
Hillslope runoff and erosion as affected by rolled erosion control systems: a field study

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Abstract:

A replicated field study using rainfall simulation and overland flow application was conducted in central Oahu, Hawaii, on a clay-dominated Oxisol with a 9% slope. Three main treatment groups were examined: a bare treatment, a group of four rolled erosion control systems (RECSs) with open weave designs, and a group of five randomly oriented fibre RECSs. A total of 1122 measurements of runoff and erosion were made to examine treatment differences and to explore temporal patterns in runoff and sediment flux.

All erosion control systems significantly delayed the time required to generate plot runoff under both simulated rainfall (35 mm h⁻¹) and the more intense trickle flow application (114 mm h⁻¹). Once runoff was generated during the rainfall application phase, the bare treatment runoff coefficients were significantly lower than those from the two groups of RECSs, as surface seal disruption by rilling is inferred to have enhanced infiltration in the bare treatments. During the more intense phase of overland flow application, the reverse pattern was observed. Interrill contributing-area roughness was reduced on the bare treatment, facilitating increased runoff to well-developed rill networks. Meanwhile, the form roughness associated with the RECSs delayed interrill flow to the poorly organized rills that formed under some of the RECSs.

Regardless of median variations between treatments, sediment output was significantly lower from all surfaces covered by RECSs. The median cumulative sediment output from the bare surfaces was 6.9 kg, compared with 1.2 kg from the open-weave RECSs and 0.2 kg from the random-fibre RECSs. The random-fibre systems were particularly effective under the more stressful overland flow application phase, with 63 times less sediment eroded than the bare treatments and 12 times less than that from the open-weave systems. Architectural design differences between the two groups of RECSs are discussed in light of their relation to erosion process dynamics and shear stress partitioning. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS rolled erosion control systems; open weave; randomly oriented fibres; runoff; sediment transport; erosion processes

INTRODUCTION

Accelerated soil erosion from human-modified hillslopes is a serious environmental problem. Order of magnitude increases in surface denudation commonly result from alteration of natural vegetation communities. Degradation of the pedosphere has both on-site and off-site implications. On-site changes associated with accelerated soil erosion include depletion of soil fertility, degradation of soil structure, reduction in effective rooting depth, and dislodgment of the most basic of all natural resources (Lal, 2003). Transport of eroded material from hillslopes has received significant attention, as sediment is both a pollutant and an effective vector for contaminant transport.

The US Clean Water Act of 1972 and subsequent amendments, notably 1987, recognized the critical importance of limiting storm-water discharge and associated sediment transport from disturbed areas. In the early 1990s, developers disturbing areas ≥ 2 ha (≥ 5 acres) were subject to US Environmental Protection

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Agency permitting conditions laid out under Phase I of the National Pollutant Discharge Elimination System (NPDES). More stringent NPDES Phase II guidelines came into effect in 2003, with permits requiring best management plans (BMPs) for erosion control to be designed and implemented for disturbed areas ≥ 0.4 ha (≥ 1 acre). Over the last two decades, various forms of erosion control legislation have been enacted at the city, state, and federal levels. Thus, legislation, ominous predictions of environmental consequences, costs, and heightened environmental consciousness have driven a burgeoning erosion control industry, both in the USA and in other developed nations (Sutherland, 1998a).

The fundamental importance of vegetation cover in reducing runoff and soil erosion has been known since the pioneering works of E. Wollney in the late 1800s (Baver, 1938). Subsequent empirical studies in the 1950s by Osborn (1954) and Hudson (1957) reinforced the importance of ground cover. The application of a variety of surface mulches, primarily straw, to highway slopes (Diseker and Richardson, 1961, 1962; Barnett *et al.*, 1967; Swanson *et al.*, 1967; Dudeck *et al.*, 1970) provided the impetus to develop more effective, easier-to-apply systems that were less likely to fail.

Rolled erosion control systems (RECSs) are considered one of the most appropriate BMPs for hillslope protection (Sutherland, 1998a,b). They are designed to reduce the energetics of rainfall and runoff, and at the same time foster an equitable microclimate for subsequent vegetation growth. A plethora of RECSs, including natural and synthetic fibres, are available to the erosion control specialist.

The effectiveness of RECSs in reducing erosion has recently been documented for highways, forest roads, railway embankments and construction sites (Gyasi-Agyei *et al.*, 2001; Grace, 2002; Benik *et al.*, 2003a,b; Mitchell *et al.*, 2003; Gyasi-Agyei, 2004; Lekha, 2004). Despite the increased publication of peer-reviewed RECS research over the last 5 years, there is still a dearth of replicated, statistically designed, studies. Additionally, to date, much of the RECS research can be categorized as 'black-box' output studies, with little attention paid to runoff and erosion processes, or to the influence of the RECS's architecture on performance. The objective of this study is to compare and contrast the runoff and sediment output dynamics of two broad categories of RECS: (1) open-weave (OW) systems with systematically arranged square or rectangular apertures, and a regular grid network of natural or synthetic fibres; and (2) randomly oriented natural or synthetic fibre (ROF) systems.

METHODS

Architecture of RECSs

Nine commercially available, and commonly applied, RECSs were selected for field examination. The range of index properties (physical, hydraulic, and mechanical) for the OW and ROF architecture groups are shown in Table I. Four OWs were tested. Three were composed of natural fibres, namely jute and two bristle coir (coconut) systems, and one was a polypropylene system. Five ROF systems were tested. Three were composed of natural fibres enclosed in netting on one or two sides (mattress coir, aspen excelsior, and a composite of 70% straw and 30% mattress coir), and two were synthetic systems (polyvinyl chloride and polypropylene).

Site selection and soil preparation

The field study was conducted in central Oahu, Hawaii, at the former site of the Hawaii Sugar Planter's Experimental Station. The soil of the site is classified as a clay Molokai Oxisol (typic eutrotorrox), with 24% sand, 34% silt, and 42% clay. The dominant clay minerals were kaolinite (73%), illite (16%), and haematite (7%). Soil pH was 7.4, with an organic carbon content of 20 g kg⁻¹, a total nitrogen content of 1.6 g kg⁻¹, and a cation exchange capacity of 19 cmol kg⁻¹. The average bulk density of the upper 10 cm of soil was 1.0 Mg m⁻³. Gravimetric soil moisture content throughout the study was <10%.

