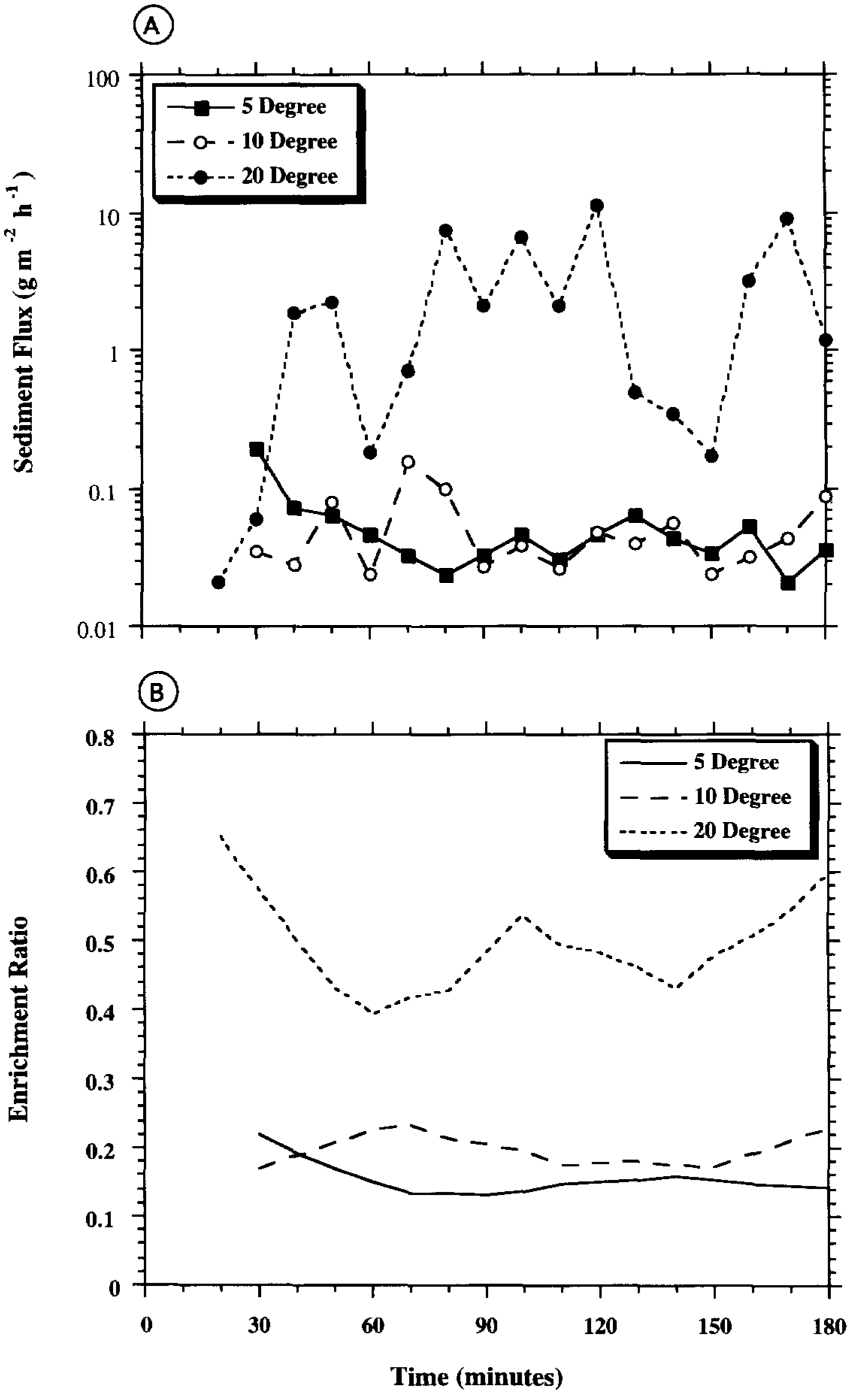

Fig. 11. (A) Temporal variation in wash flux for 250–500 μm aggregates for all slopes. (B) Temporal variation in lowess smoothed enrichment ratios for wash transported aggregates of 250–500 μm.

increase with time and this indicated that aggregate stripping or breakdown by splash detachment and preferential transport occurred throughout the event. No statistically significant relationships ($\alpha = 0.05$) were found between splash flux and splash ER$_{<63}$

