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INFLUENCE OF ROLLED EROSION CONTROL SYSTEMS ON TEMPORAL RAINSPLASH RESPONSE – A LABORATORY RAINFALL SIMULATION EXPERIMENT

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ABSTRACT

Reduction of erosion and sediment-related pollution from urban construction sites or other degraded hillslopes often relies on the initial application of suitable rolled erosion control systems (RECS) before natural vegetation cover can be established. However, research has not clearly explained why some RECS perform better than others, or under what particular conditions one system is more suitable than another. An important link between the application of the most suitable RECS and better product design is process-based studies relating the physical properties of products to the reduction of erosion subprocesses. This study investigates time-varying reduction of rainsplash detachment and transport by 13 commonly used RECS. The results indicate that product differences in the protection they provide against splash processes vary over the duration of a rain event, and that this variation is related to individual product properties, especially surface coverage and thickness. These results should aid in the design of more effective erosion control products and in the selection of the most suitable RECS for particular hillslope applications. © 1997 by John Wiley & Sons, Ltd.

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KEY WORDS: rainsplash detachment and transport; rainfall simulation; effectiveness; splash modeling; sediment size partitioning

INTRODUCTION

Degradation of the non-renewable soil resource by accelerated (human-induced) erosion is a serious environmental problem (Sutherland, 1989). Each year, approximately six billion tons of soil erode from the land in the United States (Pimentel, *et al.*, 1995). Damage from sediment and sediment-related pollution is estimated to be between US$3·7 and US$14 billion annually (Clark, *et al.*, 1985; Colacicco, *et al.*, 1989; Paterson, *et al.*, 1993; Pimentel, *et al.*, 1995). Accelerated erosion results from agriculture, silviculture, mining and activities related to urbanization, such as building construction, utility development and road building (e.g. Wolman and Schick, 1967; Anderson and McCall, 1968; Guy and Jones, 1972; Reed, 1980). Goldman, *et al.* (1986) state that when land is disturbed for construction, road building, mining, logging, landscaping or other activities, the soil erosion rate increases from 2–40 000 times. Construction areas are of particular concern because they are considered to be one of the most severe modifications of the human landscape (Meyer, *et al.*, 1971). In addition, these disturbed areas are often important non-point sources of enormous amounts of sediment and pollutants, including nutrients, petroleum products and metals (Schueler, 1987; Line, *et al.*, 1995). Recent conservation legislation (reviewed by Richter, 1987; Mertes, 1989) directed at reducing erosion, sedimentation and non-point source pollution associated with urban activities requires construction managers to stabilize disturbed areas properly. This means that hillslope and channel erosion should be minimized throughout the life of a project, and on occasions when erosion occurs, devices should be installed to keep suspended sediment and pollutants on site until the project area is fully stabilized with vegetation or other cover (Paterson, *et al.*, 1993; Dodson, 1995).

In response to greater concern about controlling urban sediment sources, a rapidly expanding and vigorous erosion control industry has emerged. In 1993, the total erosion-control market, primarily associated

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with the application of rolled erosion control systems (RECS) to construction areas and other disturbed hillslopes, grew substantially – increasing the area of slope protected from approximately 67 million m^2 in 1992 to about 73 million m^2 (Homan, 1994). However, the increased application of RECS has occurred in the absence of rigorous product performance testing, and without a detailed understanding of how specific systems influence erosion processes.

OBJECTIVES

This study investigates the performance of a wide range of rolled erosion control systems in mitigating inter-rill splash redistribution during simulated rainfall. The three main objectives of this study are (1) to determine the RECS that are most effective in reducing splash detachment, (2) to describe the time-varying effectiveness of RECS with a splash response model, and (3) to identify the physical attributes of RECS that contribute to their erosion control success. Our hypothesis is that those systems which are most effective in reducing splash detachment will also be those that have the lowest overall sediment yields. Thus, this study is an important component of a long-term assessment of RECS under varying stress levels, in the laboratory and in the field. This information will help design engineers to develop better systems, and more importantly will provide guidance to land managers and specifiers in selecting the most appropriate systems for their erosion control needs.

BACKGROUND

Rainsplash Detachment and Transport

Raindrop impact detaches soil particles and aggregates, thereby supplying sediment for transport by concentrated or unconcentrated overland flow. In addition, falling rain itself transports detached sediment by both rainsplash and rainflow processes (Moss, *et al.*, 1979). Young and Wiersma (1973) reported that 80–85 per cent of the soil originating from an eroded area was first transported into rills by either rainsplash or wash. The contribution of rainsplash detachment and transport to total erosion is controlled by many variables related to the characteristics of rainfall, soil and topography (c.f. Sutherland, *et al.*, 1996b). In this study, we focus on two important variables, surface coverage and time. Several researchers have reported non-linear relationships between soil erosion and percentage surface coverage by vegetation or mulches (e.g. Dunne, *et al.*, 1978; Morgan, 1995; Snelder and Bryan, 1995). This is of particular interest because the influence of nearly all other factors vary temporally, including the protection provided by surface covers.

Young and Wiersma (1973) reported that total sediment flux at any given time is correlated with splash transport. Furthermore, splash rate is known to decrease with time during a rain event owing to surface sealing (McIntyre, 1958; Epstein and Grant, 1967; Farres, 1978, 1987). Temporal rainsplash response on bare soil can be represented by a four-phase model (c.f. Farres, 1987; Sutherland, *et al.*, 1996b): (Phase 1) Micro-aggregates and fine particles are sheared off and removed from parent aggregates. Sediment transport by rainsplash can be significant if the kinetic energy of the rainfall is sufficiently high; therefore, this phase is characterized by an energy-limited transport capacity (Moore and Singer, 1990). (Phase 2) The main soil structural units are broken into component parts (Farres, 1987). This phase is marked by the formation of a thin, discontinuous, 'muddy' water layer that contributes to high splash rates, as the soil surface has its lowest strength and the greatest availability of material of transportable sizes at this time (c.f. Palmer, 1964; Moss, 1988; Sutherland, *et al.*, 1996b). (Phase 3) Rapid formation of a surface seal results in the accumulation of a deep protective layer of water that increases the soil's resistance to lateral shearing and raindrop impact (c.f. Sutherland, *et al.*, 1996b), thereby bringing about the completion of aggregate breakdown and a decline in splash transport. (Phase 4) Splash transport is reduced to a low constant rate owing to the presence of a thick, protective water layer, and to the absence of easily transportable particles (i.e. Phase 4 is supply-limited).

The four-phase model described above suggests that reduction of the rainsplash erosion component can be accomplished early during a rainstorm by reducing the shearing/breakdown processes and preventing surface sealing (i.e. Phases 1 and 2). This notion is supported by numerous studies showing that dissipation of raindrop energy by any means, natural or artificial, reduces erosion (c.f. Hudson, 1957; Meyer and Mannering, 1963; Taylor, *et al.*, 1964). In particular, Singer, *et al.* (1981) showed that as mulch cover increased, soil transport by both splash and interrill flow linearly decreased. These data support our hypothesis that if disturbed hillslopes are immediately covered by RECS, splash will be reduced; therefore, the availability of sediment for surface flow transport will be concomitantly reduced. Thus, the immediate application of the most effective RECS to human-modified slopes has significant potential for mitigating landscape degradation, reducing non-point source pollution and aiding in rehabilitation of disturbed areas.

