LAND DEGRADATION & DEVELOPMENT

Land Degrad. Develop. **16**: 1–13 (2005)

Published online in Wiley InterScience (www.interscience.wiley.com). **DOI**: 10.1002/ldr.679

SIMULATED RAINFALL EVALUATION OF REVEGETATION/MULCH EROSION CONTROL IN THE LAKE TAHOE BASIN—3: SOIL TREATMENT EFFECTS[Q9]

Q9

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Received 11 November 2004; Revised 28 November 2004; Accepted 4 January 2005

ABSTRACT

Revegetation, or other erosion control treatments of disturbed soil slopes in forested areas and along highways of the Lake Tahoe basin are directed at reduction of sediment loading to waterways reaching the lake. However, following treatment, little vegetation monitoring, or hydrologic evaluation has been conducted either to determine if the various treatments are successful or to assess the duration of erosion control anticipated in the field. Here, we build upon results from use of the portable rainfall simulator (RS) described in the first two papers of this series to evaluate cover and revegetation treatment effects on runoff rates and sediment concentrations and yields from disturbed granitic and volcanic soils in the basin. The effects of slope on rainfall runoff, infiltration and erosion rates were determined at several revegetated road cut and ski run sites. Rainfall simulation ($\sim 60\,\mathrm{mm\,h^{-1}}$, approximating a 100-year, 15-minute storm) had a mean drop size of $\sim 2{\cdot}1$ mm and approximately 70 per cent of 'natural' rainfall kinetic energy. Measurements of: time to runoff; infiltration; runoff amount; sediment yield; and average sediment concentration were obtained. Runoff sediment concentrations and yields from sparsely covered volcanic and bare granitic soils can be correlated to slope. Sediment concentrations and yields from nearly bare volcanic soils exceeded those from granitic soils by an order of magnitude across slopes ranging from 30–70 per cent. Revegetation, or application of pine-needle mulch covers to both soil types dramatically decreased sediment concentrations and yields. Incorporation of woodchips or soil rehabilitation that includes tillage, use of amendments (biosol, compost) and mulch covers together with plant seeding resulted in little or no runoff or sediment yield from both soils. Repeated measurements of sediment concentrations and yields in the subsequent two years following woodchip or soil rehabilitation treatments continued to result in little or no runoff. Revegetation treatments involving only use of grasses to cover the soils were largely ineffective due to sparse sustainable coverage (<35 per cent) and inadequate infiltration rates. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: Rainfall simulation; sub-alpine environment; semiarid; slopes; ski runs; road cuts; volcanic soils; granitic soils; USA

INTRODUCTION

Over the past 50 years development in the Lake Tahoe basin has caused an increased flux of sediment and nutrients into the lake contributing to the loss of Tahoe's exceptional clarity by 25 per cent from approximately 30 to 21 m. Efforts to slow nutrient input to the lake have taken many forms most of which focus on containment of sediment on site, or within the drainages from which they originate. Unfortunately, despite considerable effort and resources, little quantitative information exists concerning the performance of hillslope erosion control measures employed in the basin (Schuster and Grismer, 2004; Grismer and Hogan, 2004, 2005). However, there are ample examples of visible failures in erosion control in this semiarid, high-altitude environment of relatively shallow soils, minimal summer rains and long winters.

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Contract/grant sponsors: California Department of Transportation (CalTrans), USA. US Forest Service.

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Construction of road cuts and ski runs in the basin often results in loss of nutrient-containing topsoil essential for plant growth while exposing the remaining oft-compacted, readily erodible decomposed granite (DG) or volcanic subsoils to erosion. The resulting low organic-matter content of the DG soils (< 1 per cent) may also limit mycorrhizal infection, a potentially important component in native grass re-establishment. Compounding soil degradation and subsequent lack of plant establishment is the fact that continued erosion may result in persistent nitrogen deficiency (Claassen *et al*., 1995).

Of particular note in comparing physical conditions or parameters of ski runs and road cuts is the difference in construction methodologies: ski runs are often cut and smooth-graded using a crawler-type tractor. This process usually results in a highly compacted surface. Ski runs seldom consist of 'C' horizon material but meet the definition of 'drastic disturbance' (Box, 1978). Conversely, road cuts, while also defined as 'drastically' disturbed (as differentiated from road fills) are often cut directly into C horizons and/or parent material, with the top of the cut slope made up of remnant native soil that immediately grades into the B, C and parent-material horizons. Thus, road cuts, while not compacted *per se*, usually consist of an inherently high-density material.

Grismer and Hogan (2004, 2005) used the rainfall simulator (RS) as a means by which to standardize measurement of erosion from disturbed granitic and volcanic soils through replicated rainfall events of the same intensity, or kinetic energy, on multiple plots enabling statistical evaluation of plot physical characteristics on particular hydrologic parameters. The primary advantages of the RS are the ability: (a) to transport it to a variety of field locations as needed in order to evaluate a sufficient number of plots at any one location with statistical significance; and (b) to test a number of assumptions regarding erosion behavior using real-time measurements rather than relying on locally untested model parameters.

PROJECT OBJECTIVES

We hypothesized that native grass revegetation would be reflected in greater infiltration rates and less runoff or sediment yield in successfully restored sites and that these changes could be measured directly in the field using RS techniques. The overall project objectives included evaluation of the runoff and sediment yields associated with bare soils and a variety of revegetation/cover treatments on road cuts and ski runs of varying slopes. The specific objective herein was to evaluate the factors effecting runoff rates and sediment yields from revegetated/mulched disturbed (i.e. road cuts, ski runs) granitic and volcanic soils in the basin and subsequent comparison to those values determined previously (Grismer and Hogan, 2005) from bare and 'native' soils at the same sites.

METHODOLOGY

Rainfall-simulation tests were conducted at several granitic soil road cuts and ski runs around the basin. Where possible, we also conducted RS tests on less-disturbed, 'native' soils having some pine-needle mulch cover often located below established conifers and very near bare-soil sites. Granitic-soil sites were located on ski runs at Heavenly Valley Mountain Resort at South Tahoe and at road cuts at Luther Pass Highway 89 and mileposts 22·8 (Rubicon) and 18·5 (Bliss) along State Highway 89 south of Tahoe City, all in California. Smaller road cuts were located at Cave Rock Estates on the east shore of Tahoe in Nevada (see Grismer and Hogan, 2004). Table I summarizes the locations of all the sites at which RS experiments were conducted while Table II lists the soil-survey characteristics of these sites.