The study area was repeatedly shallow tilled (≤ 10 cm) to produce a 'powdery' surface. A plot slope of $\sim 9\%$ was selected, because this is a reference gradient for many applied soil erosion studies (Wischmeier

Table I. Summary of RECS properties (adapted from Sutherland (1998a))

Architecture	Description	Physical properties ^a	Mechanical properties ^b	Hydraulic properties ^c	Additional comments ^d
OW	100% bristle coconut fibres	LT = 45.2 ± 1.7 M/A = 467 ± 7.3 T = 7.35 ± 0.63; MD = 63.5	—	SD = 1.00 ± 0.051	Maximum slope 2 : 1 Longevity 5–10 years
OW	100% bristle coconut fibres	LT = 22.6 ± 3.3 M/A = 705 ± 41 T = 7.64 ± 1.10; MD = 92.3	WTS _{MD} = 17.5 WTS _{CD} = 14.0	SD = 1.42 ± 0.12	Maximum slope ≥ 1 : 1 Longevity 5–10 years
OW	Coarsely woven open-mesh fabric of natural jute	LT = 41.7 ± 5.3 M/A = 497 ± 11 T = 1.93 ± 0.25; MD = 258	τ _{Max} = 132	SD = 3.10 ± 0.18 n = 0.0237	Maximum slope 1 : 1
OW	Perpendicular rows of polypropylene spun and tape yarns	LT = 69.2 ± 2.3 M/A = 88 ± 1.0 T = 0.76 ± 0.12; MD = 116	TS _{MD} = 0.73 TS _{CD} = 0.44	SD = 0.38 ± 0.0222 n = 0.0213	Maximum slope 2 : 1
ROF	100% coconut fibre matrix sewn between two UV-stabilized nets	LT = 6.8 ± 0.8 M/A = 273 ± 46 T = 4.68 ± 1.00; MD = 58.3	τ _{Max} = 108	SD = 0.84 ± 0.11 n = 0.014–0.022	Maximum slope ≥ 1:1, and as a channel liner
ROF	100% aspen excelsior, net one side	LT = 24.6 ± 0.8 M/A = 489 ± 74 T = 9.07 ± 1.98; MD = 53.9	—	SD = 0.94 ± 0.15 n = 0.034	Maximum slope 1.5 : 1.0
ROF	100% polypropylene fibre matrix sewn between two nets	LT = 8.6 ± 3.4 M/A = 426 ± 70 T = 4.52 ± 0.67; MD = 94.3	τ _{Max} = 96 TS _{MD} = 3.8 TS _{CD} = 3.8	SD = 0.25 ± 0.039 n = 0.020–0.024 P = 95	Maximum slope 1 : 1 and high flow channels
ROF	Non-woven randomly oriented PVC monofilaments	LT = 43.9 ± 1.5 M/A = 1260 ± 42 T = 2.74 ± 0.23; MD = 460	τ _{Max} = 240 TS _{MD} = 2.1 TS _{CD} = 1.2	SD = 0.23 ± 0.083 P = 72; n = 0.020 V _{Max} = 6.1	Permanent erosion control
ROF	70% straw + 30% mattress coir sewn between two biodegradable jute yarn nets	LT = 14.2 ± 1.6 M/A = 549 ± 23 T = 3.92 ± 0.78; MD = 140	—	SD = 2.28 ± 0.19	Maximum slope 1 : 1 Longevity 1.5 years

^a LT (%): light transmission for photosynthetically active radiation; M/A (g m⁻²): mass per area; T (mm): thickness; MD (kg m⁻³): mass density.

^b TS_{MD} (kN m⁻¹): tensile strength (dry) in the machine (length) direction; TS_{CD} (kN m⁻¹): tensile strength (dry) in the cross (width) direction; τ_{Max} (Pa): maximum permissible shear stress; WTS_{MD} (kN m⁻¹): wet tensile strength in the machine (length) direction; WTS_{CD} (kN m⁻¹): wet tensile strength in the cross (width) direction.

^c n: Manning's n; P (%): porosity; SD: sorption (water) depth; V_{Max} (m s⁻¹): maximum suggested velocity.

^d 1 : 1 slopes = horizontal:vertical (100%; 45.0°); 1.5 : 1.0 = 66.7%; 33.7°; 2.0 : 1.0 = 50.0%; 26.6°.

and Smith, 1978; Singer and Walker, 1983). A bounded side-by-side plot was constructed of wood. Plot boundaries were 20 cm high, and each subplot had similar dimensions of 4.87 m (long) \times 0.65 m (wide), for an area of 3.2 m². Soil was excavated to a depth of \sim 10 cm and the plot frame set in place. After filling with soil sieved to pass a 4 mm square-hole field sieve, the plots were manually levelled with a rake. A metal collecting trough was fixed at the outlet of each subplot to funnel flow into separate collecting bottles located in a recessed trench. The soil was excavated after each simulated event and replaced with fresh sieved soil. The lengthy preparatory process was considered necessary to reduce variability between 'storms' in measured output parameters (cf. Wendt *et al.*, 1986; Nearing *et al.*, 1999).

Rainfall simulation and application of overland flow

A computer-controlled Norton ladder-type rainfall simulator was used to apply rainfall simultaneously to each of the plots. This device is considered the standard for research involving simulated rainfall (Blanquies *et al.*, 2003). This simulator is \sim 5 m long, 2.5 m above the soil surface, and sprays a plot width $>$ 2 m. Spraying Systems Veejet 80100 nozzles are spaced 1.1 m apart and computer oscillated across the plot to generate an average rainfall intensity of 35 mm h⁻¹. Median drop size from this simulator is 2.2 mm, and it generates a kinetic energy $>$ 80% of natural rainfall. The water source for all simulations was an irrigation line with an average temperature of 26 °C, a pH of 7.8, and electrical conductivity of 94 μ S cm⁻¹.

Each experimental run was composed of two phases. Phase 1 involved the application of rainfall from a height of 2.5 m, and the second phase involved the application of flow via a 0.65 m (wide) PVC trickle overland flow applicator at the soil surface (no rainfall input). For all experiments, phase 1 lasted 110 min after the initial runoff front reached the plot outlet. Rainfall intensities were determined from measurements made on six standard (manual) rain gauges at 30 min, 60 min, and at the end of the rainfall phase. Phase 2 continued for 30 min after runoff was recorded at the plot outlet. Phase 2 flow duration was shorter, but input rate was substantially greater (\sim 114 mm h⁻¹), thereby generating greater instantaneous shear stress and effectively extending slope length. The time lag between phase 1 and 2 was \sim 0.5 h. This was necessary to calibrate the overland flow generator system. Note that, for convenience, this time lag between phases is not plotted in the figures presented in this paper.