Rolled Erosion Control Systems and the Erosion Control Industry

The goals of the erosion control industry are to reduce erosion and sediment yields from human-modified hillslopes. Rolled erosion control systems are designed to help mitigate immediate hillslope or channel degradation problems by simulating the protective cover of vegetation (Rickson, 1995). By protecting the surface, RECS prevent aggregate breakdown and delay the development of surface seals, thereby enhancing water infiltration into the soil. RECS also act as surface roughness elements, thus reducing overland flow velocities and shear stress exerted on the slope. In addition, RECS protect seeds from erosion processes, increasing the chances of germination. Since their introduction in the late 1950s, numerous RECS have been marketed world-wide for erosion control (Ingold, 1994). Over the last 5–10 years RECS have played a dominant role in protecting disturbed hillslope areas from accelerated erosion (c.f. Theisen, 1992).

Rolled systems include erosion control mats, blankets, mattings, turf reinforcement mats and erosion control revegetation matrices. Lancaster and Austin (1994) have classified RECS into (i) low-velocity degradable systems, (ii) high-velocity degradable systems, and (iii) long-term non-degradable systems. With the range of erosion control systems marketed today, there is increased demand for research on product performance. Unfortunately, only limited research has been conducted on the effectiveness of these products. Research to date has been primarily qualitative in nature and can be best categorized as *demonstration* studies that report only a general failure or success of a product, without providing an in-depth analysis of its relationship with specific erosion processes. Additionally, most rolled erosion control system studies fail to include a suitable number of replications, and do not incorporate randomization into their experimental design. Few studies are published in scholarly journals, and thus are not subject to the peer-review process. In the National Cooperative Highway Research Program (NCHRP) 1980 report, the authors concluded that to alleviate the paucity of erosion control research data on construction sites, ‘Statistically controlled experiments are needed in testing erosion control products so as to provide the user with reliable information on their effectiveness under various conditions’ (p. 13). Several researchers have commented that this gap in fundamental knowledge can be satisfied by geomorphological research (Morgan and Rickson, 1988). In order to ensure that systems actually perform as claimed by their manufacturers, and also to ensure the development of better systems, RECS should be tested objectively at many different stress levels and under many different environmental settings. This study attempts to address the dearth in data on (i) the effectiveness of various RECS, (ii) their relationship to basic erosion processes, and (iii) the design properties that are most influential in reducing erosion.

MATERIALS AND METHODS

Soil Selection, Preparation and Characteristics

The clay Vertisol (very fine, montmorillonitic, isohyperthermic, Typic Chromustert) used in this study was selected because it is one of the most erodible on the island of O’ahu, Hawai’i (Dangler and El-Swaify, 1976),

Table I. Chemical and physical characteristics of the Lualualei Vertisol, O'ahu

Soil characteristics	Units	Soil depth (cm)	Value(s)
pH in water (1:1)	–	0–10	7·2
Organic carbon	$\mathrm{g\ kg^{-1}}$	2–20	5·0[a]
Total nitrogen	$\mathrm{g\ kg^{-1}}$	0–10	1·8
CEC	$\mathrm{cmol(+)kg^{-1}}$	2–20	47·5[a]
Exchangeable Ca^{2+}	$\mathrm{cmol(+)kg^{-1}}$	2–20	34·4[a]
Exchangeable Mg^{2+}	$\mathrm{cmol(+)kg^{-1}}$	2–20	18·4[a]
Exchangeable K^{+}	$\mathrm{cmol(+)kg^{-1}}$	2–20	0·6[a]
Smectite	$\mathrm{g\ kg^{-1}}$	2–20	175[a]
Kaolinite	$\mathrm{g\ kg^{-1}}$	2–20	110[a]
Surface area (0·2–2·0 μm)	$\mathrm{m^2\ g^{-1}}$	2–20	315[a]
Surface area (<0·2 μm)	$\mathrm{m^2\ g^{-1}}$	2–20	428[a]
Particle density	$\mathrm{Mg\ m^{-3}}$	2–20	3·19[a]
Field bulk density	$\mathrm{Mg\ m^{-3}}$	0–10	1·08–1·22[b]
Sand[c] (63–2000 μm)	$\mathrm{g\ kg^{-1}}$	0–10	28
Silt[c] (2–63 μm)	$\mathrm{g\ kg^{-1}}$	0–10	372
Clay[c] (<2 μm)	$\mathrm{g\ kg^{-1}}$	0–10	600
WASD[d] (1000–4000 μm)	$\mathrm{g\ kg^{-1}}$	0–10	145
WASD[d] (250–1000 μm)	$\mathrm{g\ kg^{-1}}$	0–10	446
WASD[d] (63–250 μm)	$\mathrm{g\ kg^{-1}}$	0–10	323
WASD[d] (<63 μm)	$\mathrm{g\ kg^{-1}}$	0–10	86
Liquid limit	%	2–20	61·5[a]
Plastic limit	%	2–20	36·8[a]
Activity	–	2–20	0·41[e]

[a] Malik (1990).
[b] Ahuja, *et al.* (1976).
[c] Primary particle size determined using the hydrometer method after sonification and chemical dispersion.
[d] Wet aggregate size distribution determined following the method of Gabriels and Moldenhauer (1978).
[e] $$\text{Activity} = \frac{(\text{Liquid limit} - \text{Plastic limit})}{\text{Clay per cent}}.$$

and its chemical and physical properties are well documented (Table I). Additionally, this soil was used in a prior study on interrill dynamics and the responses of eight RECS (Ziegler and Sutherland, in press), and thus comparisons at different stress levels can easily be made. The soil was collected from the 0–10 cm depth increment at a site in western O'ahu. Samples were sieved through a 4-mm square-hole sieve and air-dried to a mean gravimetric soil moisture content of approximately 10·3 ± 1·8 per cent (± one standard deviation).

Rolled Erosion Control Systems Tested in This Study

Eight natural (organic) and five synthetic rolled erosion control systems were tested in this study. A description of each of the selected systems and a summary of their cardinal (c.f. Ingold, 1994) characteristics, including physical, mechanical and hydraulic properties, are shown in Table II. The systems selected for study represent a comprehensive cross-section of products currently manufactured, which are easily obtainable, and are widely used by erosion control specialists to mitigate hillslope erosion and rehabilitate disturbed landscapes. The trade names of the RECS are used because they are widely recognized in the erosion control/rehabilitation literature. Some product information was supplied by the various manufacturers or was extracted from the erosion control literature. Five other RECS properties that may be related to their effectiveness in reducing erosion were measured in the laboratory. These properties are described below.

Light transmission (*LT* in Table II) values were estimated using a Sunfleck (Decagon, Pullman, WA) PAR Ceptometer and an intense light source. Light transmission (per cent) for all surface treatments was defined using the following equation:

$$LT = \frac{\mathrm{RECS_{PAR}}(\mu\mathrm{mol\ m^{-2}\ s^{-1}})}{\mathrm{Source_{PAR}}(\mu\mathrm{mol\ m^{-2}\ s^{-1}})} \cdot 100 \tag{1}$$

where PAR is photosynthetically active radiation in the 400–700 nm waveband. $\mathrm{RECS_{PAR}}$ is PAR passing through a rolled erosion control system, and $\mathrm{Source_{PAR}}$ is PAR output from the intense light source. The potential range of *LT* values is from 0 (no light transmission) to 100 per cent (total transmission). A minimum of 26 measurements were made on each of the RECS, and 52 measurements were made of the intense light source. Light transmission is thought to play a role in the germination of seeds and during the early growth stage of vegetation. A reduction in light transmission is a proxy for the surface cover percentage of RECS, i.e. the lower the light transmission, the greater the surface area covered by the system. As noted previously, the percentage cover of a surface by vegetation or by mulches has commonly been shown to be non-linearly related to soil erosion rate.

