Effectiveness of coir-based rolled erosion control systems in reducing sediment transport from hillslopes

Ross A. Sutherland*, Alan D. Ziegler

Geomorphology Laboratory, Department of Geography, University of Hawaii, 2424 Maile Way, Honolulu, HI 96822-2223, USA

Abstract

Accelerated soil erosion is ubiquitous on human-modified hillslopes. A variety of erosion control products have been developed to reduce on-site soil resource degradation, and off-site transport of sediment and sediment-associated contaminants to receiving water bodies. However, limited quantitative data are available to assess erosion reduction effectiveness, and to establish the salient properties of the erosion control products. A replicated field-based rainfall simulation study was conducted to compare the runoff and erosion effectiveness of three coir (coconut) fiber rolled erosion control systems (RECSs) with a bare (control) treatment. Detailed temporal measurements of runoff and sediment transport were made during two phases of each experiment: (1) a 110-min application of rainfall via a rainfall simulator at $35\,mm\,h^{-1}$ after runoff initiation and (2) a 30-min period, at 3 times the flow rate of phase 1, applied via an overland flow generator. All coir treatments enhanced infiltration, delayed time to runoff generation, reduced intensity of rill incision, and reduced sediment output compared to bare treatments. More importantly, statistically significant differences were observed between coir RECSs of different architecture. For the two open weave coir systems tested, the most effective design had a higher mass per area, and less open space between the regularly aligned grid of fibers. The random fiber coir architecture was the most effective, having significantly lower runoff sediment concentrations, lower sediment yields, and a lower frequency of rill initiation. The differences in system architecture are examined in light of fundamental controls on runoff and erosion processes.

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*Corresponding author.
E-mail address: Sutherla@Hawaii.edu (R.A. Sutherland).

Introduction

Human modification of the landscape commonly results in accelerated erosion and concomitant environmental degradation. On-site and off-site impacts associated with erosion are estimated to cost approximately 44×10^9 per year in USA alone (Shepley, Smith, & Jackson, 2002). Today, environmental and economic costs associated with accelerated erosion are not considered acceptable. In many developed countries, a vibrant erosion control industry (ECI) has formed to mitigate erosion on slopes modified by construction activities, road, and highway building (Sutherland, 1998b).

Erosion control specialists, construction site engineers and landscape architects have a number of 'tools' at their disposal to keep soil on site. These erosion and sediment control practitioners are required to identify the most appropriate and cost-effective best management practices (BMPs) for their erosion control plan. For immediate surface protection, the most commonly used non-structural BMPs on construction site slopes include straw bale barriers, silt fences, loose organic mulches, rolled erosion control systems (RECSs), hydraulically applied hydro-mulches, and dust suppressants (Raskin, DePaoli, & Singer, 2005; Sutherland, 1998b; USEPA, 1995).

Research has shown that RECSs (also known as 'geotextiles' in UK) are one of the most appropriate BMPs for hillslope protection (Hann & Morgan, 2006; Nelsen, 2003; Sutherland, 1998b). A wide variety of RECSs are manufactured to capitalize on a multi-million dollar market. Rolled systems can be grouped into those composed of natural fibers with life spans ranging from 0.5 to 6 years (temporary), or synthetic fibers that are considered permanent fixtures. Natural fiber RECSs include jute, coir (coconut), excelsior (wood strands), and straw. Application of RECSs usually occurs on bare slopes after broadcasting a rapidly germinating seed mixture for long-term erosion protection. Natural fiber systems are increasingly favored, as they are biodegradable, less costly to produce and to apply, environmentally friendly, equally effective in reducing erosion, and generally provide a favorable microclimate for biomass production (Sutherland, 1998b, c; Sutherland, Menard, & Perry 1998; Sutherland, Menard, Perry, & Penn, 1998). Coir, for example, has been increasingly applied to human-modified hillslopes. Several recent studies have found coir RECSs effective in reducing erosion from degraded hillslopes (Lekha, 2004), highway embankments (Benik, Wilson, Biesboer, Hansen, & Stenlund, 2003), railway embankments (Gyasi-Agyei, 2004), and from slopes similar to construction sites (Krenitsky, Carroll, Hill, & Krouse, 1998). Most published studies, however, have failed to examine the detailed temporal response of the systems under stress, and have overlooked links between system properties (e.g., fiber geometry) and basic physical erosion processes (e.g., splash, wash, and rill erosion). As Thompson (2001) states, "long-term progress in selecting erosion control measures can best be made by obtaining a better understanding of the interactions of the control measure and fundamental erosion principles".

