DOI: 10.1007/s00267-004-0219-2

Effectiveness of a Coral-Derived Surfacing Material for Reducing Sediment Production on Unpaved Roads, Schoffield Barracks, Oahu, Hawaii

ALAN D. ZIEGLER*
ROSS A. SUTHERLAND
Geography Department
University of Hawaii
2424 Maile Way, 445 Saunders Hall
Honolulu, Hawaii 96822, USA

ABSTRACT / This study evaluated the effectiveness of two application rates of a coral-derived surfacing material for both traffic and nontraffic road conditions using simulated rainfall (110–120 mm h^{-1} for 30–90 min) on 0.75-m (wide) × 5.0-m (long) plots of similar slope (roughly 0.1 m m^{-1}). The coral is a locally available material that has been applied to unpaved roads surfaces on Schoffield Barracks, Oahu, Hawaii (USA), where this experiment was conducted. The simulations show that compared with a bare control plot, the coral-based surface application rates of 80 and 160 kg m^{-2} (equivalent to only 10- and 20-mm thicknesses) reduced road sediment production by 75% and 95%, respectively, for nontraffic conditions. However, after two passes of the research vehicle during wet conditions, sediment production rates for the two coral treatments were not significantly different from those on the bare road plots. The overall effectiveness of the coral-derived surfacing material is unsatisfactory, primarily because the on-road surface thickness associated with the application rates tested was too small. These rates were selected to bracket those applied to training roads in the study area. Furthermore, the composition of the coral-based material does not facilitate the development of a sealed, erosion-resistant surface. When applied at the low rates tested, the coral material breaks down under normal traffic conditions, thereby losing its ability to counter shearing forces exerted by overland flow on long hillslopes where erosion measures are most needed. These simulations, combined with observations on roads in the study area, indicate that this material is not an appropriate road surfacing material for the site—at least for the low application rates examined. These results are preliminary; extended testing of higher applications rates at the hillslope scale under natural climate and traffic conditions is needed to better judge the effectiveness of this material over time.

Unpaved roads are important sources of sediment entering streams worldwide (Reid and others 1981; Grayson and others 1993; Gucinski and others 2001; Wemple and others 2001). Roads therefore play a key role in water quality decline, disruption of stream ecological processes, and sedimentation in downstream water systems (e.g., Hafley 1975; Cederholm and others 1981; Reid and Dunne 1984; Fahey and Coker 1992; Lee and others 1997; MacDonald and others 1997; Forman and Alexander 1998; Jones and others 2000). Compared with many other land surfaces, roads contribute disproportionately to the basin sediment yields because of several interrelated reasons (Dunne and Dietrich 1982; Motha and others 2004). Firstly, infiltration is reduced by compaction; therefore, roads have the propensity to generate erosion-producing overland flow during most rain events (Luce and Cundy 1994; Ziegler and Giambelluca 1997). Furthermore, on shallow soils subsurface flow may exfiltrate from the cutbank (Megahan 1972; Megahan and Clayton 1983; Wemple and Jones 2003), thereby enhancing the total on-road overland flow that can detach and entrain sediment. Road runoff may also drain directly into the stream channel at low-water bridges or locations where the road and ephemeral channels intersect, or form partial or complete linkages with the stream via hillslope channelization (Croke and Mockler 2001; Sidle and others 2004; Ziegler and others 2004). In such cases, little opportunity exists for sediments to be filtered in vegetative buffers (Trimble and Sartz 1957). Roads cut into hillsides on steep terrain exacerbate landslide-related sediment production by oversteepening cut and fill slopes, removing support at road cuts, overloading fillslopes, and concentrating drainage water and

KEY WORDS: Runoff; Erosion control; Ruts; Aggregate sizes; Rainfall simulation; Trafficking; Military training lands

---

*Author to whom correspondence should be addressed; *email:* adz@hawaii.edu

diverting it onto unstable hillslopes (Dyrness 1967; Sidle and others 1985; Montgomery 1994; Wemple and others 2001).

High road sediment production rates occur typically in the initial years after construction, but elevated rates can linger for many years, relative to undisturbed hillslopes (Megahan and Kidd 1972; Swift 1988). High rates of sediment production persist, in part, because loose surface material is re-supplied by inter- and intrastorm phenomena, including road maintenance activities (e.g., Megahan 1984; Swift 1988; Ziegler and others 2001b) and vehicle traffic (e.g., Sullivan and Duncan 1981; Burroughs and others 1984; Reid and Dunne 1984; Bilby and others 1989). Prior studies have shown the effectiveness of surfacing materials and vegetation measures in reducing sediment production on road surfaces (e.g., Beschta 1978; Burroughs and others 1984; Swift 1984; Kochenderfer and Helvey 1987). In the extreme, Reid and Dunne (1984) determined that a paved road segment at their NW USA site yielded less than 1% of the sediment produced on a heavily used gravel road.