Mean mass per area ($M\ L^{-2}$) was determined from five randomly selected, 225 cm^2 square samples, cut from a larger roll using a metal template (when resting upon the upper surface of a product, the template exerts a force of 14·7 N). Sample mass was recorded to $\pm 0{\cdot}001$ g using an analytical balance. The mass per area (M/A in Table II) of RECS is a commonly reported physical property; however, it is not known whether this is related to mitigation of soil erosion on hillslopes.

The average thickness (*L*) of an individual rolled erosion control system was determined under a constant pressure of approximately 1 kPa. A randomly selected sample with dimensions of 20·5 × 25·5 cm was cut from a larger roll, and measured at 12 different locations (three per side), using digital calipers, to $\pm 0{\cdot}01$ mm. Thickness (*T* in Table II) is another physical property commonly reported in the erosion control literature, but its influence on soil erosion in general, or splash in particular, is unknown. However, given two similar systems, one 'thin' and one 'thick', it is more likely that splashed sediment will be impeded and held within the thicker system.

Mass per area and thickness were combined to define the mass density (*MD* in Table II) ($M\ L^{-3}$) of all RECS using the following equation:

$$MD = \frac{\mathrm{Mass_{RECS}(kg)}}{\mathrm{Area(m^2)}} \cdot \frac{1}{\mathrm{Thickness_{RECS}(m)}} \tag{2}$$

Water sorption depth (*L*) was determined from five randomly selected samples with dimensions of 15 cm × 15 cm, wetted for 24 h, and then drained for 5 min on a wire mesh. Water sorption depth (*SD*) was calculated from the following equation:

$$SD = \frac{\mathrm{Mass\ of\ moisture\ sorbed(kg)}}{\mathrm{Area(m^2)}} \cdot C \tag{3}$$

where *C* is a conversion factor to mm. There is some indication in the literature that RECS which store more water, particularly the natural products, decrease splash detachment (Ingold and Thomson, 1990). These authors presented a bivariate plot indicating a strong non-linear relationship between splash loss and water retention (kg m^{-2}) for four natural RECS (jute, fine jute, excelsior and coir) and two synthetics (Enkamat 7010 buried and surface applied, and Tensarmat). Their statistically significant decay curve ($\alpha = 0{\cdot}05$) had a correlation coefficient (r) of $+0{\cdot}98$ ($r^2 = 0{\cdot}96$), although only seven data points were used. Sorption of significant amounts of water by RECS will also influence runoff, infiltration and evaporation. Sorption is probably only important for natural RECS, primarily in the early stages of a storm event prior to saturation.

Table II. Summary of the cardinal properties of rolled erosion control systems

Name of system	Manufacturer	Description	Physical properties[a]	Mechanical properties[b]	Hydraulic properties[c]	Additonal comments[d]
BioD-Mat™ 40	RoLanka International, Inc.	100% open-weave biodegradable bristle coconut fibres (natural)	$LT = 45{\cdot}2 \pm 1{\cdot}7$ $M/A = 467 \pm 7{\cdot}3$ $T = 7{\cdot}35 \pm 0{\cdot}63$ $MD = 63{\cdot}54$		$SD = 1{\cdot}00 \pm 0{\cdot}051$	Decomposition time 5–10 years
BioD-Mat™ 70	RoLanka International, Inc.	100% open-weave biodegradable bristle coconut fibres (natural)	$LT = 22{\cdot}6 \pm 3{\cdot}3$ $M/A = 705 \pm 41$ $T = 7{\cdot}64 \pm 1{\cdot}10$ $MD = 92{\cdot}28$	$WTS_{MD} = 17{\cdot}5$ $WTS_{CD} = 14{\cdot}0$	$SD = 1{\cdot}42 \pm 0{\cdot}12$	Decomposition time 5–10 years
BioD-Mesh™ 60	RoLanka International, Inc.	100% biodegradable system woven from spun mattress coir yarns (natural)	$LT = 13{\cdot}0 \pm 0{\cdot}84$ $M/A = 538 \pm 10$ $T = 7{\cdot}34 \pm 1{\cdot}22$ $MD = 73{\cdot}30$		$SD = 1{\cdot}97 \pm 0{\cdot}16$	Decomposition time 2–3 years
C125	North American Green®	100% coconut fiber matrix sewn between two heavyweight UV stabilized nets (natural)	$LT = 6{\cdot}8 \pm 0{\cdot}8$ $M/A = 273 \pm 46$ $T = 4{\cdot}68 \pm 1{\cdot}00$ $MD = 58{\cdot}33$	$\tau_{Max} = 108$	$SD = 0{\cdot}84 \pm 0{\cdot}11$ $n = 0{\cdot}014–0{\cdot}022$	Recommended on 1 : 1 slopes or greater, and as a channel liner
Curlex® I	American Excelsior Company	100% aspen excelsior, 80% of the fibres >15 cm long, net one side (natural)	$LT = 24{\cdot}6 \pm 0{\cdot}8$ $M/A = 489 \pm 74$ $T = 9{\cdot}07 \pm 1{\cdot}98$ $MD = 53{\cdot}91$		$SD = 0{\cdot}94 \pm 0{\cdot}15$	Recommended maximum slope 1·5 : 1·0
Futerra® Green	CONWED Fibres	Pure wood fibre hydromulch bonded to photodegradable netting (top side) with a small percentage of recycled synthetic fibers (natural)	$LT = 4{\cdot}6 \pm 0{\cdot}9$ $M/A = 214 \pm 10$ $T = 2{\cdot}27 \pm 0{\cdot}35$ $MD = 94{\cdot}27$		$SD = 1{\cdot}91 \pm 0{\cdot}11$	Recommended for slope 2 : 1 or less
Geojute® (Regular)	Belton Industries, Inc.	Coarsely woven open-mesh fabric of jute (natural)	$LT = 41{\cdot}7 \pm 5{\cdot}3$ $M/A = 497 \pm 11$ $T = 1{\cdot}93 \pm 0{\cdot}25$ $MD = 257{\cdot}50$	$\tau_{Max} = 132$	$SD = 3{\cdot}10 \pm 0{\cdot}18$ $n = 0{\cdot}0237$	Recommended maximum slope 1 : 1