Following a preliminary land survey of a site and establishment of plots and installation of plot frames (0·8 m $\times$ 0·8 m), the RS was centered over the plot frame and leveled. Detailed descriptions of the RS and plot frame are provided by Battany and Grismer (2000) and further discussed in the first paper of this series (Grismer and Hogan, 2004). The front adjustable legs of the RS tower allowed access to steeper slopes and a combination of two ladders with ladder jacks laid on the slope were used to support the front legs with minimal disturbance to the site. Three soil samples were collected from around the plot frame and later dried for 48 hours at 105°C to

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Table I. Locations of bare soil road cut and ski run sites in the Tahoe basin

Location (WGS′84[Q1])	Condition	Latitude (N)	Longitude (W)	Elevation (m)	Aspect
Granitic soils					
Bliss	Road cut	39° 03·27	120° 06·78	2010	NE
Cave Rock Estates	Road cut	39° 25·27	120° 56·78	1950	NE
Heavenly Valley LT	Ski run	38° 55·37	119° 54·97	2440	N
Luther Pass Grass Lake	Road cut	38° 47·82	119° 58·07	2100	NW
Rubicon	Road cut	39° 01·10	120° 07·53	2000	E
Volcanic soils					
Blackwood Canyon	Road cut	39° 06·27	120° 11·78	1950	N
Brockway Summit	Road cut	39° 15·49	120° 03·39	2090	WSW
Dollar Hill–west	Road cut	39° 11·73	120° 06·00	1950	S
Dollar Hill–east	Road cut	39° 11·84	120° 05·99	1950	SSE
Homewood Mtn Resort	Ski run	39° 08·27	120° 09·78	1950	E
Northstar Unit 7	Road cut	39° 16·57	120° 07·93	2010	E
Northstar Look Out Mtn	Ski run	39° 16·21	120° 08·85	2150	NE
Northstar ski run	Ski run	39° 16·04	120° 07·80	2150	E
Snowking (Juniper Mtn)	Ski run	39° 11·56	120° 13·04	2110	NE
Prosser I–80 interchange	Road cut	39° 21·27	120° 08·75	1785	N
Sierraville I–80 exchange	Road cut	39° 20·33	120° 10·15	1815	E
Trout Cr. I–80 exchange	Road cut	39° 19·91	120° 11·12[Q2]	1820	S

Table II. Summary of soil characteristics at Tahoe basin RS sites (NRCS, 1974[Q3])

Site	Soil series	Taxonomic classification	Surface texture	Basin soils (%)	Area of basin soils (ha)	pH	Permeability (mm h^{-1})	Available water cap. (mm^{-2}[Q3])
Blackwood & Northstar ski run	Waca	Medial-skeletal, amorphic, frigid Humic Vitrixerands	Cobbly coarse sandy-loam	0·3	288	5·6–6·5	5·1–16	0·06–0·08
Bliss, Luther Pass & Rubicon	Meeks	Sandy-skeletal, mixed, frigid Humic Dystroxerepts	Very stony loamy coarse-sand	1·2	1020	6·1–6·5	16–51	0·03–0·05
Brockway, Dollar Hill & Nothstar LOM	Jorge-Tahoma	Fine-loamy, isotic, frigid Ultic or amorphic, frigid Ultic Haploxeralfs	Very stony sandy-loam	0·3	288	5·1–6·0	5·1–16	0·10–0·12
Cave Rock & Incline Village & Northstar U7	Umpa	Loamy-skeletal, isotic, frigid Andic Dystroxerepts	Very stony sandy-loam	3·3	2735	—	—	—

determine pre-rainfall soil moisture at each plot. A plexiglass sheet was placed on the simulator structure above the plot frame and the rainfall rate established at 60 mm h^{-1} after which the sheet was quickly removed and rainfall initiated. Rainfall was allowed to continue until either steady runoff was obtained, or ~60 minutes had elapsed. Following removal of the RS, the surface micro-topography of the plot was measured as well as the visible wetting front depth.

Following field measurements, collected runoff samples were taken to the laboratory for filtration and chemical analyses. Samples were vacuum filtered first through a Whatman #1® filter followed by a 0·45 µm filter. The filter papers with sediment were dried at 105°C, weighed and total sediment mass per volume of runoff was determined. More recently, we have changed to ashless micron filters so as to determine the mineral fraction of retained 'sediment' through combustion techniques (e.g. Davies, 1974).

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Table III. Summary of site treatment/physical characteristics at Tahoe basin RS sites

Site	Seed mix	Amends	Fertilizer	Mulch		Tillage depth (mm)	Treat. year
				Type	Depth (mm)		
Granitic soils							
Bliss	None	Forest duff[1]	None	Pine needle (PN)	25	150	2000
Cave Rock	*Br ca*/*El el*[2] (100 kg ha^{-1})	Compost	Biosol	PN over straw	50	150	2000
Luther Pass–GV	*El el*, *El gl*, *Br ca*	Compost	Biosol	Pine needles	25	None	1999
Rubicon	Caltrans Type B grasses–planted	Compost	16-16-16	Straw & PN	~25	None	1998
Volcanic soils							
Brockway	Various grass mixes (unknown)	Compost	Biosol	PN	10	100	1998?
Dollar Hill–west	Various bunchgrass (BG) mixes	0	Biosol	PN, hand applied	30	None	1999
Dollar Hill–east	Native grasses over std. mix w[Q4]/yarrow	No	Biosol	Ground PN	50	None	1998?
Northstar Unit 7 ('Hogan Reveg')	*El el*, *El gl*, *Br ca*	Compost 100 mm	Biosol	Pine needles	25	300	2000
Northstar Lookout Mtn (LOM)	Native & adapted grasses	0	Biosol	Straw	0		2001
Snowking (Juniper Mtn)	*El el*, *El gl*, *Br ca*	Compost & woodchips	Biosol	Pine needles	25	300	2002

Q4

[1]Forest duff = broken down organic litter matter on forest floor (fine powder).
[2]Various grass species *El el* = Elymus elymoides; *Br ca* = Bromus carinatus; *El gl* = Elymus glaucus.[Q5]

Q5

Incomplete information was available on the range of revegetation or cover treatments at the various sites including as-built conditions. Revegetation, soil conditioning or covers ranged widely from simple straw or pine-needle mulch (PNM) covers to grass planting with fertilizer to complete soil rehabilitation with compost/duff and subsequent planting. Table III summarizes the various treatments used at the sites. Bare-soil conditions were considered previously (Grismer and Hogan, 2005) and are only briefly addressed here when comparing bare soil and revegetated/mulched treatment results.