Paving and/or regulating usage are not viable options on most secondary roads. In some cases, a practical strategy for reducing sediment production is resurfacing with inexpensive, coarse-aggregate materials extracted from local burrow pits, gravel bars, and/or hard rock surfaces (Foltz 1996; Foltz and Truebe 1995, 2003). Erosion-control effectiveness of such strategies depends on many factors, including surface application rate (thickness in particular), erodibility of both the surfacing material and the underlying road, traffic intensity, and site characteristics, such as rainfall intensity, slope, and flowpath distance (Foltz and Truebe 2003). Before application of any surface material, one should understand the intrinsic properties that affect erosion processes and the resilience of the material under expected physical conditions (namely, traffic intensity and climate conditions). Furthermore, surfacing materials should be evaluated under natural or simulated conditions before they are applied (cf. Foltz and Truebe 2003).

Objectives

The objective in this research experiment was to determine the effectiveness of a coral-derived surfacing material in reducing sediment production on military training roads on Schofield Barracks, Oahu, Hawaii. The coral is a locally available material in Hawaii that was being used on the military base at the time of testing. To our knowledge, it had never been examined rigorously with respect to erosion-mitigation ability in the Hawaii locale. In this study, we evaluate this ability for two surface application rates via plot-scale rainfall simulation experiments, for both traffic and nontraffic conditions. We attempt to answer the following fundamental questions: (1) do the tested application rates of the coral-derived material mitigate road erosion processes during high-energy rainfall conditions? and (2) does any reduction in sediment production afforded by the material occur when the additional stress of vehicle trafficking is applied?

Background

General material properties and historical use of coral-derived material (also known as coronous material) for use in road and airfield construction are summarized by Bullen (2003). These materials are often extracted from land-based, uplifted coral reef formations to substitute for more recognized engineering aggregates, which may not be economically obtained in some tropical island and coastal areas. Coral-derived materials have been used for road surfacing in places such as Hawaii, the Federated States of Micronesia, Papua New Guinea, the Solomon Islands, Western Samoa, Fiji, the Caroline Islands, and various military installations in the South Pacific (e.g., Bowers 1944; Corradi 1945; TRRL 1977; Bearkley 1984; Ziemer and Megahan 1991; Bullen 2003). Although coral-derived materials appear to be satisfactory for use in unsealed gravel pavement applications, they do not generally meet typical requirements for ''high-quality'' crushed work—in part, because they often contain an abundance of plastic fines (Bullen 2003). In general, they do not meet typical engineering specification tests for road-related applications (e.g., some of the tests discussed by Bofinger and Rolt 1976; Bullen and Heaton 1986; Skorseth and Selim 2000; Foltz and Truebe 2003; Bullen 2003). Coronous materials, being composed largely of calcium and magnesium carbonates, are not subject to substantial mineral alteration; however, significant alteration can occur by compaction, which often produces additional fines that affect stability of the surfacing material (Bullen 2003).

Study Site

In August 1997 we performed rainfall simulations on a recently abandoned section of the primary access road to South Firing Range 1, Schoffield Barracks, in central-west Oahu Island, Hawaii, USA. The site is located on the Schoffield Plateau, near the base of the Waianae mountain range. Rainfall is seasonal, with about 75% of the annual 1000–1100 mm occurring

Figure 1. (**a**) The car-wash-type, low-energy simulator on the experimental road section at Schofield Barracks. (**b**) The three side-by-side treatment plots. (**c**) Runoff sample being collected during a simulated event. (**d**) Deep ruts formed on an adjacent road that has been surfaced with the coral-derived material tested herein. In panels (b) and (c), the treatments from left to right are 1xCoral, 2xCoral, and bare.

from October to April. The road section runs perpendicularly to the slope contours on a relatively steep hill. It had incised into the landscape 1–4 m; thus, the surface material on the test road was a composite of Kolekole Oxisol, Helemano Inceptisol, weathered oxidic ash, and exposed saprolite (Soil Conservation Service 1981). Slope on the running surface varied from about 0.05 to 0.35 m m^{-1}. Traffic was infrequent at the time of testing, because the road had been closed after slope failure near the base. The failure was well below the 80-m upper section where we conducted the experiments. Although grass and shrubs grew in roadside margin, no surface vegetation grew on the running surface (Figure 1a).