Multimat® 100	Tenex® Geotenax Corp.	3-D structure with three layers of netting secured with multiple rows of polypropylene stitching (topsoil to be added to mat) (synthetic)	$LT = 47{\cdot}2 \pm 0{\cdot}70$ $M/A = 391 \pm 31$ $T = 17{\cdot}01 \pm 2{\cdot}41$ $MD = 22{\cdot}99$	$TS_{\rm MD} = 8$ $TS_{\rm CD} = 20$	$SD = 0{\cdot}11 \pm 0{\cdot}018$ $P = 90$	Recommended for high-flow channels and steep slopes
P300	North American Green®	100% UV stabilized polypropylene fiber matrix sewn between two nets (synthetic)	$LT = 8{\cdot}6 \pm 3{\cdot}4$ $M/A = 426 \pm 70$ $T = 4{\cdot}52 \pm 0{\cdot}67$ $MD = 94{\cdot}25$	$\tau_{\rm Max} = 96$ $TS_{\rm MD} = 3{\cdot}8$ $TS_{\rm CD} = 3{\cdot}8$	$SD = 0{\cdot}25 \pm 0{\cdot}039$ $n = 0{\cdot}020–0{\cdot}024$ $P = 95$	Recommended 1:1 slopes and high-flow channels $UV_{\rm Rest} = 90$
PEC-MAT®	GREENSTREAK® Inc.	Non-woven UV stabilized blanket of randomly oriented PVC monofilaments thermally welded (synthetic)	$LT = 43{\cdot}9 \pm 1{\cdot}5$ $M/A = 1260 \pm 42$ $T = 2{\cdot}74 \pm 0{\cdot}23$ $MD = 459{\cdot}90$	$\tau_{\rm Max} = 240$ $TS_{\rm MD} = 2{\cdot}1$ $TS_{\rm CD} = 1{\cdot}2$	$SD = 0{\cdot}23 \pm 0{\cdot}083$ $P = 72$; $n = 0{\cdot}020$ $V_{\rm Max} = 6{\cdot}1$	Permanent erosion control
SC150BN	North American Green®	70% agricultural straw and 30% coconut mattress fiber sewn between two biodegradable jute yarn nets (natural)	$LT = 14{\cdot}2 \pm 1{\cdot}6$ $M/A = 549 \pm 23$ $T = 3{\cdot}92 \pm 0{\cdot}78$ $MD = 140{\cdot}05$		$SD = 2{\cdot}28 \pm 0{\cdot}19$	Maximum slope 1:1, functional longevity 18 months
SuperGro®	AMOCO Fabrics & Fibers Co.	A geocomposite consisting of a rapidly degradable scrim and a thin web of polypropylene fiber on one side (synthetic)	$LT = 26{\cdot}3 \pm 1{\cdot}4$ $M/A = 40 \pm 3{\cdot}7$ $T = 0{\cdot}40 \pm 0{\cdot}09$ $MD = 100{\cdot}00$		$SD = 0{\cdot}50 \pm 0{\cdot}083$	Recommended maximum slope 1·5:1
TerraJute® (POLYJUTE® 407GT)	WEBTEC, Inc. (Synthetic Industries)	Open-weave photodegradable polypropylene geotextile (synthetic)	$LT = 69{\cdot}2 \pm 2{\cdot}3$ $M/A = 88 \pm 1{\cdot}0$ $T = 0{\cdot}76 \pm 0{\cdot}12$ $MD = 115{\cdot}80$	$TS_{\rm MD} = 0{\cdot}73$ $TS_{\rm CD} = 0{\cdot}44$	$SD = 0{\cdot}38 \pm 0{\cdot}022$	Recommended maximum slope 2:1 $UV_{\rm Rest} = 95$

[a] Physical properties include: LT = light transmission for photosynthetically active radiation (%); M/A = mass per area (g m^{-2}); MD = mass density (kg m^{-3}); T = thickness (mm).

[b] Mechanical properties include: $TS_{\rm MD}$ = tensile strength (dry) in the machine (length) direction (kN m^{-1}); $TS_{\rm CD}$ = tensile strength (dry) in the cross (width) direction (kN m^{-1}); $\tau_{\rm Max}$ = maximum permissible shear stress (Pa); $WTS_{\rm MD}$ = wet tensile strength in the machine (length) direction (kN m^{-1}); $WTS_{\rm CD}$ = wet tensile strength in the cross (width) direction (kN m^{-1}).

[c] Hydraulic properties include: n = Manning's roughness coefficient (s m$^{-1/6}$); P = porosity (%); SD = sorption (water) depth; $V_{\rm Max}$ = maximum suggested velocity (m s^{-1}).

[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°; $UV_{\rm Rest}$ = strength after 500 h of exposure to ultraviolet light (%).

RECS Effectiveness

The effectiveness of RECS in reducing splash output was determined from the following equation:

$$\text{Effectiveness} = \left[\frac{\text{Mean bare}_{\text{SP}} - \text{Mean RECS}_{\text{SP}}}{\text{Mean bare}_{\text{SP}}}\right] \cdot 100 \tag{4}$$

where mean bare$_{\text{SP}}$ represents the mean of 10 splash output measurements, and mean RECS$_{\text{SP}}$ represents the mean of five splash output measurements for each of the individually tested RECS. An overall value was determined for the entire storm duration (1 h) and also for 0·0–0·5 h and 0·5–1·0 h periods to determine the variation in system effectiveness with time.

Rainfall Simulation Apparatus and Setup

For this detailed interrill splash investigation we used a laboratory drip-type simulator which we have used previously in other process-based erosion studies (e.g. Sutherland and Ziegler, 1996; Sutherland, *et al.*, 1996a,b; Ziegler and Sutherland, in press). Raindrop fall height was 2·0 m, and uniform drops with a median diameter of 3·2 mm were produced. Rainfall intensity, controlled by an in-line pressure gauge, averaged 120 ± 11 mm h^{-1} ($\pm$one standard deviation) for all events. At this rainfall intensity the simulator produced an energy flux density of 0·51 W m^{-2}, which is equivalent to about 69 per cent of natural rainfall having a mean drop diameter of 2·00 mm (Sutherland, *et al.*, 1996b). To approximate a random distribution of raindrops at the soil surface, two opposing fans were used to generate turbulence.

Each translucent splash container used in this study had a volume of 2·5 L and a surface area of 166 cm^2. Prior to filling them with soil, holes were punched in the bottom of the splash cup; the holes were then covered with 2 μm pieces of filter paper. Soil at a constant moisture content ($10{\cdot}3 \pm 1{\cdot}8$ per cent) was gently packed to a mean bulk density of 1·12 Mg m^{-3}, which is similar to that found in the field (Table I). Soil was filled to within approximately 3 mm of the splash cup lip to reduce wash over by rainflow. However, some washover did occur as the soil swelled during the later stages of the simulated storm events. The soil-filled container was set within a second container (Figure 1) to form a two-tiered system. This design allowed free

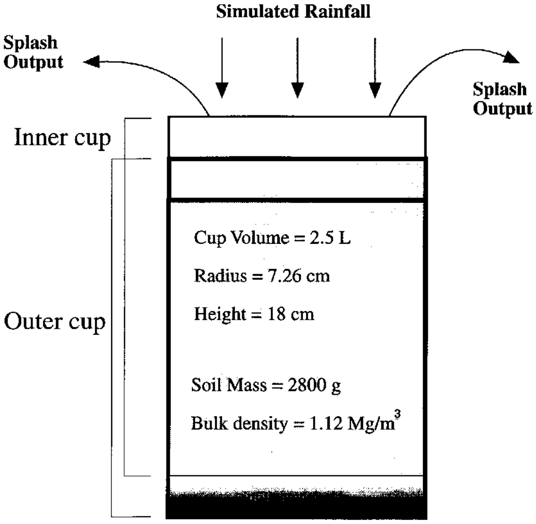

Figure 1. Two-tiered splash cup system employed in this study. Water infiltrating through the soil column of the inner cup was allowed to drain freely into the bottom cup; therefore, saturation overland flow was prevented.

drainage into the open space between the two cups, and prevented the generation of saturation overland flow. Drainage water was periodically emptied during the measurement period. Fresh soil was used for each simulation to ensure comparability in initial moisture contents and availability of material <4 mm in diameter. The two-tiered splash cups were set within 45-L containers to collect all splashed sediment.

All RECS were trimmed to be flush with the edge of the splash container, and were held in position with four 3-cm staples. Manufacturers of Multimat 100 suggest that their system should be filled with soil after installation; however, we did not do this because we agree with Rustom (1993) that 'testing with fill and/or soil cover would give a misleading picture of the overall performance of these products' (p. 52). This statement is supported by splash data from Rickson (1988), who found that buried systems performed less well than the bare control plots.