RESULTS AND DISCUSSION

Granitic Soils Treatments

We previously found that runoff and sediment yields from bare soils and hydrologic effects of various revegetation/mulch erosion control treatments were strongly soil-type dependent (Grismer and Hogan, 2004, 2005), so here we consider the effects of these treatments on each soil type individually. In this section we consider the hydrologic effects of various revegetation/mulch erosion control treatments on granitic soils, followed by a similar section discussing volcanic soils.

Table IV summarizes the rainfall simulation plot average results for all the granitic soil plots monitored in the basin including treated, native and bare soils. We briefly revisit analysis of runoff and sediment yield from bare and 'native' granitic soils followed by that from treated, disturbed soils so as to enable subsequent comparisons, or determinations of improvement in retaining sediment on the slope. Grismer and Hogan (2005) noted that bare (and native) granitic soil sediment yields were largely dependent on average downslope as shown in Figure 1 in which there is a roughly exponential increase in sediment yield (or concentration) with increasing slope. For example, sediment yields are roughly $\sim 1\ \mathrm{g\,m^{-2}\,mm^{-1}}$ at ~35 per cent slope increasing to $2{\cdot}5\ \mathrm{g\,m^{-2}\,mm^{-1}}$ at ~55 per cent

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Table IV. Summary of rainfall simulation plot average results for granitic soils in the Lake Tahoe basin

Location/Treatment	Slope (%)	Diagonal X-slope	Rough. (mm) (%)	Time to runoff (s)	Cum. @ 15 min		Infilt. ($mm\,h^{-1}$)	Runoff ($mm\,h^{-1}$)	Sed. conc. ($g\,L^{-1}$)	Sed. yield ($kg\,ha^{-1}\,mm^{-1}$)	R^2 (%)
					Runoff (mm)	Sed. (g)					
Bliss Highway 89 road cut											
Bare soil–average	56·3	39·9	6·7	354	1·0	2·40	49·46	11·54	2·43	33·7	86·0
Bare soil–steep	72·3	42·9	6·3	69	1·6	12·66	44·68	14·32	14·6	126	98·5
Pine-needle mulch (PNM)	58·1	40·5	6·9	245	0·6	1·27	49·92	8·41	1·21	23·1	90·2
Tilled in duff	58·4	40·6	10·4	1366	0·0	0·02	58·93	1·07	0·34	4·2	89·1
Tilled in duff + PNM	56·0	37·3	7·1	916	0·1	0·05	57·40	1·60	0·42	5·9	86·0
Cave Rock & Incline Village Project road cuts											
Bare soil	59·5	39·1	7·4	465	0·6	1·39	45·62	13·71	5·29	20·6	91·4
Compost + PN cover	64·5	44·4	6·2	666	0·1	0·27	57·39	2·61	0·25	4·1	83·2
Grass reveg.	60·2	38·5	15·7	70	2·4	0·57	48·07	11·93	0·17	2·6	89·2
IVP Grass reveg.	48·3	32·0	13·6	337	0·3	0·07	52·63	6·87	0·22	2·8	97·5
Luther Pass road cut–2002											
Control	51·0	35·0	11·6	147	3·3	2·41	38·09	22·58	1·08	14·2	97·3
Seed, plants & PNM	55·46	55·5	40·2	15·3	140	3·0	40·63	18·71	1·15	15·2	93·3
Amendments & PNM	52·15	52·1	38·1	11·0	106	3·1	39·11	19·72	1·31	16·8	76·1
Amends, plants & PNM	50·62	50·6	34·7	21·4	171	3·5	41·47	18·51	2·10	29·7	94·2
Compost, Biosol®, plants & PNM	51·20	51·2	33·0	11·4	129	2·7	45·81	14·19	0·84	10·6	81·9
Luther Pass road cut–2003											
Control	51·0	39·5	13·8	350	1·9	2·97	48·31	11·69	1·59	21·1	95·8
Seed, plants & PNM	57·54	57·5	41·3	17·3	233	1·9	48·03	11·97	0·90	13·5	93·3
Amendments & PNM	50·61	50·6	37·0	11·5	213	2·4	46·11	13·89	2·41	27·2	95·2
Amends, plants & PNM	55·51	55·5	39·5	11·7	189	2·8	35·43	24·57	0·83	11·7	89·7
Compost, Biosol®, plants & PNM	56·10	56·1	45·2	16·9	188	1·4	52·93	7·07	0·70	11·7	88·4
Heavenly Valley Front ski run											
Bare soil	35·5	26·8	11·8	1900	0·0	0	59·06	0·63	0·80	12·8	100·0
Bare soil	78·6	44·7	26·5	145	1·8	5·18	47·37	11·63	4·06	47·9	98·9
Grass (*Festuca* sp.)	37·4	29·4	13·1	146	3·0	2·20	38·77	21·23	0·87	14·9	87·9
Grass (*Festuca* sp.)	89·1	59·9	24·7	290	1·5	3·34	49·31	10·19	2·11	30·2	81·2
Brush/shrub	32·8	26·4	16·1	718	0·1	0·08	53·94	3·38	2·53	43·6	99·2
Brush/shrub	82·5	59·3	31·9	200	1·9	11·90	45·16	13·34	11·1	128	98·2
Heavenly Valley Long-Term (LT) plots											
Native	36·1	36·1	24·4	12·2	326	3·7	35·40	24·60	0·59	8·7	89·5
Bare–low	27·5	22·8	11·5	159	5·1	5·14	32·54	27·46	1·44	21·3	86·4
Bare–average	47·9	34·2	14·0	226	3·9	4·94	35·59	24·41	1·83	25·7	89·8
Rubicon Highway 89 road cut/fill											
Fill bare soil	58·1	38·1	11·0	187	1·7	2·17	42·0	17·0	1·32	20·3	94·6
Fill PNM cover	61·9	38·5	10·1	111	1·4	0·89	43·0	17·0	1·19	11·3	97·8
Plant reveg.	50·3	35·7	8·9	550	0·2	0·08	58·45	1·55	0·09	1·8	78·0
Native + PNM	37·4	24·2	13·3	395	0·6	0·3	56·24	3·76	0·09	1·8	69·6