Land managers, department of transportation personnel, and erosion consultants are faced with a wide variety of RECSs to choose from, but little rigorous quantitative data for optimal decision making. Even for a given natural fiber there may be several design architectures, each with unique cardinal properties (i.e., physical, chemical, and hydraulic). Coir RECSs have two common architectures. The first is a randomly oriented set of loose fibers stitched with thread between two nets. This type typically has a low mass per unit area (200–300 g m^{-2}), and limited open space between fibers (<10%). The second type of

coir system is an open weave architecture with spun coir forming an interlocking grid with significant open space. Open weave systems have higher mass per unit area compared to the random fiber architecture, with values at the low end ranging from 350 to 500 g m^{-2}; at the upper end 700–900 g m^{-2}. Open space between the grid of fibers ranges from 30% to 40% for high mass per area systems, to 50–80% for the lower mass per area systems (cf. Sutherland, 1998b).

The primary objectives of this study are to quantify the hydraulic and erosion response of various coir systems to different flow stress levels; and to link basic erosion processes with specific system design criteria. To vary flow stress levels, we applied rainfall with a field-based rainfall simulator, followed by overland flow with an overland flow generator on bare surface treatments and coir protected slopes.

Materials and methods

Treatments, site selection, and soil preparation

Three commercially available, and widely applied, coir RECSs were selected for this study. Two architectures were examined, a random fiber coir (RFC) system (Fig. 1), and an open weave coir (OWC) system (Figs. 2 and 3). We examined two open weave products, manufactured by the same company, differing in mass per unit area and degree of open space. The open weave system with the lowest mass per unit area (and greatest proportion

Fig. 1. Random fiber coir (RFC) rolled erosion control system used in this study (photograph by Laura Sutherland).

Fig. 2. Open weave coir system with 'low' mass per unit area and 'low' surface cover (OWCL) (photograph by Laura Sutherland).

Fig. 3. Open weave coir system with 'high' mass per unit area and 'high' surface cover (OWCH) (photograph by Laura Sutherland).

of open space) is designated as OWCL (Fig. 2); the system with a higher mass per area, OWCH (Fig. 3).

The field study was conducted in central Oahu, Hawaii, at the former site of the Hawaii Sugar Planter's Experimental Station (HSPES). The soil is a clay Molokai oxisol (Typic Eutrotorrox), with 24% sand, 34% silt, and 42% clay. The soil has a pH of 7.4, organic carbon content of $20\,\text{g}\,\text{kg}^{-1}$, and a total nitrogen content of $1.6\,\text{g}\,\text{kg}^{-1}$. The cation exchange capacity is $19\,\text{cmol}_c\,\text{kg}^{-1}$. Kaolinite (73%), illite (16%), and hematite (7%) are the dominant mineral components of the clay fraction. The mean bulk density of the upper 10 cm of soil is $1.0\,\text{Mg}\,\text{m}^{-3}$. Antecedent moisture content during the experiment was 9–10%.

The study area was repeatedly shallow tilled ($\leqslant 10\,\text{cm}$) by the staff of the HSPES to produce a "powdery" surface overlying a low permeability layer at depth. This site treatment was considered necessary to produce an erodible environment that would favor surface (Hortonian) runoff generation and rill development on plot slopes of 9%.

A bounded side-by-side plot frame was constructed of wood. Boundaries were 20 cm high, and the two subplots had similar dimensions of $4.87\,\text{m}\,(L) \times 0.65\,\text{m}\,(W)$, producing a subplot area of $3.2\,\text{m}^2$. Soil was excavated from an area of about $6.4\,\text{m}^2$ to a depth of 10 cm, coincident with the low permeability layer, and the plot frame set in place. The subplots were filled with soil sieved to pass a 4-mm square-hole field sieve to a depth of 10 cm and manually leveled with a rake. The frame boundaries were approximately 10 cm above the reformed soil surface. A metal collecting trough was fixed at the outlet of each subplot. These troughs funneled flow into separate collecting bottles located in a recessed trench. After each simulated event, the soil was excavated and replaced with fresh sieved soil. This approach is unique to field simulation studies. The lengthy preparatory process was considered necessary to reduce the confounding effects of different soil moisture conditions, aggregate strengths, and sediment availability between runs.