Five 1-h rainfall events were simulated on each of 13 RECS; ten events on a bare control surface. From previous splash research (Sutherland, *et al.*, 1996a,b) we determined that 1-h experiments were sufficient to examine the temporal response of surfaces to rainsplash detachment. Four splash containers were subjected to rainfall during each run. Each of the RECS were tested once in three simulator locations and twice at a fourth location. All locations were selected at random using a pseudo-random number generator. Every 5 min, a tarpaulin was stretched above the splash cups and the 45-L containers were removed from beneath the simulator. The two-tiered splash cups were then placed within 'clean' 45-L containers and immediately placed under the simulator for another 5-min period. Each 5 min sediment sample was oven-dried at 105°C for a minimum of 24 h, and then mass determinations were made to $\pm 0{\cdot}001$ g. This procedure allowed the temporal response of splash detachment for each system and the bare control to be determined from twelve 5-min samples. Note that for all RECS tested, splash output at each time interval is the mean of five replications (ten replications for the bare control); therefore, a total of 900 mass determinations of splash detachment were made in this study.

Composite samples were wet-sieved according to the procedure outlined by Gabriels and Moldenhauer (1978) and three aggregate fractions were determined for each of the surface treatments. An error occurred during the measurement of the aggregate size distribution of Multimat 100, and thus no aggregate size data are available for comparison with other products. Aggregates were divided into fine (<63 μm), medium (63–250 μm) and coarse (250–4000 μm) size classes.

Statistical Analysis

Incorporation of randomization and replication into the experimental design allowed data to be examined using analysis of variance (ANOVA). To address three research questions related to temporal variation in splash detachment, we used repeated-measures ANOVA. The first question was (i) whether splash yield (averaged over time) differed between two or more of the 14 surface covers (13 RECS and one bare control). Of more interest to this temporal-based investigation are (ii) whether or not (averaged over surface covers) splash detachment varied over time (i.e. was there a difference in splash response at time x vs. time y vs. time z, etc.), and (iii) whether or not the change in splash response over time was the same for all surface covers. SuperANOVA™ (Gagnon, *et al.*, 1989) was used to conduct the repeated measures analysis of variance. All splash data (g) were $\log_{10}$-transformed prior to analysis to stabilize the variance (Ott, 1984).

Traditionally, erosion control researchers have primarily been interested in differences in total sediment output between various RECS. Thus, to allow comparisons of our work with other data published in the erosion control literature, we examined 1-h splash yields with one-way ANOVA. If a significant F-ratio ($P \leqslant \alpha = 0{\cdot}05$) was found, *post-hoc* multiple comparison testing was performed using Fisher's protected least significant difference (PLSD) test. Again, all splash data (g) were $\log_{10}$-transformed prior to conducting ANOVA.

The non-parametric Mann–Whitney U-test was used to determine whether statistical differences existed in median values between groups of RECS. The groups were classified based on performance by using ANOVA. A non-parametric approach was used because small samples were involved and there was no way to test whether the distribution met the normality assumptions of parametric t-tests.

Modeling Splash Response

For each of the three surface cover groups and the bare soil control, we created a model of temporal splash response by fitting curves through splash yield values plotted against time. The three groups were based on system performance, as determined from ANOVA in this study. Each curve was specified as the lowest order polynomial that would fit the plotted data with $r^2 \geqslant 0{\cdot}95$. The curve-fitting program available in KaleidaGraph 3.0.4 (Abelbeck Software, 1994) was used for all modeling.

RESULTS AND DISCUSSION

Total Splash: Repeated Measures ANOVA

The repeated-measures ANOVA (Table III) gave the following results in relation to our three research questions:

(i) highly significant differences ($P = 0{\cdot}0001$) in mean splash detachment existed between the 14 surface covers averaged over the twelve 5-min measurement periods, indicating that at least two surface covers differed significantly in splash response;
(ii) splash detachment (averaged over surface covers) varied significantly with time ($P = 0{\cdot}0001$), i.e. throughout the 1-h even duration there were times when splash output was significantly higher or lower than at other times;
(iii) there was a highly significant ($P = 0{\cdot}0001$) interaction between time and surface cover, indicating that the patterns of splash detachment over time differed depending on surface cover.

Repeated-measures analyses allowed us to establish that different RECS provide different degrees of protection from splash processes, and that the protection varies over the event duration. Therefore, these results served as a basis from which we designed further analyses.

Table III. Repeated measures analysis of variance results for splash detachment

Source	df[a]	*F*-value	*P*-value	G–G value[b]	H–F value[c]
Surface cover	13	30·346	0·0001		
Subject (group)	61				
Time interval	11	42·300	0·0001	0·0001	0·0001
Time interval × surface cover	143	2·083	0·0001	0·0001	0·0001
Time interval × subject (group)	671				

[a] df represents degrees of freedom: for surface cover, 14 − 1 = 13; for subject (group), 75 − 14 = 61 (where bare = 10 replications + (13RECS × 5 replications) = 75); for time interval, 12 − 1 = 11 (twelve 5-min measurement periods); for time interval × surface cover, 13 × 11 = 143; for time interval × subject (group), 61 × 11 = 671.
[b] G–G represents the Greenhouse–Geisser epsilon and is a conservative statistic which measures the extent to which the correlation of the observations violates the validity of the *P*-values.
[c] H–F represents the Hunyh–Feldt epsilon and is a more liberal statistic which measures the extent to which the correlation of the observations violates the validity of the *P*-values.

Total Splash: One-way ANOVA

The results from one-way ANOVA indicated that all RECS, with the exception of Multimat 100, significantly reduced total splash detachment compared with the bare control treatment (Table IV). Based on *post-hoc* testing, surface treatments were classified into three groups. Group 1 surface treatments, which were the most effective in reducing splash output, included seven RECS, six natural products (Futerra, C125, Curlex I, BioD-Mat 70, SC150BN and Bio-D-Mesh 60) and one synthetic product (P300). Group 2 surface treatments were significantly less effective than Group 1 systems but were more effective than those in Group 3 (bare control surface and Multimat 100). Group 2 included five RECS, two natural (Geojute and

Table IV. Summary of mean splash detachment values for three time periods from 14 different surface treatments

Surface treatment	Replications	Mean splash detachment 0·0–0·5 h (g)	Mean splash detachment 0·5–1·0 h (g)	Mean splash detachment 0·0–1·0h (g)	Group number
Futerra	5	0·015	0·032	0·067^{a*}	1**
C125	5	0·043	0·119	0·194^{ab}	1
Curlex I	5	0·058	0·189	0·254^{ab}	1
BioD-Mat 70	5	0·069	0·206	0·305^{bc}	1
P300	5	0·052	0·358	0·508^{bc}	1
SC150BN	5	0·156	0·272	0·513^{bc}	1
BioD-Mesh 60	5	0·279	0·771	1·069^{c}	1
Geojute	5	1·081	1·581	2·679^{d}	2
SuperGro	5	1·528	2·679	4·227^{d}	2
PEC-MAT	5	1·199	3·581	4·819^{d}	2
TerraJute	5	2·449	4·256	6·792^{d}	2
BioD-Mat 40	5	2·897	5·236	8·185^{d}	2
Multimat 100	5	13·900	21·038	35·156^{e}	3
Bare	10	25·704	19·409	45·499^{e}	3

*Mean splash detachment values for the entire 1-h duration of the storm with the same letter are NOT significantly different at the $\alpha = 0·05$ level as determined by Fisher's protected least significant difference test.

**Based on *post-hoc* multiple comparison results of mean splash detachment for events of 1-h duration, three statistically separate groups were identified: Group 1 is composed of seven RECS, and is the most effective; Group 2 is composed of five RECS, and is considered to be of moderate effectiveness; and Group 3 (which includes Multimat 100 and the bare soil control) is the least effective group.