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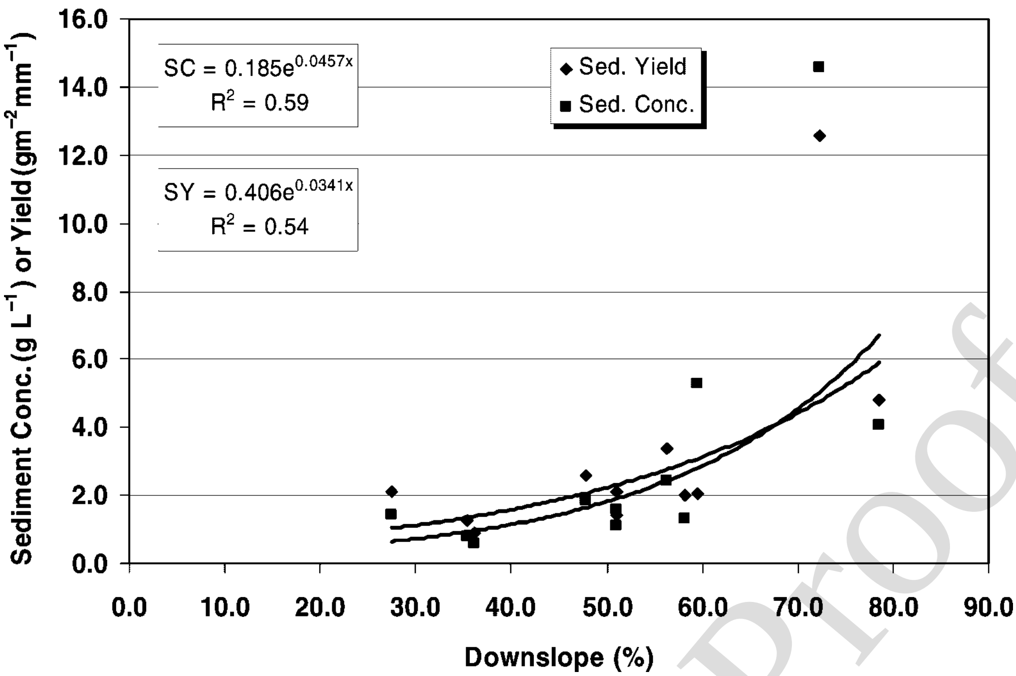

Figure 1. Runoff sediment concentration (SC) and yield (SY) from bare and native granitic soil plots as they depend on plot slope.

slope and $\sim$9 g m^{-2} mm^{-1} at $\sim$75 per cent slope. Native soil plots were on generally smaller slopes and sediment yields from these plots were less than, but undistinguishable from, that of disturbed bare soil plots on similar slopes. Generally, sediment yields from granitic soils were relatively small as compared to those from volcanic soils except on very steep slopes.

Granitic soil treatments ranged from simple pine-needle mulch (PNM) cover (common on 'native' soils), the use of soil amendments (e.g. compost, Biosol$^{®}$, forest duff) and seeding/planting a grass cover, or some combination thereof. The 'standard' grass/*Festuca* sp. treatment generally involved hydroseeding a mixture of a fescue seed mix, fertilizer, wood fiber mulch and tackifier in a one-step process. These ingredients are mixed into a slurry and applied to the surface of a slope (see Table III). Soil amendment treatments included either tilling or complete mixing of compost into organic-poor soil to improve soil tilth, water-holding capacity, nutrient cycling and infiltration rates. PNM covers are commonly found on the forest floor in less disturbed areas and provide a long-lasting surface protection to raindrop impacts and subsequent splash-induced soil-particle detachment. Though not an actual 'treatment', at the Heavenly Valley ski run, we also took measurements in a 'brush' area on a steep slope. Figure 2 graphically illustrates sediment concentrations and yields from all of the granitic soil treatments as a function of average slope. Runoff from the steep 'brush' plots resulted in sediment concentrations and yields similar to that from bare soils at the same slope. Aside from runoff sediment values from the brush plot, there was no significant correlation (95 per cent level) between sediment concentrations or yields and slope in contrast to that from bare soil plots (see Figure 1). All of the remaining treatments, either individually or in combination, resulted in sediment concentrations and yields less than $\sim$4 g L^{-1} or g m^{-2} mm^{-1}, respectively. Complete revegetation plus soil-rehabilitation treatments (e.g. Cave Rock) resulted in runoff sediment values similar to that from native plots and much less than 1 g L^{-1} or g m^{-2} mm^{-1}. To better illustrate the effects of the complete revegetation treatments, we noted that most of the granitic-plot slopes were between 50 and 60 per cent and that averages from plots within this range could be compared. Taking averages of all plots in this slope range for each category of treatment we developed a comparison between bare, complete revegetation (i.e., Hogan reveg.), soil amendments and PNM and soil amendments and plants in terms of cumulative runoff and sediment at 15 minutes, sediment concentration and sediment yield for a $\sim$55 per cent slope as shown in Figure 3.

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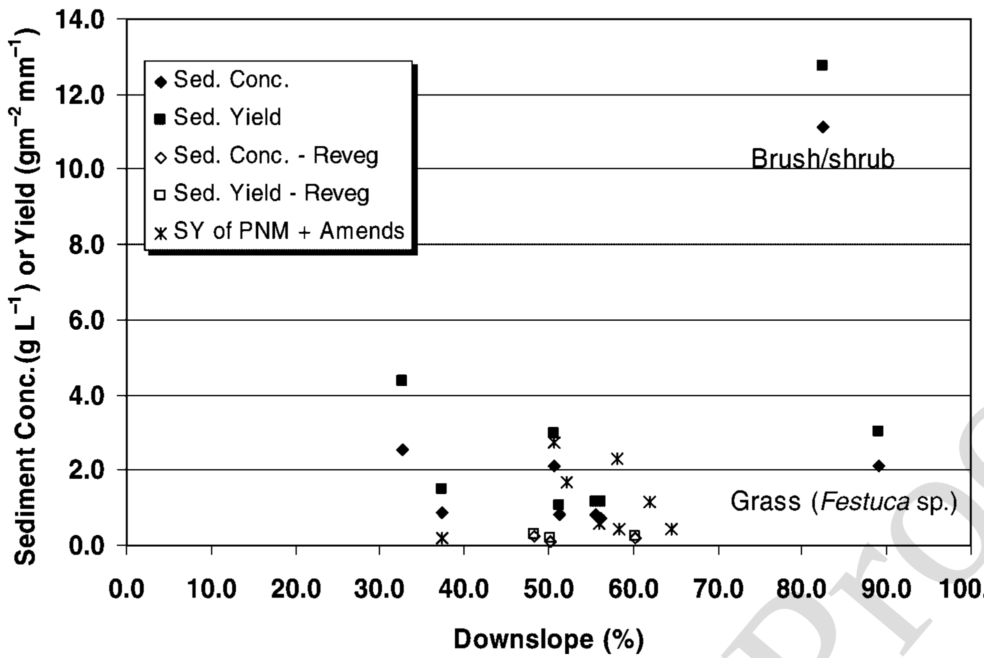

Figure 2. Runoff sediment concentration and yield from treated granitic soil plots as they depend on plot slope.