Phase 1 runoff samples from each subplot were collected at time zero (runoff initiation) and every 5 min thereafter until 110 min, when the simulator was turned off (23 measurements per event). Phase 2 runoff samples were collected at time of runoff initiation, and at 1 min intervals to 5 min, then every 5 min thereafter until 30 min, when the overland flow applicator was shut off (11 measurements per event). Runoff samples were collected in 1 l bottles and the time to filling was recorded by stopwatch. Samples were allowed to settle for a minimum of 24 h, or until a clear supernatant was observed. Samples were subsequently decanted and the slurry transferred to a pre-weighed beaker for oven drying at 105 °C for 48 h. Samples were placed in a desiccator for a minimum of 1 h, and mass determinations made at \pm 0.001 g.

Surface treatments and experimental design

In addition to the nine RECSs examined, a bare (control) surface treatment was included. Over a 3-week period, paired bare plots were examined at the beginning of the experiment, approximately half way through, and at the end. Treatments for RECSs were randomly assigned by date and plot side (left or right); each treatment was replicated three times. During the study, 1122 measurements of runoff and sediment concentration were made: 759 during phase 1 and 363 during phase 2. Per treatment group, 204 measurements were made for the bare surface (138 for phase 1, and 66 for phase 2), 408 measurements for the OW RECSs (276 for phase 1, and 132 for phase 2), and 510 measurements for the ROF RECSs (345 for phase 1, and 165 for phase 2).

Analysis of group data (bare, OW, and ROF) for individual variables was conducted using the nonparametric Kruskal–Wallis (K–W) test at an α level of 0.05. If a significant difference was observed (i.e. $P < \alpha$), then *post hoc* testing with the nonparametric Mann–Whitney (M–W) test after 'Bonferroni adjustment' was employed

to assess differences between pairwise comparisons. The 'Bonferroni adjustment' was applied to keep the experiment-wise error rate to a specified level ($\alpha = 0.05$; 5%). This was achieved by dividing the α level by the number of pairwise comparisons, in this study three (bare versus OW, bare versus ROF, and OW versus ROF). Therefore, for any one comparison to be considered significant, the P value obtained must be less than $\alpha_{\text{critical}} = 0.0167$ (i.e. $0.05/3$), not 0.05. This adjustment decreases the chance of making a Type I error to acceptable levels.

Each system was cut to the exact dimensions of the plot, and fastened with 0.3 cm (diameter) \times 2.5 cm (wide) \times 15 cm (long) staples. The staple density exceeded all manufacturer's guidelines in order to reduce the edge effects associated with the small plots used in this study. Six staples were affixed at the top and bottom of each plot, and three rows, one along each boundary and one in the centre at 0.5 m intervals downslope (~ 12 staples per square metre). After the completion of phase 2 of each experiment, the RECSs were removed and discarded. Observations were made of the plot surface morphology before the soil was excavated.

RESULTS

Rainfall and overland flow input

The rainfall intensity and overland flow application rate applied to each of the three treatment groups (bare, OW, and ROF) were compared using the nonparametric K–W test (Table II). There were no statistically significant input differences between treatment groups at $\alpha = 0.05$, for either phase 1 ($P = 0.80$) or phase 2 ($P = 0.85$).

Runoff generation lag times

The lag time between application of rainfall (phase 1) and the arrival of runoff at the plot outlet varied significantly between treatments (K–W test $P = 0.013$). *Post hoc* testing (i.e. $\alpha_{\text{critical}} = 0.0167$) indicated that time to generate runoff on the bare surfaces was significantly faster than for the surfaces with RECSs (Table III). Typically, runoff reached the bare plot outlet after 33 min of rainfall input, some 9 min faster than the two statistically similar RECS groups.

During the application of overland flow (phase 2), runoff reached the plot outlet significantly faster for the bare treatments (K–W test $P = 0.001$) than the two RECS treatments (Table III). For the bare treatment the runoff lag was 62 s, or two times faster than that from the ROF RECSs (123 s), and 2.4 times faster than that from the OW RECSs (150 s). In terms of the initial flow velocities, the runoff wave travelled at 3.3–4.0 cm s⁻¹ from the RECS-covered plots, and at 8.0 cm s⁻¹ for the bare surfaces.

Table II. Summary of median (plus/minus median absolute deviations from the median, MAD) rainfall intensities (110 min duration) and overland flow application intensities (30 min duration)

Treatment	n^a	Rainfall intensity ^b (mm h ⁻¹)	Overland flow application intensity ^b (mm h ⁻¹)
Bare	6	33.5 \pm 3.1 ^A	114 \pm 0.4 ^A
OW	12	34.5 \pm 1.8 ^A	112 \pm 3 ^A
ROF	15	34.9 \pm 1.7 ^A	114 \pm 1 ^A

^a The bare treatment was replicated six times, four OW systems were replicated three times, and five ROF systems were replicated three times.

^b Values with the same superscript letter (column-wise) are *not* significantly different at $\alpha_{\text{adj}} = 0.0167$.

Table III. Median (\pm MAD) runoff generation lag times for the rainfall phase and overland flow application phase

Treatment	Rainfall phase lag time ^a (min)	Overland flow phase ^a	
		Lag time (s)	Velocity (cm s ⁻¹)
Bare	32.7 \pm 4.3 ^A	62.0 \pm 11.2 ^A	8.0 \pm 1.4 ^B
OW	42.1 \pm 3.2 ^B	150 \pm 24 ^B	3.3 \pm 0.5 ^A
ROF	41.7 \pm 2.9 ^B	123 \pm 30 ^B	4.0 \pm 0.8 ^a

^a Values with the same superscript letter (column-wise) are *not* significantly different at $\alpha_{\text{adj}} = 0.0167$.

Runoff coefficient

The runoff coefficient (ROC) was computed for all treatments after runoff generation occurred as

$$\text{ROC} = \frac{\text{Volume of water runoff}}{\text{Volume of water applied}} \times 100$$

A total of 34 ROCs were computed throughout an individual event (23 for phase 1 and 11 for phase 2), and an integrated ROC value was computed for the entire event.

The temporal variation in median ROCs for the three treatments for both rainfall and overland flow phases is shown in Figure 1a. Median ROCs, with associated error bars (plus/minus median absolute deviations from the median (MAD)) are plotted separately for the rainfall phase (Figure 1b) and for the overland flow applicator phase (Figure 1c). Statistical treatment summaries for the two separate experimental phases are reported in Table IV.