BioD-Mat 40) and three synthetic systems (SuperGro, PEC-MAT and TerraJute). The average temporal splash responses of each of the individual groups are presented in Figure 2. Note that a logarithmic scale was used, and that the groups are clearly discriminated from one another. In the sections below, the reasons for between-group differences will be explored in detail, with reference to some of the cardinal properties of the RECS.

Futerra, with an overall effectiveness rating of 99·85 per cent (Equation 4), was the most effective rolled erosion control system in reducing splash detachment (Table V). All Group 1 systems had overall effectiveness ratings greater than 97 per cent; Group 2 values ranged from 82 to 94 per cent. All RECS

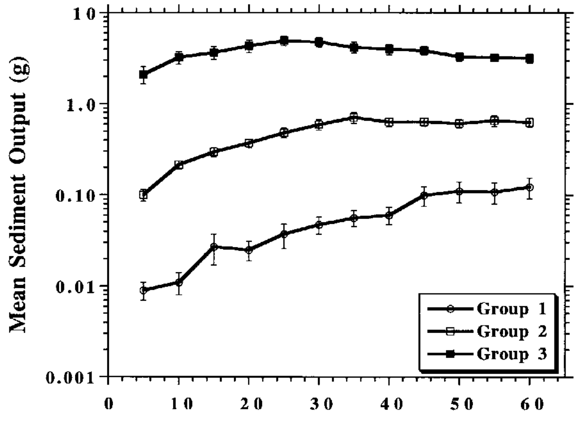

Figure 2. Temporal variation in mean splash detachment for the various surface covers classified by analysis of variance into three groups. Note that the error bands associated with each data point represent ± one standard error about the mean.

Table V. Effectiveness of 13 rolled erosion control systems in mitigating splash (SP) detachment for three time periods

Surface treatment	SP reduction effectiveness 0·0–0·5 h (%)	SP reduction effectiveness 0·5–1·0 h (%)	Change in SP reduction effectiveness (%)	Overall SP effectiveness 0·0–1·0 h (%)	Group number
Futerra	99·94†	99·83†	−0·11‡	99·85†	1§
C125	99·83	99·39	−0·44	99·57	1
Curlex I	99·77	99·03	−0·75	99·44	1
BioD-Mat 70	99·73	98·94	−0·79	99·33	1
P300	99·80	98·15	−1·64	98·88	1
SC150BN	99·39	98·60	−0·79	98·87	1
BioD-Mesh 60	98·92	96·03	−2·89	97·65	1
Geojute	95·79	91·85	−3·94	94·11	2
SuperGro	94·06	86·20	−7·86	90·71	2
PEC-MAT	95·33	81·55	−13·78	89·41	2
TerraJute	90·47	78·07	−12·40	85·07	2
BioD-Mat 40	88·73	73·02	−15·71	82·01	2
Multimat 100	45·92	−8·39	−54·32	22·73	3
Bare	0·00	0·00	0·00	0·00	3

†Effectiveness in reducing splash (SP) detachment is defined for each time increment relative to the Bare control output (see Eq. 4).

‡Change in splash reduction effectiveness represents the splash reduction effectiveness during the first half hour of simulation minus that during the second half hour. Negative values reflect a "poorer" performance during the second half hour (0·5–1·0 h) of the rainfall experiments.

§Classification of surface treatments into groups is based on results presented in Table IV.

decreased in their splash reduction effectiveness during the second half-hour of the simulations (Table V). For example, Group 1 system effectiveness decreased by 0·1–2·9 per cent during the 0·5–1·0 h period; Group 2 systems decreased in effectiveness by 3·9–15·7 per cent, and the effectiveness of Multimat 100 decreased by 54·3 per cent. In fact, splash output from plots covered with Multimat 100 during the 0·5–1·0 h period was greater than that from the bare control plots (21·0 vs 19·4 g; Table IV) – this is indicated by a negative effectiveness factor (i.e. −8·4 per cent). In support, Rickson (1988) found that when 3-D systems were buried with soil, as suggested by the manufacturers, they performed less well than the bare control.

A Model of Temporal Dynamics of Splash Reduction

In this study, the four-phase temporal rainsplash model (discussed above in Background) describes well the observed rainsplash response of the bare soil control. Figure 3 represents a model of the bare soil splash response. The curve is a fourth-order polynomial ($r^2 \approx 0{\cdot}96$) fitted through ten data points at each time increment. The numbers correspond to the four phases of the temporal rainsplash model. Rainsplash response was characterized by a rapid increase in sediment redistribution during the first 20 min of the 1·0 h event (Phase 1); the maximum splash output occurred at approximately 20–25 min (Phase 2). The second half of the rain event was characterized by a marked reduction in splashing as a protective water layer formed on the soil surface (Phase 3). Near the end of the 1·0 h period, splash output rate leveled to a near-constant value (Phase 4).

To judge the performance of the RECS tested in this study, we now compare the bare soil splash model to three other models created from the splash responses of Group 1 systems (G1), Group 2 systems (G2) and Multimat 100 (MM). Note that G1 and G2 are the same system groups defined previously by one-way ANOVA (Table IV), and that MM and the bare soil control have now been separated. Panel I of Figure 4 shows the temporal splash response curves of the three cover groups compared with that of the bare soil control. Panels II–IV show the responses of each cover group (plotted with different y-axes). The points

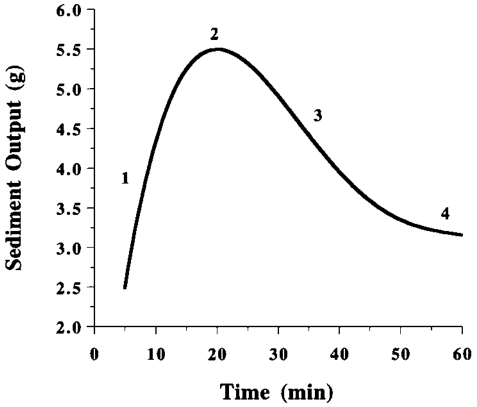

Figure 3. A model of the temporal splash response of the bare soil control plot. Numbers 1–4 refer to the four-phase splash model described in the Background section. The curve is a fourth-order polynomial fitted through 10 splash output measurements at each 5-min interval. During Phases 1 and 2, aggregates are broken down into smaller particles by raindrop impact. Maximum splashing occurs in Phase 2 with the formation of a thin layer of muddy water. Splash rate decreases in Phase 3 as the easily transportable aggregates are removed and a thick protective water layer forms above the sealed surface. Phase 4 is characterized by a reduction of splash transport to a near-constant rate.