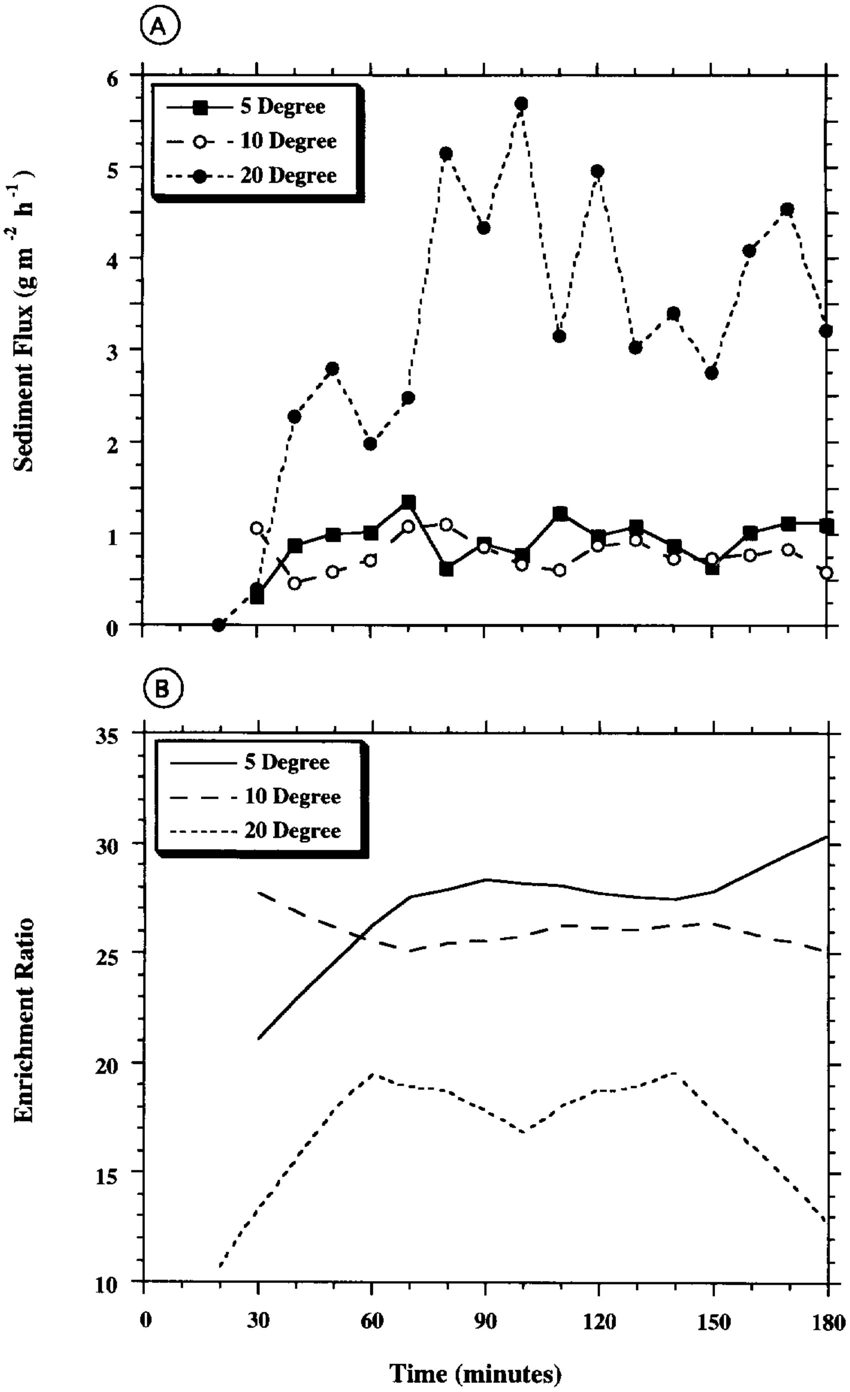

Fig. 12. (A) Temporal variation in wash flux for < 63 μm aggregates for all slopes. (B) Temporal variation in lowess smoothed enrichment ratios for wash transported aggregates of < 63 μm.

on 5 and 10° slopes (Table 5). Data for the 20° slope indicated a significant relationship ($\alpha = 0.01$) with an r_s^2-value of 21%.

Wash transport of 250–500 μm aggregates (Fig. 11A) indicated the following slope relationships: $20° > 10° \approx 5°$, with on average 55 times more aggregate mass transported from the 20° slopes. Several sediment pulses were apparent from the 20° slope, and many correspond to periods of increased splash transport (Fig. 9A).

Wash ER_{250}-values exhibited general time-trend patterns (Fig. 11B) similar to those for splash (Fig. 9B), but values were significantly lower for wash transported aggregates. Wash ER_{250}-values for 5 and 10° slopes were significantly lower than those for 20° slopes. These data reflect the limited ability of runoff to transport medium-sand size aggregates detached by splash.

Correlations were highly significant between wash aggregate transport (250–500 μm) and ER_{250}-values for all slopes, with r_s^2 values of 51 to 73% (Table 5). Linear or non-linear increases in ER_{250} were associated with increased wash aggregate transport.