Two complementary levels of statistical testing were applied to the time-varying ROC data. The first was at a general level, whereby the median ROC for each time increment for a given treatment was computed and medians compared using the nonparametric Friedman test for three or more matched groups of data. *Post hoc* testing followed using the Wilcoxon test if *P* values were <0.05 during the Friedman test. When three pairwise comparisons were conducted with the Wilcoxon test, a 'Bonferroni adjustment' was applied (i.e. $\alpha_{\text{critical}} = 0.0167$) to test for differences. For both experimental phases, significant differences were noted in the time-varying median ROC values ($P \leq 0.0001$). For the rainfall phase, the general pattern indicated that the ROF systems had significantly higher ROCs than the OW RECSs or the bare treatment, with no differences between the latter two treatment groups. During phase 2, the ROC from the bare treatment was

Table IV. Median (\pm MAD) ROCs for separate experimental phases with the number of measurements per phase

Treatment	$n_{\text{Rain}}^{\text{a}}$	Rainfall phase ROC ^b (%)	n_{OF}^{c}	Overland flow phase ROC ^b (%)
Bare	138	65.1 \pm 12.1 ^A	66	91.3 \pm 3.3 ^B
OW	276	68.1 \pm 9.6 ^A	132	83.4 \pm 4.7 ^A
ROF	345	72.4 \pm 6.6 ^B	165	84.1 \pm 5.5 ^A

^a Number of measurements made during the rainfall phase (i.e. Bare, 6 replications \times 23 measurements per replication = 138; OW, 4 systems \times 3 replications per system \times 23 measurements per replication; ROF, 5 systems \times 3 replications per system \times 23 measurements per replication).

^b Values with the same superscript letter (column-wise) are *not* significantly different at $\alpha_{\text{adj}} = 0.0167$.

^c Number of measurements made during the overland flow application phase (11 per replication).

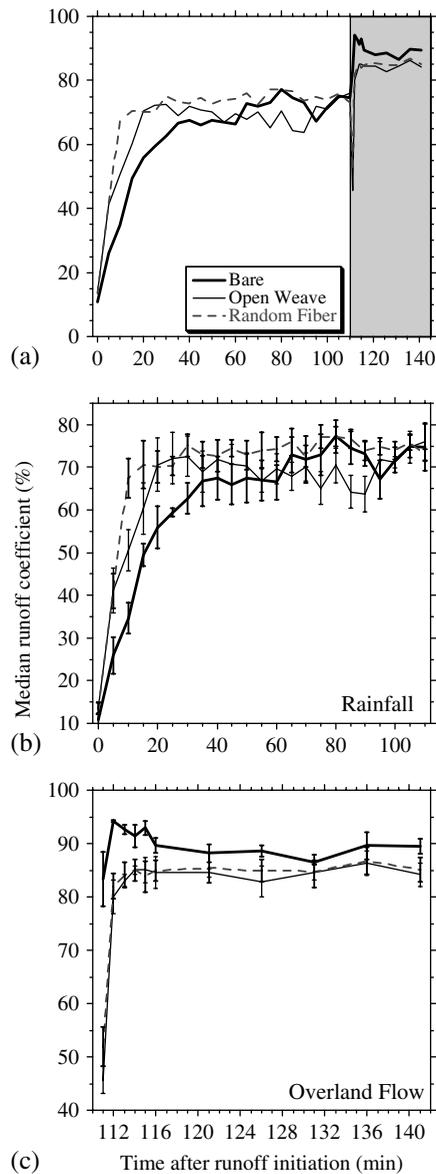


Figure 1. Temporal variation in treatment group median ROCs for all measurement periods (a), for the rainfall phase (b), and for the overland flow application phase (c). Error bars in (b) and (c) reflect plus/minus median absolute deviations from the median (MAD). The shaded area in (a) reflects phase 2 of the experiment

significantly greater than that from either the OW or ROF RECSs, and no statistical difference was observed between RECSs.

A second, more detailed level of statistical inquiry involved using all treatment data for each of the 34 measurement periods (rather than smoothing by medians). Thus, for each measurement period, there were 6, 12 and 15 data points to be analysed by the K–W test for bare, OW, and ROF treatment groups respectively. *Post hoc* testing with the M–W test was applied if necessary. For phase 1, the ROCs were statistically similar for all treatments at time 0 min, and from 35 to 110 min. For the period $0 < t \leq 30$ min, the ROC from the

bare treatment was significantly lower than that from the RECS-covered plots. During phase 2, the bare ROC was significantly greater than that from the RECSs for the first 10 min; thereafter, no statistical differences were observed.

Cumulative sediment output

The median cumulative total sediment output followed the sequence of bare > OW RECSs > ROF RECSs, in the ratio 33:6:1 (Table V). The time-varying cumulative output is shown in Figure 2. Partitioning cumulative sediment output in terms of experimental phase indicated that 60–68% of the total sediment flux was associated with the more intense overland flow application phase for bare and OW treatment groups. Only 31% of the total sediment output occurred during phase 2 from the ROF treatment group. The ratio of cumulative sediment output for phase 1 was 19:3:1 for bare:OW:ROF. During phase 2, the ratio was 63:12:1 for bare:OW:ROF.

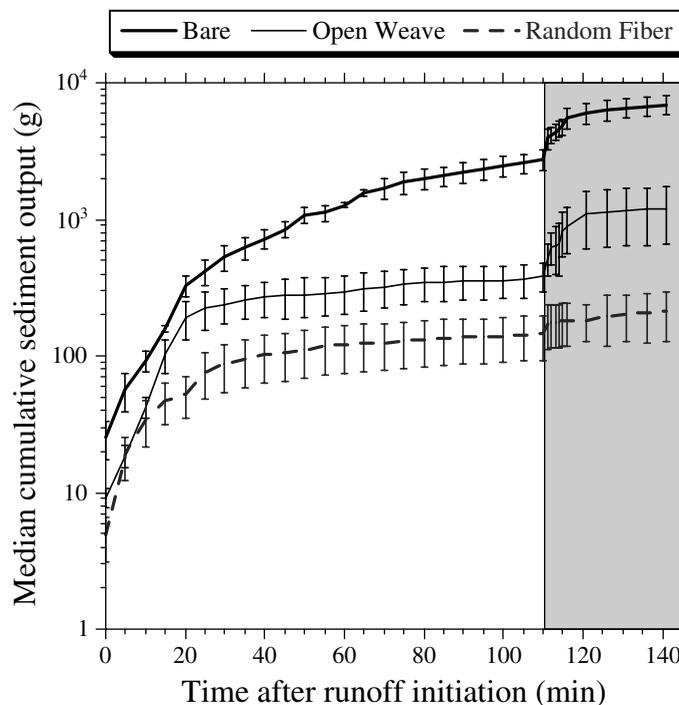


Figure 2. Temporal variation in median (\pm MAD) cumulative sediment output for bare, OW, and ROF treatments. The shaded area reflects phase 2 of the experiment