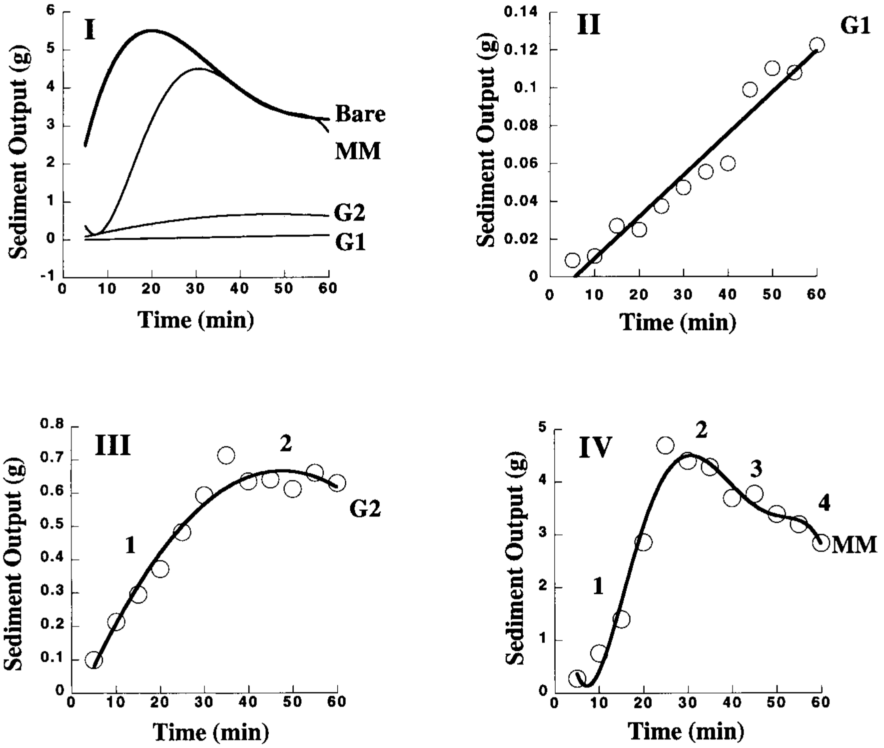

Figure 4. Comparison of the splash model for the bare soil control (Figure 3) with that of each of the three RECS group determined in this study. Panels II–IV show individual responses for each RECS group appearing in Panel I. All groups produced changes in temporal splash response compared with the bare soil control model. Group 1 systems (G1) provided the greatest reduction in splash redistribution – this is evident because none of the four model phases was well developed. Temporal responses for Multimat 100 (MM) was very similar to that of the bare soil control; this product provided the least protection from splash redistribution. Group 2 (G2) RECS reduced much of the breakdown and shearing processes of Phases 1 and 2 of the temporal model; however, they performed at an effectiveness level significantly lower than that of the G1 systems. G1 RECS are Futerra, C125, Curlex I, BioD-Mat 70, P300, SC150BN and BioD-Mesh 60; G2 RECS are GeoJute, SuperGro, PEC-MAT, TerraJute and Bio-D-Mat 40.

represent the mean of five measured splash yield values vs. time, and the curves are polynomials fitted through the data points. The main points which should be noted regarding system performance are listed below.

(1) A simple quantitative index that highlights differences in temporal splash response between system groups is the slope (g min^{-1}) of the line connecting the origin (i.e. time = 0) and the maximum splash yield value (i.e. the rising limb of splash response). For example, the slope for the bare soil control response was 0·22, which was only slightly higher than that of Multimat 100 (0·19). In comparison, the slopes for the G1 (0·02) and G2 (0·002) systems, which significantly reduced splash output compared with MM and the bare control, were one and two orders of magnitude lower, respectively.

(2) The splash response for G1 systems (Panel II, Figure 4) was best represented by a straight line ($r^2 \approx 0{\cdot}95$). None of the four phases of the splash response model was apparent, except perhaps a very diminished rising limb of splash response. The absence of a splash output peak and the continued increase in output at the end of the event indicates that these systems prevented early flushing of easily transportable sediments by rainsplash and rainflow processes. The overall low output (and high effectiveness, Tables III–IV), especially during the first half of the event, indicates that the systems protected the surface from shearing and breakdown processes (Phases 1 and 2), and also prevented the formation of a surface seal and the ensuing thin, muddy layer of water that normally contributes to high splash rates on a bare soil surface (Phase 2). Much of this protection was provided through absorption of raindrop kinetic energy and/or trapping of splashed sediment.

(3) The splash response of G2 initially appeared to be very similar to that of G1 (see Panel I, Figure 4); however, a closer examination (Panel III, Figure 4) revealed some important differences in the protection provided by these products. The curve that best fitted the splash response of G2 was a parabola ($r^2 \approx 0{\cdot}96$), which indicates that a peak in splash output was obtained (unlike G1), and thus easily transportable sediments were removed at some point. Phase 1 and 2 of the model were present in the response curve, although they occur later and at a reduced magnitude compared with the bare soil control. The emergence of a thin, highly splashable water layer (Phase 2) represents a critical threshold where the protection afforded by this group of RECS was diminished. Splash output leveled off immediately following the splash peak; however, a drastic reduction from the maximum splash value did not occur (i.e. Phase 3 was absent, diminished or not yet realized).

(4) Panel IV (Figure 4) indicates the presence of all four phases of the splash model in the splash response of Multimat 100 (MM). The curve is a fifth-order polynomial ($r^2 \approx 0{\cdot}97$); the dip between 5 and 10 min is an artifact of curve fitting and should be ignored, as should the sharp decline at the end of the 1·0 h period. Splash reduction by MM was significantly less than that by G1 and G2 systems. In fact, the splash response of MM was only different from the bare soil in timing and magnitude during the first 0·5 h of the event (Phases 1 and 2). For example, splash detachment from the bare surface was on average 1·85 times greater than from MM during the first 0·5 h of the experiment. On the other hand, total splash detachment from MM peaked during the second half-hour, producing a greater splash output value than the bare control (Table IV). These data indicate the limited surface coverage provided by MM (light transmission was 47%; Table II) was able to reduce splash transport of large particles in the early stages of the simulation; however, it was not able to prevent the shearing and breaking down of aggregates, which lead to surface sealing (Phase 1), to any great extent. Therefore, the formation of a thin muddy water layer (Phase 2) was only delayed. During the second 0·5 h period a thick protective water layer developed, and as in the case of the bare soil control simulations, splash output decreased and leveled off (Phases 3 and 4). The slightly greater splash output for MM during the second half of the simulations compared with the bare soil may be the result of the abundance of easily transportable sediments that were not flushed during the early phases.

Importance of Time in Erosion Process Studies

In the past, many RECS studies have been conducted for short durations, e.g. 10 min for Jennings and Jarrett (1985), 15 min for Rickson (1988) and 10 min for Godfrey and Curry (1995). Our splash response data (Figure 4) indicate the importance of temporal monitoring of rolled erosion control system performance over time; in addition they indicate the need to measure over a sufficient number of time periods. In the first place, the entire 1-h simulation duration was needed to observe all four phases of the splash response model fully. If simulations were conducted for shorter durations, the process linkages reported above would not have been apparent, and the identification of thresholds in system response would have gone undocumented. For example, G1, G2 and MM all had similar near-linear splash responses during the first 20 min, with differences existing only in the magnitude of splash output (Figure 4). However, beyond 20 min, the temporal response of these three groups became substantially different.

Properties of RECS and Their Relationship to Splash Detachment

Minimum, median and maximum physical and hydraulic property values for each of the two system groups (Groups 1 and 2) and Multimat 100 are summarized in Table VI. Substantial differences in properties exist between the three groups, that may be related to their effectiveness in mitigating splash detachment. For example, Multimat 100, which performed the worst, was very different from the Groups 1 and 2 systems: it was the thickest system (17 mm), had high light transmission (i.e. low surface cover), and had the lowest mass density and lowest sorption depth of all other RECS examined. The high open area and grid structure resulted in only minimal reduction in the kinetic energy of raindrop impact at the soil surface. Thus, the resulting high splash detachment could not be offset by the thickness of the product because of its open structure.

Table VI. Summary statistics for five physical properties of rolled erosion control systems, classified according to splash mitigation performance

Physical property	Group 1	Group 2	Multimat 100
Light transmission (%)	13·0[a] (4·6–24·6)[b]	43·9 (26·3–69·2)	47·2
Mass per area (g m^{-2})	489 (214–705)	467 (40–1260)	391
Thickness (mm)	4·68 (2·27–9·07)	1·93 (0·4–7·35)	17·01
Mass density (kg m^{-3})	92·28 (53·91–140·05)	115·8 (63·54–459·90)	22·99
Sorption depth (mm)	1·42 (0·84–2·28)	0·50 (0·23–3·1)	0·11

[a] Values represent median values based on a sample size of seven for Group 1 systems and five for Group 2 systems. Multimat 100 was the only rolled erosion control system in Group 3.
[b] Values in parentheses represent minimum and maximum values in each group.