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 subplots. This device is considered the standard for research involving simulated rainfall (Blanquies, Scharff, & Hallock, 2003). This simulator is approximately 5 m long, 2.5 m above the soil surface, and sprays a plot width $>2\,\text{m}$. Spraying Systems Veejet 80100 nozzles are spaced at 1.1 m apart and oscillated across the plot to generate an average rainfall intensity of $35\,\text{mm}\,\text{h}^{-1}$ (equivalent to about $110\,\text{l}\,\text{h}^{-1}$). 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 water temperature of $26\,^\circ\text{C}$, a pH of 7.8, and electrical conductivity of $94\,\mu\text{S}\,\text{cm}^{-1}$ at $25\,^\circ\text{C}$.

Each experimental run consisted of two phases. Phase 1 involved the application of simulated rainfall from a height of 2.5 m; the second, application of surface flow via a $0.65\,\text{m}\,(W)$ 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 subplot outlet. Rainfall intensities were determined from measurements made with six standard (manual) rain gauges at 30, 60 min, and at the end of the rainfall phase. Phase 2 continued for 30 min after runoff was recorded at the subplot outlet. Although phase 2 flow duration was shorter than phase 1, input volumes were substantially greater ($360\,\text{l}\,\text{h}^{-1}$), thus generating a greater instantaneous shear stress. The time lag between phase 1 and 2 was

approximately 0.5 h. This was necessary to calibrate the volume of overland flow from the runoff generator. Note that the time lag between phases is not plotted in the figures presented in this paper for convenience.

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. Phase 2 runoff samples were collected at time of runoff initiation, and at 1 min intervals to 5 min, and every 5 min thereafter until 30 min when the overland flow applicator was shut off. Runoff samples were collected in 1-l bottles, and 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 beaker for oven drying at 105 °C for 48 h. Following drying, samples were placed in a desiccator for 1 h, and mass determinations made at ±0.001 g. During each phase, field assistants made extensive observations of the state of each of the subplots, including assessment of surface beveling of the RECSs.

Hillslope surface treatments

In addition to the three coir treatments, a bare surface treatment was examined. Over a 3-week period, the bare treatment was replicated 6 times and each of the RECSs 3 times. Subplot treatments were randomly assigned. Salient properties of coir systems are listed in Table 1. Each rolled system was cut to the exact size of the subplot, and fastened to the soil surface with 15-cm U-shaped staples. Staples were inserted at 0.5 m intervals along each length-wise boundary and down the center of subplots. To reduce edge effects, staple density exceeded manufacturer guidelines. After the completion of phase 2 of each experiment, the RECSs were removed and discarded. Observations were made of the subplot surface morphology before the soil was excavated.

Table 1
Summary of cardinal properties of coir-based rolled erosion control systems

Property	Units	OWCL[a]	OWCH[b]	RFC[c]
Thickness	mm	7.4	7.6	5.0
Mass/area	$g\,m^{-2}$	470	710	270
Light transmission	%	45	23	7
Functional longevity	Year	4–6	4–6	3
Machine direction tensile strength (dry)	$kN\,m^{-1}$	11.4	25.4	3.12
Transverse direction tensile strength (dry)	$kN\,m^{-1}$	10.9	17.2	3.05
Recommended slope		2:1	>1:1	1:1
Permissible shear stress	Pa	145	215	108

[a]OWCL is an open weave coir system of relatively low mass per area. This product is woven from machine-spun bristle coir twines, and has openings of 1.9×1.9 cm ($3.6\,cm^2$).

[b]OWCH is an open weave coir system of relatively high mass per area. This product is woven from machine-spun bristle coir twines, and has openings of 1.3×1.3 cm ($1.6\,cm^2$).

[c]RFC is a random fiber coir system stitched with degradable thread between two UV stabilized polypropylene nettings.

Results

Water input and runoff generation

Rainfall application did not differ significantly between treatments ($\alpha = 0.05$). The overall mean rainfall intensity was $35 \pm 3 \, \text{mm h}^{-1}$ (± 1 standard deviation), with the bare treatment = $34 \pm 4 \, \text{mm h}^{-1}$; OWCL = $35 \pm 1 \, \text{mm h}^{-1}$; OWCH = $36 \pm 2 \, \text{mm h}^{-1}$; and RFC = $36 \pm 2 \, \text{mm h}^{-1}$.