Table V. Median (\pm MAD) cumulative sediment output and phase partitioning

Treatment	Total sediment output ^a (g)	Rainfall phase proportion (%)	Overland flow phase proportion (%)
Bare	6910 \pm 1100 ^C	39.9	60.1
OW	1200 \pm 540 ^B	32.3	67.7
ROF	210 \pm 84 ^A	68.8	31.2

^a Values with the same superscript letter (column-wise) are *not* significantly different at $\alpha_{\text{adj}} = 0.0167$.

Sediment yield

Time-varying sediment yields for the treatment groups are shown in Figure 3a for both experimental phases. Figure 3b and c provides detailed representations of sediment yield variations with associated error bars for phases 1 and 2 of the experiment. Statistical testing of the time-varying median sediment yield data indicated that bare treatments exceeded OW RECSs and, in turn, sediment yield from these exceeded output from ROF RECSs for both phases (phase 1 $P < 0.0001$; phase 2 $P = 0.0033$).

Taken as a whole, all time increments by individual treatments, the median sediment yield for the bare surfaces ($583 \pm 415 \text{ g m}^{-2} \text{ h}^{-1}$) was significantly greater than that from the OW RECSs ($55 \pm 43 \text{ g m}^{-2} \text{ h}^{-1}$),

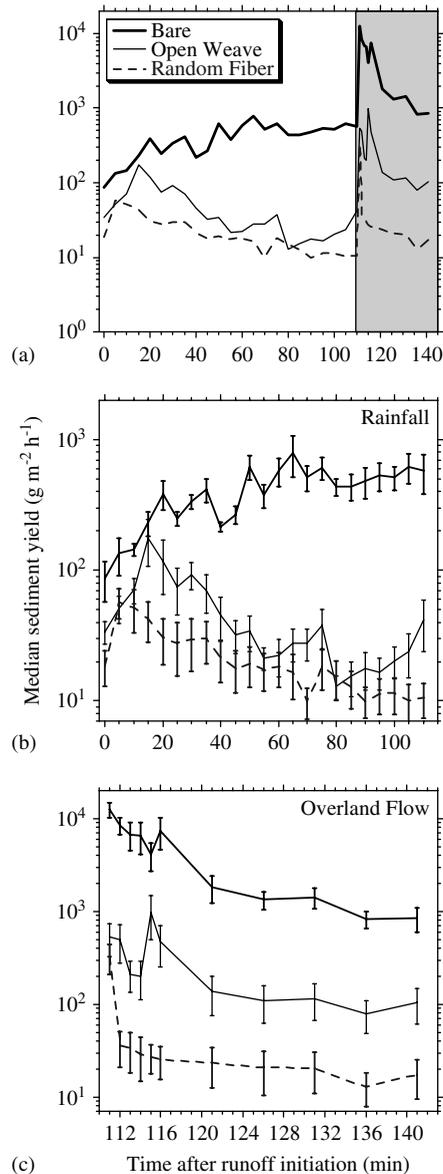


Figure 3. Temporal variation in (a) treatment group median sediment yield for all measurement periods, (b) for the rainfall phase, and (c) for the overland flow application phase. Error bars in (b) and (c) reflect \pm MAD. The shaded area in (a) reflects phase 2 of the experiment

Table VI. Median (\pm MAD) sediment yield (SY) for the entire experiment and for each of the individual phases

Treatment	n_{Σ}^a	Phase 1 + 2 SY ^b (g m ⁻² h ⁻¹)	n_{Rain}^c	Rainfall phase 1 SY ^b (g m ⁻² h ⁻¹)	n_{OF}^d	Overland flow phase 2 SY ^b (g m ⁻² h ⁻¹)
Bare	204	583 \pm 415 ^C	138	361 \pm 189 ^C	66	3780 \pm 3070 ^C
OW	408	55.2 \pm 42.7 ^B	276	36.2 \pm 25.1 ^B	132	153 \pm 140 ^B
ROF	510	22.6 \pm 18.0 ^A	345	19.3 \pm 14.5 ^A	165	35.9 \pm 33.3 ^A

^a Represents the total number of SY measurements for each treatment (i.e. Bare, 6 replications \times 34 measurements per replication = 204; OW, 4 systems \times 3 replications per system \times 34 measurements per replication; ROF, 5 systems \times 3 replications per system \times 34 measurements per replication).

^b Values with the same superscript letter (column-wise) are *not* significantly different at $\alpha_{\text{adj}} = 0.0167$.

^c Represents measurements only during the rainfall phase (23 per replication).

^d Only for the overland flow application phase (11 per replication).

and both exceeded that from the ROF RECSs (23 \pm 18 g m⁻² h⁻¹). This pattern between groups was also statistically established for each of the experimental phases (Table VI).

Sediment yield effectiveness

A common approach in the erosion control literature is to compute the effectiveness of surface treatments relative to a control treatment. We adapt the original splash detachment effectiveness equation of Osborn (1954) to compute the median sediment yield effectiveness of the RECSs:

$$\text{SY}_{\text{Effect}} = \frac{\text{SY}_{\text{Bare}} - \text{SY}_{\text{RECSs}}}{\text{SY}_{\text{Bare}}} \times 100$$

The temporal variation in $\text{SY}_{\text{Effect}}$ for the OW and ROF RECSs is given in Figure 4a, with separate plots for the rainfall phase (Figure 4b) and the overland flow application phase (Figure 4c).

Absolute differences in $\text{SY}_{\text{Effect}}$ for each measurement period for the two RECS groups are shown in Figure 5. A robust, lowess smoother (Cleveland, 1979) was fitted to the medians to examine the general time-varying relationship. A box-plot is inset to give an overall picture of the median absolute differences between ROF systems and OW systems. Numeric values inset at the top of Figure 5 represent median $\text{SY}_{\text{Effect}}$ estimates for specific time intervals during the experiment.