Methods

Physical–Chemical Properties

We collected several physical–chemical properties to provide information regarding the physical nature of the road and the surrounding nonroaded land surfaces. Prior to testing, we divided the road section into 12 approximately 7-m-long sections. Within each section, we made the following measurements: (1) three bulk density (ρ_b) values were determined in the upper 5 cm of the soil by collecting a 90-cm^3 core, then oven drying for 24 h at 105°C; (2) one saturated hydraulic conductivity (K_s) was determined in situ with a Vadose Zone (Amarillo, TX) disk permeameter (described in Ziegler and Giambelluca 1997); (3) 10 penetration resistance (PR) values were determined with a static Lang penetrometer (cf. Bradford 1986); (4) 11 vane shear strength (τ_v) values were determined with a pocket torvane; and (5) three organic carbon (OC) and total nitrogen (TN) values were determined from the soil cores collected for the ρ_b measurements (determined at the University Hawaii, Soils and Agronomy, Agriculture Diagnostics Service). All PR and τ_v measurements were made during similar soil moisture conditions (see below). Differences in sample numbers among the properties reflect time requirement for making a measurement.

Surface Treatments

The first coral application rate tested was 80 kg m^{-2} (1xCoral); the second was two times greater (2xCoral: 160 kg m^{-2}). These rates were chosen to bracket that applied to some training area access roads on the military base (based on our observations; the actual application rate was not disclosed). Each treatment was applied by hand, and then compacted by stomping; no heavy compaction machinery was used. The thickness

Table 1. Physical characteristics of the road surface and adjacent off-road area

Property	Units	Road	n	Off road	n
ρ_b	Mg m^{-3}	1.32 ± 0.02	36	0.96 ± 0.03	9
PR	MPa	6.2 ± 0.1	120	4.4 ± 0.2	30
τ_v	KPa	21.6 ± 0.5	132	19.0 ± 1.1	15
K_s	mm h^{-1}	28.4 ± 4.5	12	—	—

Values are means ± 1 SE; ρ_b, bulk density; PR, penetration resistance; τ_v, vane shear strength; K_s, saturated hydraulic conductivity.

Table 2. Percentage of material passing through various sieve sizes for (a) the coral material tested herein, (b) Grading D specification, and (c) the Base 1 specification for gravel road pavements for developing countries; and (d) typical increase in particle size fractions of coral-derived surfacing materials after compaction

Sieve size (mm)	(a) Hawaiian coral material tested[†]	(b) Grading D specification (%)	(c) Base 1 specification (%)	(d) Increase after compaction[††] (%)
32	100	—	—	—
25.4	82	100	—	—
19*	75	90–60	100	na
16	69 ± 6	—	—	—
9.5	43	—	100–80	11
8	37 ± 3	—	—	—
4.75	26	55–30	85–60	10
4	24 ± 2	—	—	—
2	16 ± 2	—	70–45[†††]	7[†††]
1	11 ± 1	—	60–35[†††]	6[†††]
0.6	8	27–11	—	5
0.5	7 ± 1	—	—	—
0.3	5	—	40–20	4
0.25	5 ± 0.3	—	—	—
0.125	3 ± 0.1	—	—	3
0.075	1	15–6	25–10	—
0.0625	1 ± 0.1	—	—	—

[†] Measured values are mean ± 1 SD (n = 5); values without standard deviations were interpolated to compare with percentages required to meet Grading D specification for good-quality surfacing aggregate (Foltz and Truebe 2003) or the recommended values for Base 1 gravel pavements in developing countries (Bofinger and Rolt 1976).

* indicates that the measured/estimated percentage for the Hawaiian coral material is acceptable, as compared with at least one of the standards.

[††] Data from Bullen (2003).

[†††] Values are reported for 2.36- and 1.18-mm sieve sizes in Bullen (2003); data for 19-mm fraction are not applicable because the original percentage passing through was 100%.

of the two application rates was equivalent to only about 10 and 20 mm, respectively.

Extracted from a landfill on the Island of Oahu, the coral material is an inexpensive surfacing material that is available in Hawaii. This ''pit-run'' coral-derived material had not been sorted prior to application. It therefore consisted of fragmented coral, fine sands, and marine shells—it is best described as a soft-rock aggregate. Table 2 shows the percentage of material passing through various sieve sizes.