During phase 1, the time required to initiate runoff differed significantly ($\alpha = 0.05$) between treatments (Kruskal–Wallis test followed by *post hoc* testing). The bare treatments were the first to generate runoff, with an average time of $33 \pm 4 \, \text{min}$. Runoff generation was significantly delayed on the coir RECSs, but no statistical differences were observed between RECSs. On average, runoff reached the plot outlet 7 min later for OWCL-treated slopes ($40 \pm 3 \, \text{min}$), 9 min later for OWCH ($42 \pm 4 \, \text{min}$), and 11 min later for RFC ($44 \pm 4 \, \text{min}$).

At the beginning of phase 2, the overland flow applicator phase, travel time of the leading edge of flow was measured over a distance of 4.87 m. Mean flow velocity for the leading edge of the initial overland flow wave was significantly faster for the bare treatments ($9.6 \pm 3.8 \, \text{cm s}^{-1}$) compared to the RECSs. No significant differences were noted between RECSs, with leading edge velocities of $2.9 \pm 0.4 \, \text{cm s}^{-1}$ for RFC, $3.0 \pm 0.4 \, \text{cm s}^{-1}$ for OWCH, and $3.5 \pm 0.9 \, \text{cm s}^{-1}$ for OWCL.

Time to runoff for both phases of the experiment were significantly longer for the RECS treatments. However, if discharge is examined only for the 140 min period of runoff (ignoring the initial lag differences between bare and RECSs), there were no statistical differences between treatments. The temporal variation in runoff rates for the RECSs is shown in Fig. 4, in which the bare treatment is excluded for clarity, as there is significant overlap at this scale. Though differences were not significant, runoff coefficients (ROC = [volume of runoff/volume of input]100) were lower for the RECSs, with the sequence: OWCH ($65 \pm 16\%$) < OWCL ($69 \pm 15\%$) < RFC ($72 \pm 13\%$) < bare ($77 \pm 19\%$).

Sediment concentration

The temporal variation in sediment concentration for each of the treatments is shown in Fig. 5. The nonparametric Friedman test (followed by *post hoc* testing) was applied to medians as sediment concentration data were not normally distributed. Data for both experimental phases are shown in Table 2, with statistically significant differences between treatments noted. Treatment ordering, from the highest to lowest sediment concentration, was bare > OWCL > OWCH > RFC. Median concentrations for the RFC treatment were approximately two or three orders of magnitude lower than those for the bare treatment for phase 1 and phase 2, respectively. Concentrations for RFC and OWCH treatments were one-to-two orders of magnitude lower than those for the OWCL-treated slopes. Peak concentrations typically occurred for all treatments during the first flush of runoff, with substantial increases associated with the application of overland flow during phase 2. Peaks in sediment concentration were coherent with visual estimates of the onset of rill initiation on bare treatments. Sediment concentration peaks for RECS treatments were assumed to be associated with rill formation below the RECSs, but visualization was not practical during an event.
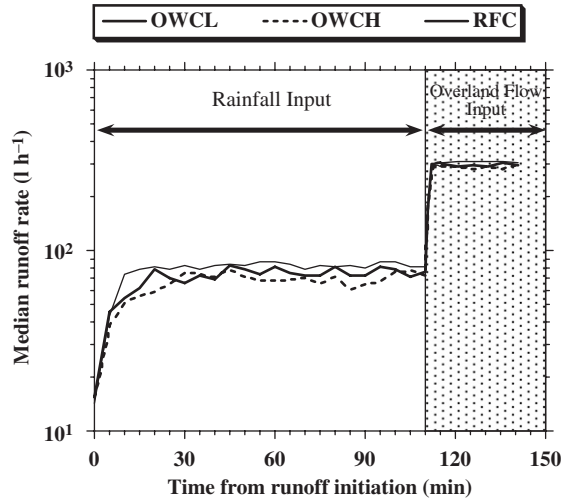
Fig. 4. Temporal variation in runoff rate for 110 min of simulated rainfall at 35 mm h^{-1} or 110 l h^{-1} (phase 1), and 30 min of overland flow at 360 l h^{-1} (phase 2) for three coir fiber rolled erosion control systems. OWCL represents an open weave architecture with a low mass per unit area; OWCH represents a relatively high mass per area open weave system; and RFC is a random fiber coir system stitched and held between two nets.
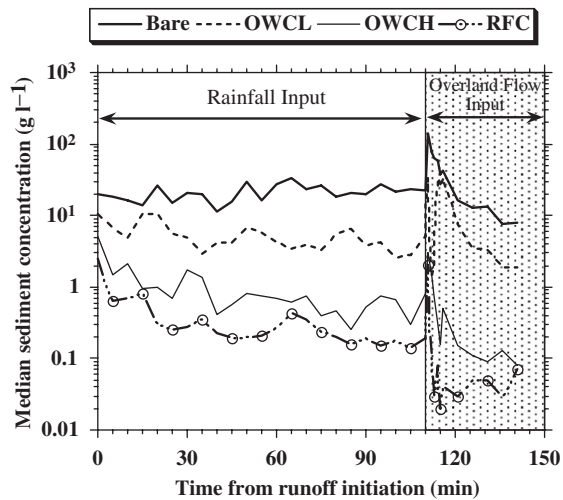

Fig. 5. Temporal variation in runoff sediment concentration for a bare treatment, and three coir fiber rolled erosion control systems.