Sediment transport by wash of < 63 μm aggregates (Fig. 12A) was 3.7 times greater from the 20° slope treatments than from the 5 and 10° slopes. This increase, though substantial, was an order of magnitude lower than the 55 times increase in the 250–500 μm fraction, and data for other wash aggregate size fractions: 2000–4000 μm, ∞; 1000–2000 μm, 24 times; 500–1000 μm, 29 times; 125–250 μm, 56 times; and for 63–125 μm, 61 times. Thus, with increased slope, and thus increased shear stress and stream power, wash transport increased amounts of all aggregate fractions, particularly the coarse sand-sized and granule-sized aggregates.

Wash for all slopes exhibited $ER_{<63}$-values $\gg 1.0$ (Fig. 12B), and these were much higher than those for splash (Fig. 10B). Smoothed ER data showed different $ER_{<63}$ time trends with slope angle, particularly for the 20° slope treatments. Correlation of $ER_{<63}$-values with wash transport were significant at $\alpha = 0.05$ for the 5 and 10° slopes, but patterns were complex and the r_s^2-values were only about 18% (Table 5). The pattern for the 20° slope was unique since a negative non-linear monotonic relationship was noted between $ER_{<63}$ and wash sediment flux < 63 μm. This relationship was significant at $\alpha = 0.01$, and the r_s^2-value was 30%.

4. Conclusions

Rainfall simulations conducted on a clay-rich, well-aggregated Oxisol indicated interrill processes preferentially transported aggregates < 63 μm. In addition, splash ER_{500}-values were > 1.0, indicating preferential transport relative to the original soil matrix. Wash exhibited low ER-values ($\ll 1.0$) for all aggregate sizes > 63 μm. These results indicate that on short interrill slopes (≤ 0.60 m), typical of agricultural furrow side-slopes, under high rainfall intensity wash is not energetic enough to entrain, re-entrain, or transport sand-sized particles in proportion to that which exists in the original soil matrix. Slope angle influenced wash enrichment, with ER-values for aggregates > 63 μm transported from the 20° slopes significantly greater than those for the 5 and 10° slopes, but still < 1.0. ER-values for the < 63 μm fraction for 5 and 10° slopes were high, with average values of about 30 compared to 10 for 20° slopes.

However, in terms of the total mass < 63 μm transported by wash, the 20° slopes output on average 3.7 times more material than that from the gentler slopes. Variation in wash ER_{250}-values indicated significant positive linear and non-linear monotonic relationships with wash mass for all slopes.

Splash, being more energetic than wash, detached and transported a wider range of aggregates, including the granule-size fraction. However, ER-values for the coarsest fraction were $\ll 1.0$. Average splash ER-values for all aggregates between 63 and 2000 μm (excluding 500–1000 μm) were between about 0.70 and 1.00, indicating transport in relative proportion to the original soil matrix. Splash $ER_{<63}$-values showed a general increase with time for all slopes, and the total mass flux of this aggregate size fraction was poorly correlated with enrichment.

In total these data indicate that interrill erosion is a selective process and the two components differ in their magnitude and in their time trends for all aggregate size fractions investigated. Traditionally it has been assumed that only interrill wash is selective for finer fractions; however, data presented here supports selectivity of splash for silt and clay-sized aggregates, and also for medium sand-sized aggregates. The implications of preferential fine sediment redistribution and transport is that the original soil will become coarser with time, nutrient content will likely decrease if no amendments are added, and these changes will be eventually reflected in productivity declines. Thus, surface cover management is critical to reduce fine particle selectivity and decrease the overall mass flux from interrill areas.

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References

Alberts, E.E., Wendt, R.C. and Piest, R.F., 1983. Physical and chemical properties of eroded soil aggregates. Trans. Am. Soc. Agric. Eng., 26: 465–471.

Allan, R.J., 1986. The Role of Particulate Matter in the Fate of Contaminants in Aquatic Ecosystems. Sci. Ser. No. 142, Inland Water Directorate, Environment Canada, Burlington, Ont., 128 pp.

Efron, B. and Tibshirani, R.J., 1993. An Introduction to the Bootstrap. Chapman and Hall, New York, NY, 436 pp.

Ekern, P.C., 1950. Raindrop impact as the force initiating soil erosion. Soil Sci. Soc. Am. Proc., 15: 7–10.

Ellison, W.D., 1944. Studies of raindrop erosion. Agric. Eng., 25: 131–136.

El-Swaify, S.A., 1980. Physical and mechanical properties of Oxisols. In: B.K.G. Theng (Editor), Soils With Variable Charge. New Zealand Soc. of Soil Sci., Offset Publications, Palmerston North, pp. 303–324.

Farmer, E.E., 1973. Relative detachability of soil particles by simulated rainfall. Soil Sci. Soc. Am. Proc., 37: 629–633.