Relationship between runoff coefficient and sediment yield

To explore the relationship between sediment yield and ROC, bivariate plots were constructed for both experimental phases (Figure 6a and b) with separate lowess curves fit to each treatment group. A total of 759 measurements were plotted in Figure 6a, and 363 data points in Figure 6b.

DISCUSSION

Runoff

The protection offered by the RECSs significantly delayed time to runoff generation during both experimental phases compared with the bare treatment (Table II). A 9 min delay in runoff generation was observed for the rainfall phase, and greater than twofold time delays were encountered for phase 2. The extended lag time for the RECSs can be attributed to greater surface roughness, thereby decreasing flow velocity, increasing ponding volumes (i.e. detention storage), and enhancing infiltration.

Flow velocities from the RECS-covered hillslopes during phase 2 of the experiment, when surface moisture contents were near saturation following phase 1, were half those from the bare surface (i.e. 3.3–4.0 cm s⁻¹

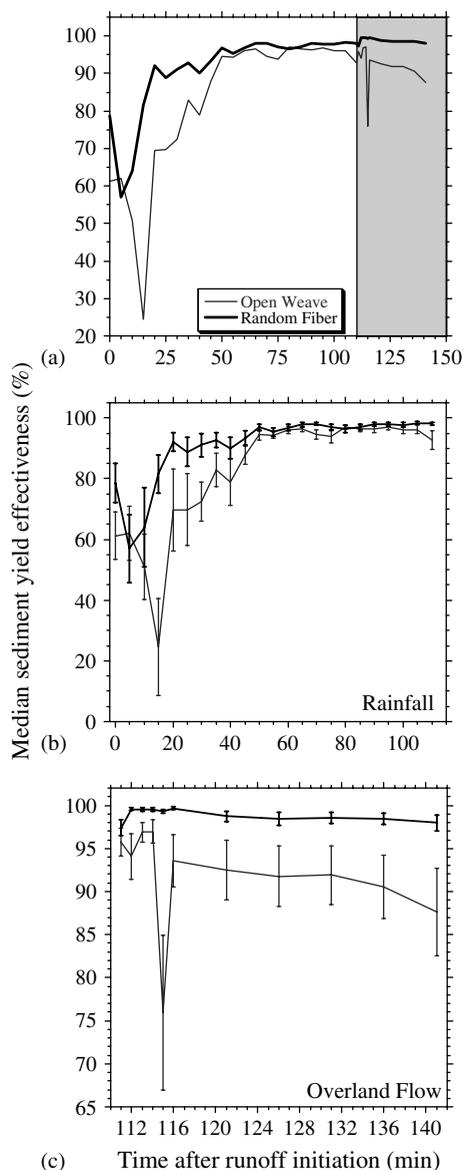


Figure 4. Temporal variation in (a) treatment group median sediment yield effectiveness for all measurement periods, (b) for the rainfall phase, and (c) for the overland flow application phase. Error bars in (b) and (c) reflect \pm MAD. The shaded area in (a) reflects phase 2 of the experiment

versus 8.0 cm s^{-1}). These flow velocities are comparable to those reported in the erosion control literature. For example, the rainfall simulation experiment of Meyer *et al.* (1970) conducted on 40 m^2 plots, with a 15% slope: flow velocities on bare to minimally straw-mulched surfaces were between 7 and 14 cm s^{-1} and decreased to 5.6 cm s^{-1} on plots with mulch at 2.24 Mg ha^{-1} . Loch and Donnollan (1988) applied rainfall to a cracking clay soil at a rate of 95 mm h^{-1} on plots 4 m (wide) \times 22.5 m (long). They found that overland flow velocities decreased from 10.3 cm s^{-1} on a minimally stubbled plot (0.1 Mg ha^{-1}) to 3.2 cm s^{-1} on plots with stubble mulch covers of 3 Mg ha^{-1} .

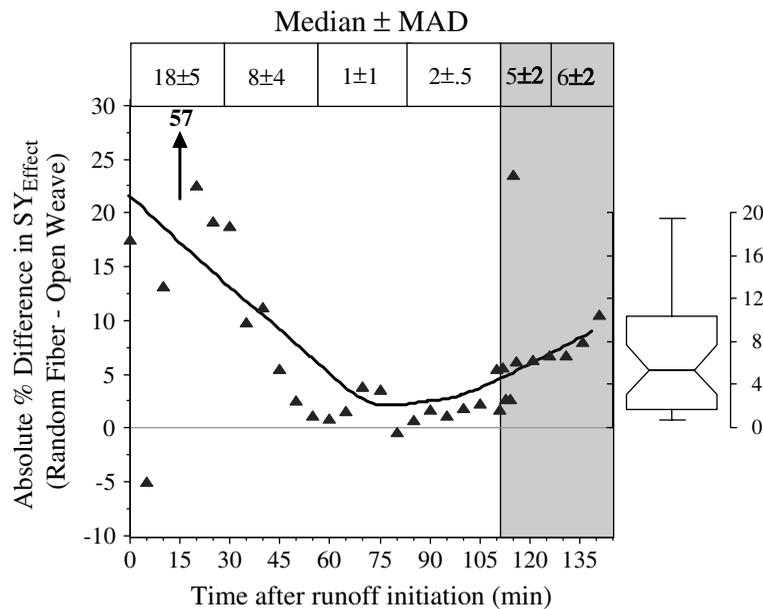


Figure 5. Variation in the absolute difference in sediment yield effectiveness between ROF systems and OW systems. The curve was fit by the lowest smoother to medians

Following the initiation of runoff, ROCs were computed for the 110 min duration of phase 1 and for the 30 min period of overland flow application (Figure 1). For the rainfall phase, the ROC for the bare treatment group was significantly lower than those for the RECSs for at least 30 min. This was somewhat unexpected, based on studies examining loose surface mulch material applied to hillslopes (e.g. Gilley *et al.*, 1986; Baumhardt and Lascano, 1996). However, there is conflicting information on the relation of runoff to contact cover in the literature. Moore *et al.* (1979) reported that increasing grass cover had little effect on reducing runoff or increasing infiltration in soils that were compact or prone to sealing. Rickson (1990) found that runoff volumes in a laboratory study of RECSs (jute, coir, polymer mesh, and excelsior systems) covering a highly erodible sandy loam soil (slope 16.7%) were not significantly different from a bare treatment. Bryan (1990) observed that the ROC was strongly influenced by rill incision through the surface crust, i.e., higher ROCs were associated with less intense rill incision and crust scouring. Therefore, we suggest that the lower ROCs from the bare treatment group reflect surface seal breakdown on the clay-rich soil, followed by rill initiation, expansion, and bifurcation. The areal disruption of the surface layer over the bare plots was greater than that from the RECSs, and this could increase infiltration into the subsurface layer and temporarily decrease runoff.