Sediment output

Temporal variations in sediment yield from the treatments are illustrated in Fig. 6. Statistical testing indicated significant differences between treatments during the separate phases of the experiment (Table 3). The ordering sequence of treatment response was identical to that for sediment concentration. Yields were lowest from the RFC treatment,

Table 2
Runoff sediment concentrations from 3.2 m² plots on a 9% hillslope

Treatment[1]	Sediment concentration (g l^{-1}) rainfall phase[2]	Sediment concentration (g l^{-1}) overland flow phase
RFC	0.24 ± 0.06^{a3}	0.05 ± 0.02^{a}
OWCH	0.74 ± 0.21^{b}	0.16 ± 0.08^{b}
OWCL	4.8 ± 1.0^{c}	3.6 ± 2.1^{c}
Bare	20.9 ± 4.6^{d}	38.0 ± 25.1^{d}

[1]RFC is a random fiber coir system; OWCH is an open weave, high mass per area coir system; OWCL is an open weave, low mass per area coir system; and bare is the control treatment.

[2]Median values are reported with ± median absolute deviations from the median (MAD) for three replications of coir treatments, and six for the bare control.

[3]Values with the same letter (column-wise) are not significantly different at $\alpha = 0.05$.
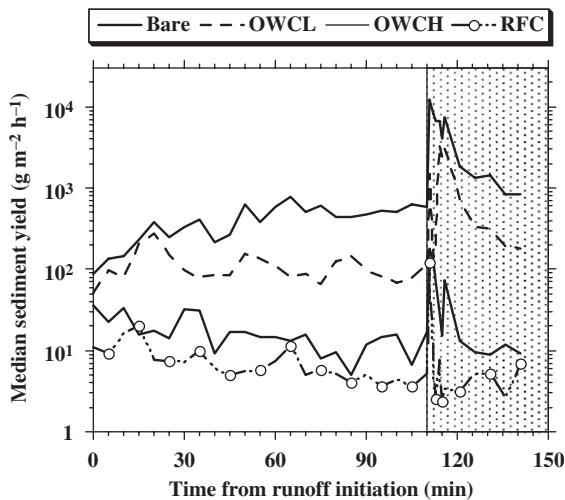

Fig. 6. Temporal variation in sediment yield for a bare treatment, and three coir fiber rolled erosion control systems.

Table 3
Sediment yield from 3.2 m² plots on a 9% hillslope

Treatment[1]	Sediment yield (g m^{-2} h^{-1}) rainfall phase[2]	Sediment yield (g m^{-2} h^{-1}) overland flow phase
RFC	5.8 ± 1.7^{a3}	5.3 ± 2.4^{a}
OWCH	15.9 ± 2.9^{b}	15.3 ± 6.4^{b}
OWCL	96.8 ± 17.5^{c}	333 ± 195^{c}
Bare	434 ± 144^{d}	4080 ± 2750^{d}

[1]RFC is a random fiber coir system; OWCH is an open weave, high mass per area coir system; OWCL is an open weave, low mass per area coir system; and bare is the control treatment.

[2]Median values are reported with ± median absolute deviations from the median (MAD) for three replications of coir treatments, and six for the bare control.

[3]Values with the same letter (column-wise) are not significantly different at $\alpha = 0.05$.
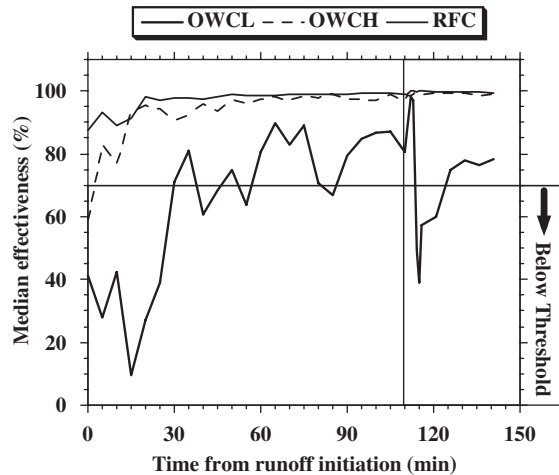
Fig. 7. Erosion effectiveness for three coir fiber rolled erosion control systems for two phases of flow (rainfall, 110 min duration of runoff at $110 \, l \, h^{-1}$; and overland flow application at $360 \, l \, h^{-1}$ for 30 min).