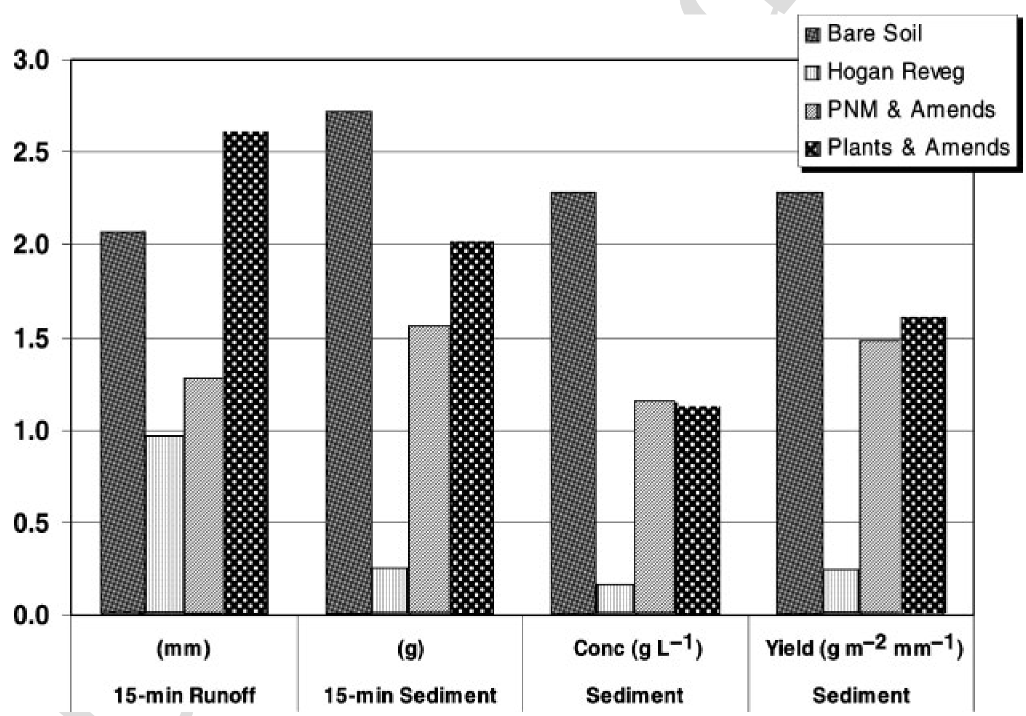

Figure 3. Average runoff sediment concentration and yield from two granitic sites with plot slopes between 50 and 60 per cent.

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The longer-term erosion-control effectiveness of revegetation/mulch treatments on these nutrient-deficient disturbed soils remains a serious concern. In repeated measurements of runoff and sediment yield at the Luther Pass site in 2002 and 2003, we found no significant changes in effectiveness. These two years of measurements, however, represent more than three years after the original installation and unfortunately there is no pre-treatment erosion-related information available.

In comparing soil-treatment effects on runoff and sediment parameters for the granitic soils on a $\sim$55 per cent slope it is apparent that soil amendments with either a plant or PNM covers reduce sediment loss from the hillslope. Average sediment concentrations decline by approximately 50 per cent and sediment yields fall by over 30 per cent. However, despite such reductions, these values exceed those from 'native' soils. On the other hand, complete soil/plant restoration treatments reduced sediment concentration and yield by an order of magnitude resulting in values similar to, or less than, those from native soil plots.

Volcanic Soils Treatments

As with the granitic soils, we briefly review runoff rates and sediment yields from bare and native volcanic soils followed by that for treated disturbed soils. Table V summarizes the rainfall simulation plot average results for the bare and 'native' volcanic soil plots, while Table VI summarizes those results for the treated plots monitored in the basin. In contrast to those for the granitic soils, bare native volcanic soil runoff sediment concentrations and yields were only very weakly dependent on average downslope, though the same trend of increasing sediment loss with increasing slope was observed. Bare volcanic soil sediment concentrations and yields are several times greater than that from granitic soils. For comparison purposes, the least squares regression exponential equations relating sediment concentrations and yields to downslope are provided in Figure 4 (see also Figure 1). At an average plot slope of 50 per cent the average sediment yield from the bare volcanic soils is $\sim 10\,g\,m^{-2}\,mm^{-1}$ as compared to $\sim 2\,g\,m^{-2}\,mm^{-1}$ for granitic soils. On the other hand, sediment-loss values from the native volcanic soils were similar to those from native granitic soils for the same storm intensities.

We briefly recall here that early studies by Wischmeier and Meyer (1973) indicated that on a short run of $\sim$9 m and slope of 20 per cent, application of roughly $1\,Mg\,ha^{-1}$ woodchips or straw cover reduced soil loss by 32 per cent and 69 per cent, respectively; increasing woodchip cover to $10\,Mg\,ha^{-1}$ virtually eliminated soil loss. As discussed below, we also found that incorporation of similar application rates of woodchips dramatically decreased sediment concentrations and yields on various slopes of the Tahoe basin.

Erosion control and revegetation treatments are crucial to stabilizing disturbed volcanic soil hillslopes due to the relatively high runoff sediment concentrations and fine particle size associated with the volcanic soils. In many cases, such treatments can be quite effective, though there is considerable variability in the runoff sediment concentrations. Treatments varied greatly from hydroseeding on CalTrans (California Department of Transportation) slopes (Highway 80 projects) and some ski runs (e.g. Look Out Mountain runs) to a complete mixing of compost into the soil as at Unit 7 to 'ripping' in of compost and woodchips to 30 cm depth (Snow King, Juniper Mountain). The range of treatments was similar to that of granitic slopes, as described previously. As summarized in Table VI, incorporated woodchips and soil restoration revegetation (i.e., Hogan reveg.) are effective in eliminating erosion from the hillslope as no runoff occurred. Grouping the remaining treatments into two categories of: (a) covers (standard grass/*Festuca* sp., PNM, hydromulch and straw); and (b) combined soil amendments (i.e., compost and biosol) and plant seeding. Both were effective in controlling rainfall-induced erosion. With the exception of the standard grass/*Festuca* sp. treatment, the remaining treatments resulted in runoff sediment concentrations and yields that did not correlate with downslope for the range of slopes considered. Hydromulch was visibly degraded within one year of application.