In contrast, during the overland flow application phase, the ROC for the bare treatment was significantly greater than that from the RECSs (91% versus 83–84%), with the greatest differences in the first 10 min of flow. Thereafter, ROCs were statistically comparable between treatments, though median ROCs from the bare treatments were always higher (Figure 1c). After 110 min of rainfall the surface soil was near saturation, with the interrill surface areas of the bare treatments typically smoothed due to raindrop impact and, therefore, offering little in the way of form resistance to the overland flow wave. A smooth interrill surface combined with a highly dissected and integrated rill network produced greater runoff volumes. Both groups of RECSs effectively reduced ROCs during the overland flow application phase due to fibre damming, which enhanced ponding depth; and for certain systems, fibre integration into the surface (noted following product removal at the end of the experiment) could have increased infiltration. These factors, combined with a less dissected surface and the potential to increase flow path distance via fibre channelling, resulted in reduced ROCs during phase 2 from the RECSs.

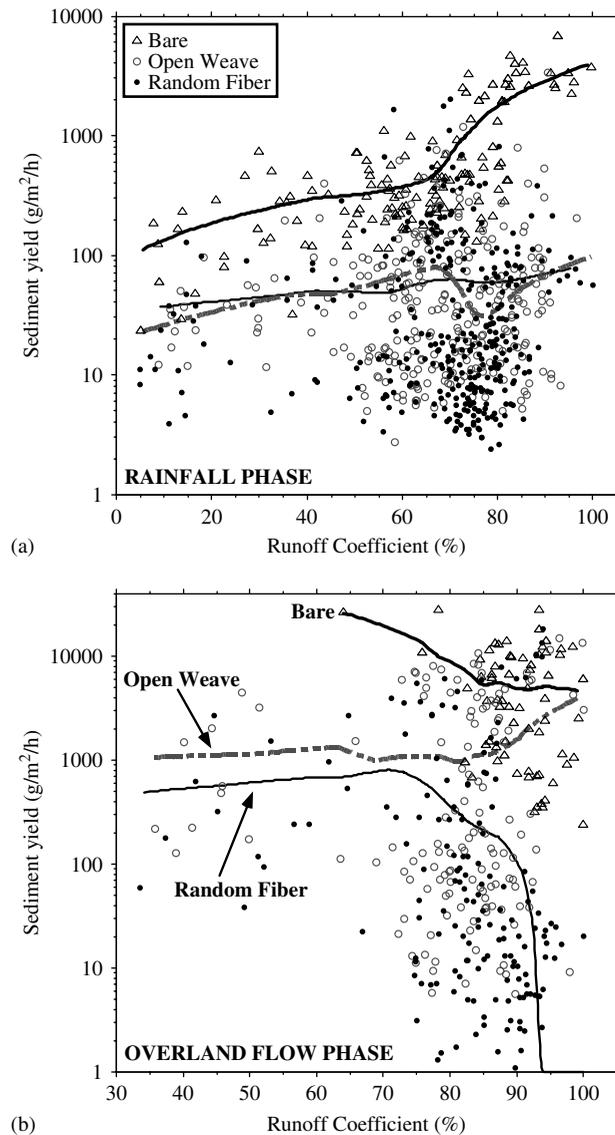


Figure 6. Sediment yield response to runoff for (a) the rainfall phase and (b) the overland flow application phase ($n = 759$). Curves for each treatment group were fit with a lowess smoother ($n = 363$)

Erosion

As expected, bare surfaces produced the greatest output of sediment during all phases of the experiment compared with the RECSs (Tables V and VI; Figures 2 and 3). The bare surface was subject to direct raindrop impact, thereby increasing the amount of sediment detached by splash processes, enhancing seal development and transport of sediment, at first by unconcentrated overland flow and then by flow in rills. The transition from interrill flow to rill incision is critical both for erosion rates and for the geomorphic evolution of hillslopes (Bryan, 2000).

During phase 1, observations indicated that rilling occurred on all bare plots within the first 20 min after runoff generation. The most common rill development scenario we observed involved the formation of one

or more knickpoints 2–3 m downslope of the upper plot boundary. Rill incision and extension downslope occurred as the flow concentrated, and upslope migration of headcuts followed suit. Small-scale mass wasting was common in headcut areas, as they tended to either bifurcate or form broad arcuate features. At the beginning of phase 2 there was significant flushing of colluvially deposited material in rill beds in the bottom third of the plot. Flushing was also coupled with an increase in rill drainage density and overall enhancement of rill capacity. The substantial increases in sediment yield during phase 2 are clearly shown in Figure 3a and c. There was a significant decay in sediment yield from bare plots after the first 10 min of overland flow application, and this response reflects flushing of loose material early in the event, increasing rill network stabilization, and potential supply limitations.

Application of a surface contact cover has been shown to be effective in reducing splash detachment and interrill and rill erosion (Duley and Russel, 1942; Osborn, 1954; Faucette *et al.*, 2004; Greene and Hairsine, 2004; Wilson *et al.*, 2004). The results from this study indicate that rolled systems are also an effective technology in reducing erosion, and for some systems they prevent the interrill–rill threshold from being crossed. The major advantage of RECSs over growth of natural vegetation on disturbed slopes is that surface protection is immediate.

In this study, RECSs were divided into two general groups based on their architecture. Though individual systems within a group were compositionally different, and their performance was not monolithic, significant differences were observed in their general group performance with respect to erosion. The ROF group of RECSs was the most effective in controlling soil erosion, with a median cumulative soil loss six times less than with the OW systems. The ROF systems were most effective under the high stress overland flow application phase. Sediment yields from the ROF systems were significantly lower for almost all time periods during the experiment (Figure 3a–c), and as a group regardless of time. This resulted in superior effectiveness in reducing erosion (Figures 4 and 5).