and were typically two or three orders of magnitude lower than those from the bare treatment. Sediment transport during the 30-min overland flow application phase was more variable than during the rainfall application phase. Coefficients of median variation ([median absolute deviation from the median/median]100) for phase 2 sediment yields were 1.6–3.2 times greater than that during phase 1. Median sediment yields for the RFC and OWCH treatments were similar between phases, despite over 3 times the rate of flow applied during phase 2. In contrast, sediment yield for the OWCL treatment increased by about 3 times, while the bare treatment exhibited a 10-fold increase in sediment output.

Sutherland (1998a) defined an index of erosional effectiveness for RECS as: [(bare sediment yield−RECS sediment yield)/bare sediment yield]100. Here we use an erosion effectiveness threshold value of 70% to distinguish between acceptable and non-acceptable performance.

The temporal variation in erosional effectiveness values for the three RECSs are shown in Fig. 7, and a detailed statistical summary appears in Table 4. At no time during the experiment did the effectiveness of RFC-treated slopes fall below the 70% threshold; only during the first flush of phase 1 did the effectiveness of OWCH fall below 70% (59%). In contrast, the OWCL-treated slopes had a minimum erosional effectiveness value of 10%. Effectiveness was below the 70% threshold for OWCL-covered slopes during the first 25 min of phase 1, and for a total of 45 min out of 110 min (41% of the time). During phase 2, effectiveness was below the threshold for 8 min during the 30 min of overland flow. Despite significant periods below the threshold, the overall OWCL median effectiveness for all phases of flow was $75 \pm 12\%$.

Discussion

Runoff generation and overland flow leading edge velocity

The coir RECSs significantly delayed the time to runoff generation and enhanced infiltration during the early portion of the rainfall phase compared to the bare surface

Table 4
Statistical summary of the effectiveness of three coir-based RECSs in reducing sediment output from 3.2 m^2 plots over a period of 110 min of rainfall, and 30 min of overland flow application

Statistical property[a]	OWCL$_{RF}$ (%)[b]	OWCL$_{OF}$ (%)	OWCH$_{RF}$ (%)	OWCH$_{OF}$ (%)	RFC$_{RF}$ (%)	RFC$_{OF}$ (%)
Median	71.2	76.5	96.9	99.0	98.5	99.8
MAD	11.8	16.5	1.5	0.4	0.5	0.1
Minimum	9.5	39.1	58.9	98.4	87.3	99.0
Maximum	89.7	98.4	98.9	99.6	99.4	100
10th	27.7	45.2	81.7	98.5	90.9	99.1
25th	47.1	58.0	93.3	98.7	97.3	99.6
75th	82.4	85.6	97.5	99.4	99.1	99.9
90th	87.6	97.5	98.7	99.6	99.2	100

[a]MAD represents the median absolute deviation from the median; 10, 25, 75, and 90 are percentiles of the distribution.
[b]OWCL is an open weave, low mass per area coir system; OWCH is an open weave, high mass per area coir system; and RFC is a random fiber coir system. RF represents the 110-min phase of simulated rainfall at 35 mm h^{-1} (equivalent to 110 l h^{-1}), and OF represents the 30-min phase of overland flow applied at 360 l h^{-1} by a runoff generator.

treatment. Enhanced infiltration below RECS-treated slopes reflects the lower probability of raindrops directly impinging on the soil surface, and causing aggregate disintegration. Therefore, this would help to maintain a stable hydraulic interface. Once runoff was initiated on all treatments there were no significant differences between runoff coefficients—although absolute values were lower on the coir treatments (between 5% and 12%). To some degree, lack of a statistical difference between treatments reflects data variability, and the confounding influence of a low permeability soil layer at a shallow depth.