Runoff sediment concentrations and yields from the standard grass (*Festuca* sp.) treatments having grass cover in the range of 25 to 45 per cent showed a similar downslope dependence to that from bare soils, though regressions were less significant than those for bare granite soils (see Figure 4). Coincidentally, the exponential regression equations for sediment yields as a function of slope were practically the same for the volcanic grass (*Festuca* sp.) treatment and bare granitic soils with the exception that yields from the grass-treated volcanic soils are 30 per cent greater at any given slope. New straw cover resulted in lower sediment concentrations and yields than the standard

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Table V. Summary of rainfall simulation plot average results for bare volcanic soils in the Lake Tahoe basin[Q6]

Location/Treatment	Slope (%)	Diagonal X-slope (%)	Rough. (mm)	Time to runoff (s)	Cum. @ 15 min		Infilt. ($mm\,h^{-1}$)	Runoff ($mm\,h^{-1}$)	Sed. conc. ($g\,L^{-1}$)	Sed. yield ($kg\,ha^{-1}\,mm^{-1}$)	R^2 (%)
					Runoff (mm)	Sediment (g)					
Blackwood bare soil	61·4	37·9	10·6	857	0·06	0·03	60·00	0·47	1·89	19·2	100·0
Brockway bare soil	51·5	32·4	10·6	242	2·35	16·0	36·19	23·47	11·31	123	99·4
Brockway bare duff	48·0	31·2	12·3	613	0·43	6·33	53·75	6·25	17·33	210	96·6
Dollar Hill bare soil	48·5	33·6	10·2	325	0·86	2·66	47·3	12·8	4·19	43·4	99·4
Homewood Mtn ski run[Q7]	22·1	15·5	10·9	510	0·94	8·18	42·87	17·13	7·64	91·7	96·3
Bare soil	32·8	23·6	8·9	343	1·64	8·62	33·33	26·67	4·58	72·0	94·6
Bare soil	56·9	37·8	14·4	233	2·78	18·0	39·63	20·37	13·53	131	99·3
Native	74·4	48·3	18·0	350	1·97	3·58	47·08	12·92	1·98	21·6	99·1
Northstar Unit 7 road cut											
Bare–old std. grass reveg.	48·9	31·0	16·8	453	0·93	5·30	39·87	20·13	4·92	66·4	96·0
Bare–old std. grass reveg.	47·9	36·6	15·1	600	0·40	1·63	48·48	11·52	6·73	58·5	99·3
Bare/native	55·1	36·9	26·6	307	2·33	11·8	43·71	16·29	7·04	73·4	96·4
Northstar Lookout Mtn. ski run											
Bare non-planed ski run	39·8	26·7	14·6	233	2·11	18·0	33·34	26·66	12·64	155	94·4
Planed ski run bare soil	34·0	21·4	23·7	420	0·73	3·34	47·48	12·52	5·80	72·1	99·0
Native w/PNM by non-planed ski run	45·1	31·5	10·6	449	1·51	1·71	47·66	12·34	1·79	25·0	89·0
Native w/PNM by planed ski run	45·0	30·0	22·2	272	1·10	0·43	52·08	7·92	0·49	6·2	97·2
I-80 Prosser/Sierraville road cut											
Bare soil	32·4	29·7	9·5	236	0·89	2·41	54·40	5·60	3·40	46·9	98·4
Bare soil	60·9	43·9	9·3	83	4·22	43·6	39·27	21·73	15·58	161	99·3

Q7

Q6

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Table VI. Summary of rainfall simulation plot average results for treated volcanic soils in the Lake Tahoe basin