Tied probability values (P values) from the Mann–Whitney U-test for the five property comparisons are shown in Table VII. The data indicate that there was a highly significant difference ($\alpha = 0{\cdot}01$) in median light transmission between the two groups of data. Group 1 systems covered significantly more of the soil surface and thus prevented the expenditure of drop energy directly on the soil surface. At an α-level of 0·10, Group 1 systems had median thickness values statistically greater than those of Group 2 systems, although minor overlap occurred between group values. Thus, thicker Group 1 RECS performed better, since it was likely that splash-detached sediment would be caught within the framework of the structure. These data indicate that a greater surface coverage, combined with a thick structure, was effective in reducing splash. Systems with many openings (i.e. low surface coverage), regardless of thickness, were less effective in reducing splash. Mass per area and sorption depth were not significantly different at the $\alpha = 0{\cdot}10$ level between the two groups of systems. Sorption depth and properties such as flexibility (stiffness or drapeability; c.f. Ingold, 1994; Koerner, 1994) may be more important for mitigating overland flow transport of sediment than for

Table VII. Tied-probability values for comparisons between physical properties of Group 1 and Group 2 rolled erosion control systems

Physical property	Tied P-value[a]
Light transmission (%)	0·0045[b]
Mass per area (g m^{-2})	0·570
Thickness (mm)	0·062[c]
Mass density (kg m^{-3})	0·088[c]
Sorption depth (mm)	0·372

[a] Tied P-values determined using the Mann–Whitney (non-parametric) U-test.
[b] Value significant at $\alpha = 0{\cdot}01$.
[c] Value significant at $\alpha = 0{\cdot}10$.

reducing rainsplash erosion processes. In support, we have observed in a field investigation (work in progress) that systems failing to conform closely to surface irregularities are sometimes subjected to localized flow concentrations that result in the initiation of rill networks. These products tend to be ones that are rigid or fail to sorb much water.

Size Partitioning of Splash Detached Sediment

It is important to characterize the size of sediment transported by interrill splash because the finest fractions (<63 μm, silt plus clay) are important vectors for chemical transport of radionuclides, nutrients, pesticides, herbicides, etc. (c.f. Horowitz, 1991). Therefore, if RECS reduce total sediment transport but allow an increase in the mass of fines removed, the impact on off-site water quality and on-site nutrient concentrations may be significant. The percentage of fine, medium and coarse wet-sieved aggregates for Group 1 RECS, Group 2 RECS, bare soil (representative of Group 3 surface covers) and the *in situ* soil are presented in a ternary diagram (Figure 5). These data indicate that sediment transported from the plots with the least surface coverage (bare and Group 2) were the most similar to the *in situ* soil (I in Figure 5). The aggregate size distribution of splashed sediment from the Group 2 RECS (G2) was slightly finer than that from the bare

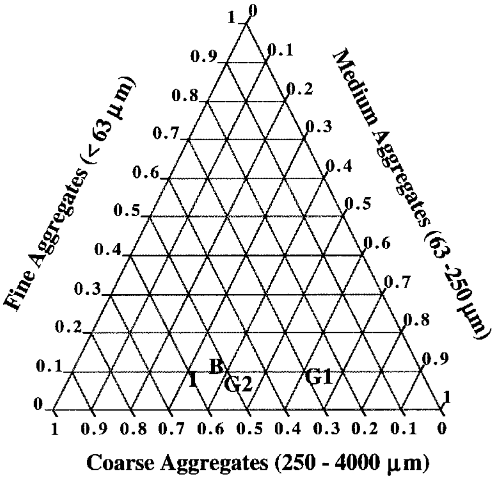

Figure 5. A ternary diagram indicating the wet-sieved aggregate size distribution from two RECS groups, the bare soil control (B) and the *in situ* soil (I). G1 represents the distribution of splashed sediment from Group 1 RECS (Futerra, C125, Curlex I, BioD-Mat 70, P300, SC150BN and BioD-Mesh 60); G2 represents the distribution of splashed sediment from Group 2 RECS (GeoJute, SuperGro, PEC-MAT, TerraJute, BioD-Mat 40).

treatment (B), but substantially coarser than the Group 1 RECS (G1). The percentage of aggregates in each of the three fractions reflects the interaction of kinetic energy with the surface soil. Coarse aggregates were transported when rainfall energy was unimpeded by cover (bare) or minimally impeded by cover (Group 2 RECS). As the percentage of cover and the thickness of the systems increased (Group 1 RECS), less raindrop impact energy was available to detach and transport the material from the splash cups. In addition, it is likely that the coarser aggregates detached from the G1-covered plots were caught within the fibers, and not transported out of the plot. This trapping effect may lead to an overall reduction in the size of splashed sediment. In summary, although Group 1 RECS preferentially transported finer aggregate sizes, the overall sediment production (mass) of fines was less than with the Group 2 systems or the bare soil control.

SUMMARY AND CONCLUSION

This temporally based investigation of interrill splash transport demonstrated the following points regarding several commonly used rolled erosion control system.

(1) RECS differed statistically in the protection they provided against rainsplash detachment and transport of sediment. All but one system significantly reduced splash output compared with the bare soil control, but among the systems providing adequate protection, two statistically separate groups emerged. The seven products comprising the ‘best’ group of RECS all reduced splash output by $\geqslant 97$ per cent for the 1-h simulated events; the other group was somewhat less effective (82–94 per cent).

(2) Reduction in splash detachment and transport by RECS varied throughout the duration of the 1-h simulated rain event. Notably, some systems performed adequately until a critical threshold when the mitigation of splash transport broke down. This threshold often corresponded with the formation of a thin, muddy water layer that resulted from surface sealing. RECS that absorbed much of the kinetic energy of raindrop impact prevented surface sealing, and were therefore the most effective.

(3) As indicated in point (2) above, splash protection provided by RECS can be related to their design. The systems which performed best were characterized by a combination of high surface coverage and substantial thickness.

In conclusion, if rolled erosion control systems are to be effective in reducing erosion and sediment-related pollution from construction areas and other degraded hillslopes, systems must be carefully designed to mitigate important erosion subprocesses. This study indicates that in order to reduce the rainsplash detachment and transport of sediment, design engineers need to incorporate high surface coverage and reasonable thickness into product design. However, what is not known from the present study is the optimal surface coverage that provides adequate surface protection while allowing a suitable vegetation cover to become established. It is the development of a natural, protective vegetation cover that will provide long-term sustainability of hillslope systems because most RECS, particularly organic systems, eventually biodegrade.

Although surface coverage appears to be the most important product attribute in mitigating splash processes, we fell that *three dimensionality* (i.e. thick, flexible, intertwined fibers) is an important attribute for the reduction of total erosion processes (splash and hydraulic) on degraded hillslopes. For example, reduction of sediment detachment and transport by overland flow requires RECS that drape snugly on irregular soil surfaces, and whose fibers trap moving sediment and resist surface flow. Future research should include rill-length, temporal-based studies to ascertain product performance in reducing hydraulic erosion processes.

Finally, this study emphasizes that when testing RECS performance, temporal responses should be monitored, and studies should be conducted for an appropriate period of time in order to fully characterize the response. Such attention to time ensures the identification of critical thresholds where systems become less effective. Short-duration experiments may fail to reach threshold points, and thus provide a poor indication of system effectiveness.

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