During the initial application of overland flow during phase 2, the RECSs significantly retarded the leading edge flow velocities by approximately one-third (2.9–3.5 cm s^{-1}) compared to the bare treatment (9.6 cm s^{-1}). This was expected as surface cover, natural or artificial, provides surface roughness, which directly impacts sediment transport relationships. For example, flow competence (maximum particle size moved) and transport capacity (amount of sediment moved) would be significantly reduced on surfaces with a higher random roughness index. Meyer and Wischmeier (1969) suggested that the transporting capacity of overland flow varies with the fifth power of velocity. Additionally, the application of RECSs alters the shear stress partitioning of overland flow at the hillslope surface (Thompson, 2001). For a bare surface, flow shear stress acts directly on the soil surface, i.e., grain or effective shear stress. When roughness elements are present, rocks, vegetation, or RECSs, shear stress is partitioned between grain and form shear stress, with the later developing from pressure imbalances between upslope and downslope portions of the roughness elements (Léonard & Richard, 2004). An increase in form shear stress contributes to a decrease in leading edge flow velocity observed in phase 2.

Sediment output

Site preparation produced an erodible environment for testing of RECSs under different stress conditions. The application of RECSs to the hillslope significantly decreased

sediment concentrations (Fig. 5) and sediment yields (Fig. 6) compared to bare treatments for all phases of the experiment. For the bare treatment, sediment concentration remained consistently high throughout the rainfall phase, with pulses reflecting extensive rill development by headward migration and incision. With an increase in flow energy from phase 1 to phase 2, sediment concentration from the bare treatments increased by an order of magnitude. This flushing was followed by a general decrease as sediment availability became limited. Sediment concentrations from coir-treated hillslopes generally decreased with time during the rainfall phase, particularly for OWCH and RFC treatments. Application of overland flow to the RECSs during phase 2 increased sediment concentrations by one-to-two orders of magnitude, but they quickly decreased to levels below those at the end of the rainfall phase, especially for OWCH and RFC.

The three coir RECSs showed significant differences in sediment concentration and rate of sediment output. The open weave system with the lowest mass per unit area was the least effective in limiting sediment concentrations or yields. Visual observations of plots after individual experiments indicated that all replicates of the OWCL-treated slope were extensively rilled—second only to the bare treatment. Only one of the three OWCH treatments developed rills, but these were discontinuous and failed to develop an integrated network. Rilling was negligible on all RFC-treated slopes. The formation of rills marks an important erosion threshold, that is, the transition from dispersed interrill flow to channelized flow. The importance of rills has a long history dating to Horton's (1945) conceptualization of drainage network development based on initiation of rills and system expansion by headward extension, micropiracy, and cross-grading. Ideally, an effective erosion control system should prevent the transition from an interrill (splash and wash) dominated transport surface to an incised rill dominated transport surface, even during high magnitude storm events. Given the sediment concentration data, sediment yield data, and observations on rill network patterns, the performance ranking of treatments was RFC > OWCH > OWCL > bare.

Links between RECS design and runoff and erosion processes

The data in this study shed light on the important RECS design properties that are associated with enhancing infiltration, delaying time to runoff initiation, decreasing leading edge flow velocity, reducing the likelihood of rill initiation, lowering sediment concentrations, and decreasing sediment yield. The OWC systems were both manufactured by the same company, but differed primarily in their degree of open space and their mass per unit area. The low-density OWCL system exposed more soil directly to rainfall impact thus making more detached sediment available to the runoff stream. The lower mass of OWCL system was likely a major reason for the observed increase in frequency of beveling compared to OWCH. Beveling is an important RECS-associated process, because as the degree of beveling increases the contact area between the RECS and the soil surface is reduced. With decreased surface contact, the potential for flow concentration and rill initiation increases beneath RECSs. Therefore, both reduced open area and a higher mass per unit area are favorable design properties for an open weave architecture. A future goal of open weave RECS design would be to achieve an optimal balance of these salient physical properties with biomass production.

Contrasting the open weave architecture of OWCH with the random fiber system indicated statistically lower sediment concentrations and sediment outputs from RFC

treatments (Tables 2 and 3). Additionally, the erosion effectiveness of RFC-treated slopes were superior to those covered by OWCH (Table 4). The OWCH system was less flexible than the RFC system, and if rill initiation were to occur, the less flexible product would bridge the rill rather than drape over the surface. Additionally, it became obvious when removing RECSs after completion of phase 2, that individual fibers in the RFC system were able to work their way into the surface pore space, thus adding additional resistance to the surface. The large spun coir network of OWCH prevented the same degree of fiber integration with the surface. The RFC system had a much lower degree of open space (7% vs. 23%) and it was not arranged in open blocks of 1.6 cm^2 (Fig. 1 vs. Fig. 3). As Greene and Hairsine (2004) state, "because cover decreases kinetic energy of the rain that is released and dissipated to the soil surface, it reduces the amount of detachment, and hence erosion that can occur".