Location/Treatment	Slope (%)	Diagonal X-slope (%)	Rough. (mm)	Time to runoff (s)	Cum. @ 15 min Runoff (mm)	Cum. @ 15 min Sed. (g)	Infilt. ($mm\,h^{-1}$)	Runoff ($mm\,h^{-1}$)	Sed. conc. ($g\,L^{-1}$)	Sed. yield ($kg\,ha^{-1}\,mm^{-1}$)	R^2 (%)
Brockway Summit road cut											
Pine-needle mulch	55·2	34·0	15·3	238	2·33	1·73	43·6	16·4	0·63	11·4	87·4
PNM + compost	50·3	35·7	14·3	483	0·44	0·40	50·5	9·5	0·74	9·9	63·6
Dollar Hill road cut											
Pine-needle mulch (PNM)	54·3	35·6	11·9	263	0·71	0·43	55·4	7·6	0·66	8·2	91·9
PNM + Bunchgrass (BG)	55·8	36·4	14·3	237	1·73	3·14	46·2	15·3	2·10	22·9	95·9
PNM + BG + duff	54·6	36·4	14·2	803	0·11	0·19	57·3	2·7	1·70	17·0	97·7
Old PNM + yarrow	49·8	33·5	9·3	272	1·86	8·73	41·0	20·0	7·76	88·2	96·1
Homewood Mtn. ski run											
Woodchips	20·9	15·3	7·3	No runoff	0·00	0·00	> 60	0·0	0·00	0·00	NA
Std. grass/*Festuca* sp.	20·4	14·7	8·7	428	3·05	1·31	32·3	27·7	0·55	6·7	89·3
Std. grass/*Festuca* sp.	38·1	27·0	12·3	1416	0·94	1·10	42·9	17·1	0·97	10·0	99·8
Std. grass/*Festuca* sp.	61·5	43·2	29·6	1078	0·00	0·00	55·3	4·7	2·07	27·5	97·7
Brush	37·8	25·8	14·8	519	2·00	1·13	39·8	20·2	0·69	8·4	93·5
NorthStar Unit 7 road cut											
Hogan reveg. ’02	53·5	36·1	17·8	No runoff	0·00	0·00	> 60	0·0	0·00	0·00	NA
Hogan reveg. ’02	52·9	35·3	13·5	No runoff	0·00	0·00	> 60	0·0	0·00	0·00	NA
Hog. reveg. ’02–Rain = 120 $mm\,h^{-1}$	72·3	93·9	11·4	322	2·49	1·30	103·9	16·1	0·71	9·1	95·9
Hogan reveg. ’03–Rain = 80 $mm\,h^{-1}$	41·2	39·4	11·1	No runoff	0·00	0·00	> 80	0·0	0·00	0·00	NA
Hogan reveg. ’03–Rain = 80 $mm\,h^{-1}$	50·5	43·3	17·4	No runoff	0·00	0·00	> 80	0·0	0·00	0·00	NA
Hogan reveg. ’03–Rain = 80 $mm\,h^{-1}$	67·0	45·9	16·3	No runoff	0·00	0·00	> 80	0·0	0·00	0·00	NA
Northstar LOM ski run–2002											
Planed ski-run w/6 mm straw	34·6	25·8	7·5	413	0·45	2·70	45·0	15·0	2·16	47·3	55·7
Grass reveg. by lift	50·5	31·5	11·6	1157	0·01	0·01	58·0	0·7	0·00	17·4	98·8
Grass reveg. above lift	43·2	27·2	17·2	807	0·16	0·73	55·1	3·3	1·87	27·1	97·1
Ski run below ski lift–grass + PNM	27·5	19·9	13·3	2400	0·00	0·00	> 60	0·0	0·00	13·3	100·0
Ski run below ski lift–grass + PNM	47·0	30·7	12·6	757	0·30	2·53	49·3	10·7	4·38	69·7	90·4
Northstar LOM ski run–2003											
Reveg. in lift bowl	51·8	40·3	19·3	964	0·00	0·00	57·7	2·3	1·56	24·2	99·7
Reveg. above lift bowl	49·5	38·7	12·3	769	0·10	0·10	58·5	1·5	0·98	15·8	100·0
2002 Reveg. along RC above lift–hydroseed + Biosol + PNM	61·2	44·4	23·6	No runoff	0·00	0·00	0·0	> 60	0·00	0·00	NA
I-80 Prosser/Sierraville road cut–2002											
Straw cover	81·9	21·6	11·4	405	0·12	0·37	54·4	6·6	1·00	19·7	89·6
Hydromulch	65·0	22·2	15·4	287	2·32	1·31	41·4	19·1	0·65	9·2	94·4
Woodchip mulch	45·0	16·6	16·0	No runoff	0·00	0·00	> 60	0·0	0·00	0·00	NA
I-80 Prosser/Sierraville road cut–2003											
Straw cover	75·6	48·7	18·1	701	0·47	0·91	56·3	3·7	2·06	24·0	96·6
Hydromulch	58·7	40·2	11·3	927	0·00	0·00	55·3	4·7	1·42	14·3	100·0
Woodchips	51·0	36·5	32·4	No runoff	0·00	0·00	> 60	0·0	0·00	0·00	NA
Trout Creek I-80 road cut–2003											
New Hogan reveg. w/PNM	55·2	40·4	12·0	No runoff	0·00	0·00	> 60	0·0	0·00	0·00	NA
Std. grass/*Festuca* sp.	63·7	39·4	16·0	274	1·00	3·00	49·7	10·3	3·45	36·7	98·7
Snowking/Juniper Mtn–2003											
Std. grass/*Festuca* sp.	44·5	32·2	22·4	200	2·92	19·17	40·0	25·0	8·80	103	99·0
Hog. reveg. w/PNM–100 $mm\,h^{-1}$	39·5	32·9	12·1	1080	0·00	0·00	94·2	5·8	0·59	6·2	99·7
150 mm woodchips–120 $mm\,h^{-1}$	44·5	36·6	19·8	No runoff	0·00	0·00	> 180	0·0	0·00	0·00	NA

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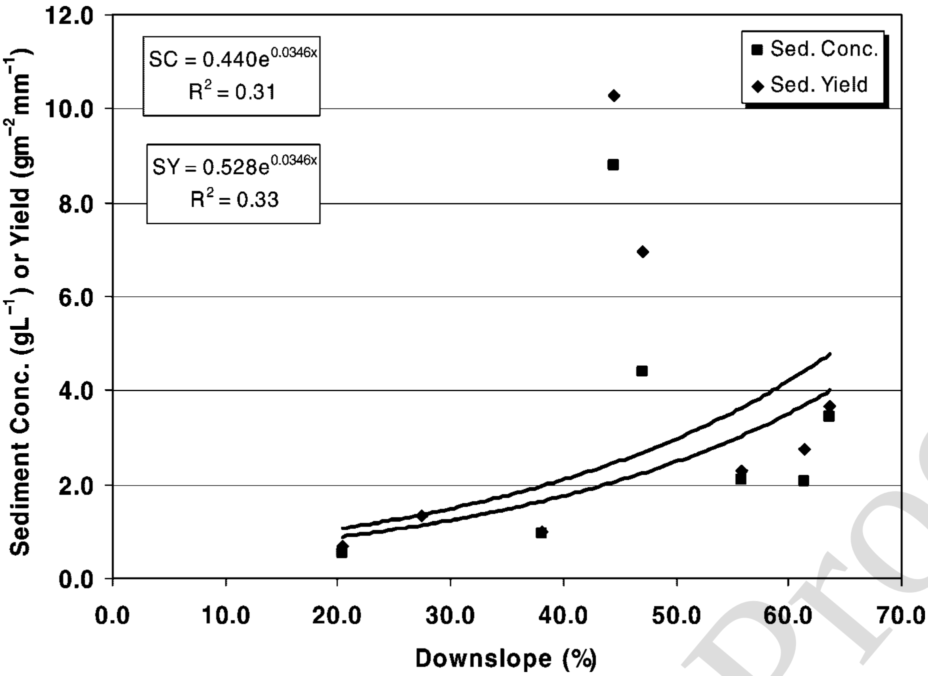

Figure 4. Runoff sediment concentration and yield from standard grass (*Festuca* sp.) treated volcanic soil plots as they depend on plot slope.

grass treatment though degraded straw was of little value for erosion control (e.g. Northstar LOM). Similarly, pine-needle mulch covers were more effective than straw or grass covers in retaining sediment on the slope. It appears that while the grass treatments provide some cover effects to reduce raindrop-splash effects, they offer little additional infiltration capacity (reduced runoff), or ability to retain sediment on the slope after raindrop impact.