The link between runoff, as expressed through the ROC index, and sediment yield for phase 1 (Figure 6a) and phase 2 (Figure 6b) indicates significant differences in response, as shown by the lowess curves. For the bare treatment there was a general increase in sediment yield with ROC during the rainfall phase, particularly when ROCs were $\geq 70\%$. Sediment yields for the RECSs were less responsive to ROC increases during phase 1. The major distinction between treatments occurred during phase 2 (Figure 6b). The bare treatment displayed a general decrease in SY with increases in ROC, and this may reflect the flushing discussed earlier with movement towards a detachment-limited condition (i.e. transport from the surface is potentially faster than the rate of sediment supply). Sediment yield showed little sensitivity to ROC between 35 and 70% for ROF systems, and between 35 and 85% for OW systems. Beyond a ROC of 85% for OWs there was a steep increase in sediment yield, as rilling and flushing of redeposited sediment occurred. Sediment yield decreased substantially above an ROC of 75% for the ROF systems, and there was negligible sediment flux at the highest ROCs (i.e. $\geq 93\%$).

ROF systems were more effective in reducing erosion than the OW systems. For phase 1, ROF SY_{Effect} ($94 \pm 6\%$) was significantly greater than OW SY_{Effect} ($91 \pm 7\%$; $P = 0.004$). For phase 2, ROF SY_{Effect} was $99 \pm 1\%$, significantly greater than the $93 \pm 6\%$ for the OW systems ($P < 0.0001$).

Index property differences between rolled system groups

Weggel and Rustom (1992) argued that understanding the mechanics of the erosion process on slopes protected with various geosynthetic systems (RECSs) may foster the design of improved systems for specific applications. Sutherland *et al.* (1997) noted that splash detachment, from 166 cm² plots under rainfall simulation, was limited with rolled systems that combined high surface coverage and substantial thickness. Ziegler and Sutherland (1998), in an interrill study (0.18 m² plots), observed that cover percentage, three-dimensionality, and drapability were favourable RECS attributes in the mitigation of interrill erosion.

Although a detailed discussion of the index property differences between rolled system groups is beyond the scope of this study, some general observations can be made from our experiences. A few properties

were noteworthy in their relationship with erosion process dynamics. The design of OW systems dictates an orderly distribution of open space, i.e. square or rectangular apertures. These open areas allow direct impact of raindrops on the soil surface, which facilitates raindrop detachment and accelerates structural decay via surface sealing and aggregate slaking. The result is greater sediment availability for interrill or rill flow.

Though not all OWs are created equally, each of the individual products tested experienced substantial rilling during at least one replication. The cross-slope-oriented fibres generally delayed flow (via micro dams), with the thicker RECSs being generally more effective in reducing sediment output. However, differences in fibre stiffness, drapability, and distance between fibres affected flow hydraulics and erosion response. Stiff coir fibres, when wetted, tended to bevel between staple locations. The likelihood of separation was somewhat reduced for a heavy coir system with more closely spaced fibre strands. With the separation of the rolled system from the soil surface, the partitioning of shear stress would be affected (Abrahams and Parsons, 1994). Under such separation conditions, a greater proportion of overland flow shear stress would be borne by the grain resistance (soil grains and micro-aggregates), and less by the form and/or wave resistances. This would result in an increase in sediment output, and may lead to flow concentration and rill initiation. Allen (1996) noted that excessive fibre stiffness would prohibit a product from conforming to the surface, facilitating undesired flow channels underneath the erosion control layer. In a rigid bed flume study, the detachment of the RECS from the bed caused flow to 'pipe' between the bed and liner (Gharabaghi *et al.*, 1999). Similarly, Hytiris *et al.* (2001) documented the case of a poorly secured synthetic geomat on a flume bed detaching, and this induced increased velocity in the boundary region. In a rainfall simulation study, Krenitsky *et al.* (1998) found that an OW coir product (DeKoWe-700 similar to one of the RECSs tested in this study, i.e. 705 g m^{-2}) was less effective than a jute or excelsior system. This was because the coir fibres expanded when wetted and much of the mat pulled up from the soil surface, resulting in increased erosion.

On the whole, ROF systems were superior in their ability to reduce sediment output. Four of the five systems tested had individual fibres that could potentially integrate with the surface soil. When removing the systems after phase 2, the degree of resistance was associated with fibre integration. The PVC ROF system had 'welded' fibres; therefore, there was no linkage developed with the surface soil. The 70% straw + 30% coir blend showed poor integration, particularly for the larger diameter straw fibres. The remaining systems, i.e. mattress coir, aspen excelsior, and synthetic polypropylene, displayed significant integration with the soil surface. The PVC and 70% straw + 30% coir systems were the poorest performers in terms of reducing sediment output and degree of rill formation. Thus, there seems to be a connection between fibre integration and erosion performance. We suggest that, with fibre contact, flow resistance is maintained and boundary detachment is less likely. Shear stress will be dissipated on the form rather than on the grain, decreasing detachment potential and reducing flow transport capacity. Additionally, the fibre surface bonding will effectively lengthen the overland flow path, thereby decreasing the energy grade and reducing shear stress.

CONCLUSIONS

A replicated field experiment with separate simulated rainfall and overland flow application phases provided the necessary data for a statistical examination of the differences in runoff response and erosion process dynamics between a bare treatment and two architecturally distinct groups of surface covering. Runoff occurred more quickly on the bare treatments during both the rainfall and overland flow phases. RECSs delayed the generation of runoff by maintaining structural surface integrity, and offering greater form and/or wave resistance via the ability of individual fibres to enhance infiltration, form micro dams and lengthen overland flow paths. During the rainfall application phase (i.e. phase 1 at 35 mm h^{-1}), after runoff started, the ROCs from the bare treatments were significantly lower than those from both groups of RECSs. Though somewhat unexpected, it is likely that increased rilling during the rainfall phase facilitated clay seal destruction and enhanced infiltration into the subsurface. During the overland flow application phase, ROCs were significantly higher from the bare surface, and this was due to a better integrated rill network with smoothed interrill

contributing areas. The roughness of the RECS-covered surfaces and a more poorly developed rill network would reduce runoff.

Regardless of RECS applied, all reduced sediment output significantly compared with the bare treatment. However, performance was not consistent within RECS treatment groups or between groups. The ROF group proved superior to OW systems in mitigating erosion, particularly under the high stress conditions associated with application of overland flow. Median sediment yield effectiveness for the ROF RECSs during this phase was 99%, compared with a significantly lower value of 93% for the OW RECSs. Additionally, the frequency of rilling and magnitude of rill incision were generally lower on average from the ROF RECSs, particularly for those systems that had significant fibre integration into the clay soil surface. Further exploration could link salient index properties of the best-performing RECSs examined in this study with erosion processes.

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