Studies have commonly shown an exponential decrease in soil erosion with increasing vegetation cover (Morgan, 1995). Greene and Hairsine (2004) state that the decline in soil loss with increasing contact cover is universal but the reasons for, and shape of, this trend vary. An increase in surface cover corresponds to an increase in the range of conditions under which the soil surface is stable to dispersion, and is therefore less likely to crust, seal or slake. A plot of contact cover percent for the treatments examined in this study (estimated as 1—light transmission, cf. Sutherland & Ziegler, 1996) vs. sediment concentration displays the typical exponential relationship (Fig. 8). Despite the limited number of data points in Fig. 8, the coefficients of determination were high and statistically significant at $P < 0.02$ for both phases of the experiment (i.e., phase 1, $r^2 = 97.6\%$; phase 2, $r^2 = 99.4\%$). Therefore thin, flexible fibers in a randomly oriented matrix, with limited open space may be optimal for reducing erosion and preventing or mitigating the formation or expansion of rill networks.
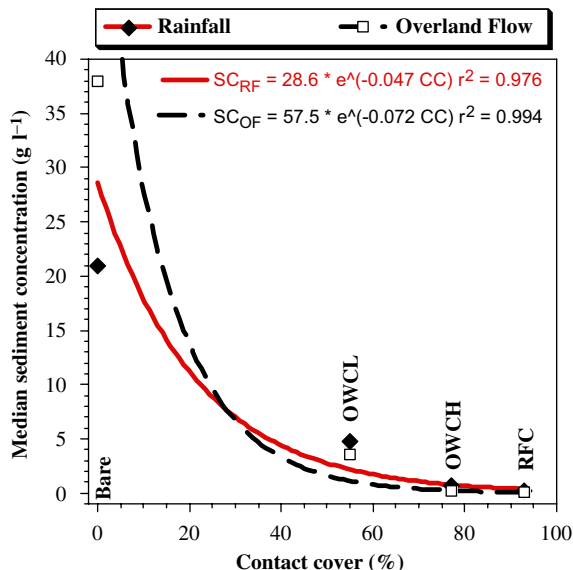

Fig. 8. Variation in sediment concentration (SC) with degree of contact cover (CC) for a bare treatment and three coir-based rolled erosion control systems. The two experimental phases have been separated, i.e., rainfall (RF), 110 min duration of runoff at 110 l h^{-1}; and overland flow (OF) application at 360 l h^{-1} for 30 min.

Conclusions

Human-modified slopes are a ubiquitous feature associated with urban growth. With slope disturbance, comes accelerated soil erosion and the increased potential for deleterious downstream impacts. To effectively mitigate these impacts, erosion and sediment control specialists require quantitative data from replicated studies to identify optimal practices, such as RECSs, under different stress conditions. In the present study, a replicated field experiment with separate rainfall and overland flow application phases provided the necessary temporal data to statistically explore hydraulic and erosion differences between bare (control) and coir-based RECSs. This study highlights the ability of RECSs to significantly reduce erosion on highly erodible disturbed hillslopes. Additionally, we found significant differences in the erosion effectiveness among coir-based systems. From an erosion reduction perspective, an effective OWC system would have limited open space and a relatively high mass per unit area (e.g., OWCH; Fig. 3). The benefits of a coir system like OWCH over one with greater open area and lower mass per unit area (e.g., OWCL; Fig. 2) are as follows: (1) the proportion of the hillslope area open to raindrop impact is low, therefore less sediment is available for detachment and transport; (2) more kinetic energy is dissipated directly on the coir fibers; and (3) the higher mass reduces the likelihood of coir strand beveling and detachment of the RECS from the soil surface, and this decreases the potential for flow concentration and rill initiation.

A second coir architecture, random fiber matrix, was found to be more effective in controlling erosion than the best performing open weave system. Compared to the open weave systems, the random fiber system had less continuous open space, was more flexible, and had thin fibers that integrated themselves into the soil pore space. These properties are effective in reducing splash detachment, increasing the likelihood of infiltration, reducing the shear stress exerted by overland flow on the soil surface, and decreasing the potential for rill initiation.

An understanding of the most important properties of RECSs that relate to runoff and erosion reduction are necessary to develop increasingly effective BMPs for disturbed hillslopes.

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