More complete soil restoration, revegetation treatments generally provided the greatest infiltration capacity and least or no runoff from the test plots of any slope tested. As noted above, woodchips incorporated into the soil provided similar infiltration capacity and sediment retention. Interestingly, in grouping the older revegetation treatments that resulted in runoff (e.g. Northstar LOM), the resulting exponential regression equation for sediment concentration as a function of slope was the same as that for bare granitic soils with the exception that values are half as great at a given slope. As in Figure 3, Figure 5 illustrates a comparison of treatment effects on erosion and runoff parameters from plot slopes between 50 and 60 per cent and underscores the efficacy of keeping the water in the soil as there is no runoff or sediment yield from 300 mm-deep woodchip-treatments and more complete soil rehabiliatation and revegetation (‘New Reveg.’). Rainfall simulation tests on revegetation and woodchip-treatment plots resulting in no runoff at 60 mm h^{-1} rainfall intensities were replicated with rainfall intensities of 80, 100 or 120 and 180 mm h^{-1} (RS upper limit) to attempt to induce runoff. Rainfall intensities as great as 180 mm h^{-1} did not result in runoff from the woodchips, while intensities of 100 mm h^{-1} at Snowking and 120 mm h^{-1} at Northstar Unit 7 road cut resulted in runoff having very low sediment concentrations $\sim$0·6 g L^{-1} only after considerable rainfall. Repeated RS measurements at these locations for a second year did not change these results, though the question of their longer-term (i.e., 5–10 years) value remains unknown.

SUMMARY AND CONCLUSIONS

Revegetation of road cuts, fills and other disturbed areas such as ski runs and abandoned roads is intended to stabilize those drastically disturbed areas so that sediment is not transported to adjacent waterways. Erosion and sedimentation has resulted in water quality degradation, an extremely critical issue in the Lake Tahoe basin. Many

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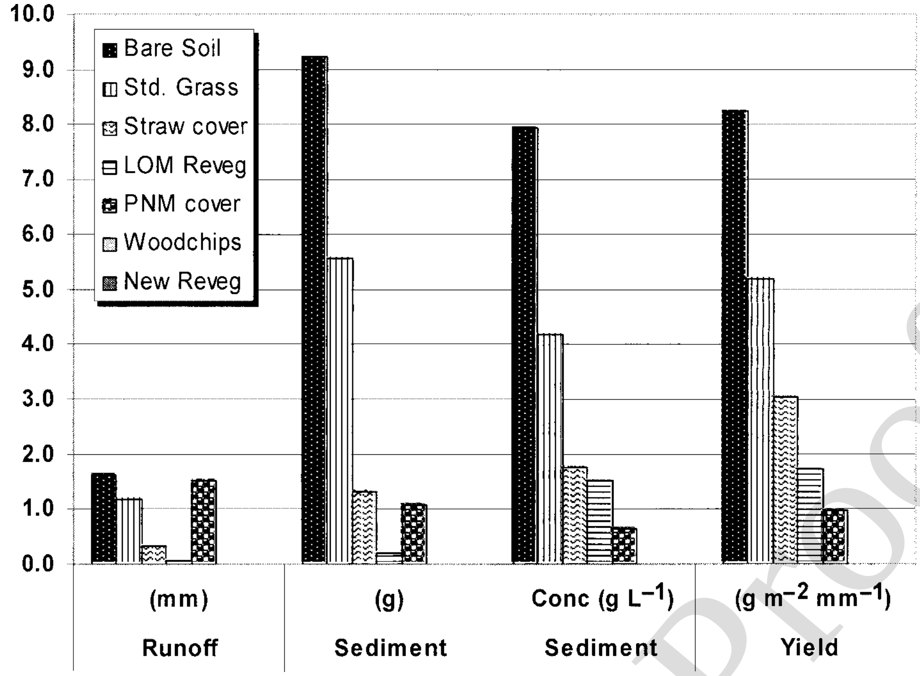

Figure 5. Comparison of cumulative runoff and sediment at 15 minutes and sediment concentration and yield from bare and treated volcanic plots on 50–60 per cent slopes (note that there is no runoff or sediment from the 'Woodchip' or 'New Reveg.' treatments).

revegetation efforts in this semiarid, sub-alpine environment have resulted in low levels of plant cover, and continued sediment movement off site, thus failing to meet project goals and arrest lake water quality decline. Further, recent shift in emphasis from 'revegetation' to 'sediment source control' implies that the ability to control erosion may involve more than vegetation alone. When a systematic assessment of erosion variables is considered, it becomes clear that soil physical and biological functions play a major role in controlling erosion through a number of mechanisms. The revegetation/mulch efforts considered here indicate that the addition of organic matter and physical treatment of severely disturbed soils can increase soil-infiltration rates, reduce runoff and sustain plant growth. However, there are two significant and critical information gaps relative to developing and assessing whether an erosion-control treatment is functional and sustainable. First, there is a complete lack of information on long-term soil changes brought about by physical and biological treatment of disturbed, erosion-prone soil. Second, to date, there has been no adequate direct physical method of assessing or monitoring project effectiveness relative to runoff or sediment movement. While vegetative cover is generally assumed to have a significant effect on sediment reduction from disturbed sites, physical quantification of those effects is lacking and here we found that sparse grass covers alone ($\sim$35 per cent) were not effective in controlling erosion in the Tahoe basin.

Rainfall simulation plot studies were used to determine slope, cover (mulch and vegetation) and surface roughness effects on infiltration, runoff and erosion rates at several road cuts and ski runs across the basin. A rainfall rate of $\approx$60 mm h^{-1}, approximating the 100-year, 15-minute design storm, was applied over replicated 0·64 m^2 plots in each treatment type, 'native', less-disturbed forest soils and over bare-soil plots for comparison. Simulated rainfall had a mean drop size of $\approx$2·1 mm and approximately 70 per cent of 'natural' kinetic energy. Measured parameters included time to runoff, infiltration, runoff/infiltration rate, sediment discharge rate and average sediment concentration. Runoff rates, sediment concentrations and yields were greater for volcanic soils compared to those from granitic soils for nearly all cover conditions. Measurements of particle-size distributions, using sieve and laser counting methods, indicated that the granitic soils had larger grain sizes than the volcanic

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soils and that road-cut soils of either type also had larger grain sizes than their ski-run counterparts. RS-measured runoff and erosion rates and sediment yields from the bare soils were significantly correlated with plot slope with the exception of volcanic road cuts. For example, bare-soil sediment yields from volcanic soils ranged from 20 to 120 as compared to 3 to 30 $kg\,ha^{-1}\,mm^{-1}$ for granitic soils. While pine-needle mulch cover treatments alone substantially reduced sediment yields from all plots, more complete soil rehabilitation through incorporation of soil amendments (including woodchips) virtually eliminated runoff and sediment yields in many cases. Information is lacking, however, as to the long-term effectiveness of many revegetation, mulch or woodchip treatments. An assessment of this effectiveness is presently underway.

ACKNOWLEDGEMENTS

This research was supported by the California Department of Transportation (CalTrans) and the US Forest Service. The authors are indebted to the assistance of M. Curtis, A. Ellis and D. Rider in the field measurements.

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