Gabriels, D. and Moldenhauer, W.C., 1978. Size distribution of eroded material from simulated rainfall: Effect over a range of texture. Soil Sci. Soc. Am. J., 42: 954–958.

Ghadiri, H. and Payne, D., 1980. A study of soil splash using cine-photography. In: M. De Boodt and D. Gabriels (Editors), Assessment of Erosion. Wiley, Chichester, pp. 185–192.

Ghadiri, H. and Payne, D., 1986. The risk of leaving the soil surface unprotected against falling rain. Soil Tillage Res., 8: 119–130.

Ghadiri, H. and Rose, C.W., 1991a. Sorbed chemical transport in overland flow: I. A nutrient and pesticide enrichment mechanism. J. Environ. Qual., 20: 628–633.

Ghadiri, H. and Rose, C.W., 1991b. Sorbed chemical transport in overland flow: II. Enrichment ratio variation with erosion processes. J. Environ. Qual., 20: 634–641.

Gilley, J.E., Finkner, S.C., Spomer, R.G. and Mielke, L.N., 1986. Size distribution of sediment as affected by corn residue. Trans. Am. Soc. Agr. Eng., 29: 1273–1277.

Govers, G., 1985. Selectivity and transport capacity of thin flows in relation to rill erosion. Catena, 12: 35–49.

Hart, B.T., 1982. Uptake of trace metals by sediments and suspended particulates: A review. Hydrobiologia, 91: 299–313.

Kansas Geological Survey, 1992. Surface III, Macintosh Version. Kansas Geological Survey, Lawrence, KS, variable pagination.

Luk, S.-H., 1983. Effect of aggregate size and microtopography on rainwash and rainsplash erosion. Z. Geomorph., 27: 283–295.

Mazurak, A.P. and Mosher, P.N., 1968. Detachment of soil particles in simulated rainfall. Soil Sci. Soc. Am. Proc., 32: 716–719.

Mazurak, A.P. and Mosher, P.N., 1970. Detachment of soil aggregates in simulated rainfall. Soil Sci. Soc. Am. Proc., 34: 798–800.

Meyer, L.D., Rhoton, F.E. and McDowell, L.L., 1986. Physical properties of eroded sediment. In: Proceedings of the Fourth Federal Interagency Sedimentation Conference, Las Vegas, NV, Volume II, pp. 8-1–8-9.

Meyer, L.D., Line, D.E. and Harmon, W.C., 1992. Size characteristics of sediment from agricultural soils. J. Soil Water Conserv., 47: 107–111.

Moss, A.J., 1991. Rain-impact soil crust. II. Some effects of surface-slope, drop-size and soil variation. Aust. J. Soil Res., 29: 291–309.

Moss, A.J. and Green, P., 1983. Movement of solids in air and water by raindrop impact: Effects of drop-size and water-depth variations. Aust. J. Soil Res., 21: 257–269.

Moss, A.J., Walker, P.H. and Hutka, J., 1979. Raindrop-stimulated transportation in shallow water flows: An experimental study. Sediment. Geol., 22: 165–184.

Palis, R.G., Okwach, G., Rose, C.W. and Saffigna, P.G., 1990. Soil erosion processes and nutrient loss. II. The effect of surface contact cover and erosion processes on enrichment ratio and nitrogen loss in eroded sediment. Aust. J. Soil Res., 28: 641–658.

Parsons, A.J., Abrahams, A.D. and Luk, S.-H., 1991. Size characteristics of sediment in interrill overland flow on a semiarid hillslope, southern Arizona. Earth Surf. Process. Landforms, 16: 143–152.

Proffitt, A.P.B., Rose, C.W. and Lovell, C.J., 1993. Settling velocity characteristics of sediment detached from a soil surface by raindrop impact. Catena, 20: 27–40.

Savat, J., 1982. Common and uncommon selectivity in the process of fluid transportation: Field observations and laboratory experiments on bare surfaces. In: D.H. Yaalon (Editor), Aridic Soils and Geomorphic Processes. Catena Suppl., 1: 139–160.

Sharpley, A.N., 1985. The selective erosion of plant nutrients in runoff. Soil Sci. Soc. Am. J., 49: 1527–1534.

Sutherland, R.A., Wan, Y., Ziegler, A.D., Lee, C.-T. and El-Swaify, S.A., 1996. Splash and wash dynamics: An experimental investigation using an Oxisol. Geoderma, 69: 85–103.

Velleman, P.F., 1992. Data Desk^4: Statistics Guide, Volume II. Data Description, Ithaca, NY, variable pagination.

Watters, R.L., Hakonson, T.E. and Lane, L.J., 1983. The behavior of actinides in the environment. Radiochim. Acta, 32: 89–103.

Young, R.A., 1980. Characteristics of eroded sediment. Trans. Am. Soc. Agric. Eng., 23: 1139–1142, 1146.