Rainfall Simulations

We used a low-energy rainfall simulator (LES) that consists of a rectangular frame hosting eight 60° axial full cone nozzles (0.04 mm orifice diameter; Lechler, St. Charles, IL), situated in two rows of four, and directed toward the road surface (Figure 1a). Water from a 1850-L refillable storage container was delivered to the simulator through 2.5-cm flexible PVC hose by a 1-hp centrifugal pump, powered by a portable generator. Mean fall height was 2.7 m. Spacing of the nozzles was 1.45 m. We designed the ''carwash-type'' LES to allow vehicles to pass beneath during simulation events. Operating pressure for the experiments was 25 psi (172 kPa), which typically produces rainfall intensities of 90–120 mm h^{-1}. Median drop size at this pressure is 0.99 mm (based on engineering data from the manufacturer). We regard this simulator to be of low energy because of the small drop sizes produced, as compared with a high-energy simulator used in prior work at the same site (Ziegler and others 2000).

We choose five road subsections at random for the experiments. At each location, one bare control and two application rates of a coral-derived material were tested in side-by-side plots, also assigned at random (Figure 1b). Thus, we performed simulations on a total of 15 subplots—five replications for each treatment. We avoided simulating in locations where saprolite was exposed. Prior to testing, the simulation surfaces were therefore covered with a thin layer of loose material that was either detached from the road surface by past traffic or had perhaps originated from piles of ravel that lay at the base of the cut slopes. Slope angles, determined from Abney level measurements taken every 0.25–0.5 m along a transect running through each simulation plot, varied only slightly from 0.09–0.11 m m^{-1} among all subplots.

We arranged tubular-shaped, sand-filled, geotextile bags (3.0 m × 0.2 m × 0.1 m) below the simulator to form three rectangular subplots (0.75-m width × 5.0-m length). The LINQ GTF 200 woven geotextile bags, which we have used in other road simulation studies (Ziegler and others 2000, 2001a,b), has a permeability of 0.005 cm s^{-1}. At the base of each subplot, the geotextile bags were arranged into triangles that directed runoff into a hand-dug drainage trench (Figure 1c). This 0.5-m-long triangular-shaped section of each subplot was treated with a 5:1 mixture of water and an acrylic vinyl acetate polymer (Soil Sement; Midwest Industrial Supply, Inc., OH) to prevent sediment from detaching from this ''nontreatment'' area.

On each of the three treatments, we performed two simulation phases, referred to hereafter as pretraffic and posttraffic phases. Prior to the pretraffic phase, antecedent soil moisture was determined from grab samples (10–20 g) taken from the surface of the individuals plots. During the pretraffic phase, runoff samples were collected at the time of runoff (TORO), then again at 1.0, 2.5, 5.0, 7.5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, and 90 min thereafter.

Immediately after the final pretraffic measurement, the simulator was switched off. Two ''passes'' of a three-quarter-ton pickup truck were then made within each plot. Because we wanted to leave the plot boundaries in place and protect the sealed plot outlet, ''trafficking'' consisted of backing the truck down through the entire length of the plot, then driving out. Thus, the detachment forces exerted by tires of the vehicle on the road surface were likely less than those of a vehicle driven at a normal operating speed. After a rainfall hiatus of 30 min, the 30-min posttraffic simulations were conducted. Samples were again collected when runoff resumed, and then at 2.5, 5.0, 7.5, 10, 15, 20, and 30 min afterwards. Owing largely to time restrictions, the length of the posttraffic simulations was shorter (30 versus 90 min). In addition, because of limited availability of the three-quarter-ton pickup truck, we only performed posttraffic simulations after three of the pretraffic simulations.

Rainfall rate during each simulation was determined from 15 10-cm manual gauges placed on the subplot borders during both pre- and posttraffic phases. Event-averaged intensity was calculated by the total depth divided by simulation time. Energy flux density (EFD, J m^{-2} h^{-1}) was calculated as in Ziegler and others (2000) using a raindrop D_{50} value of 0.99 mm. Runoff for both the pretraffic and posttraffic phases was sampled by filling a 510-mL collection bottle. Instantaneous discharge rates were determined by dividing the sample volume by the time to fill each bottle.

After settling for several days, the supernatant in each bottle was decanted. The samples were then oven-dried at 105°C for 24 h to determine the mass of solid material present. When calculating discharge, all sample volumes were reduced to account for the presence of sediment. Instantaneous sediment concentrations were calculated as sediment mass per corrected discharge volume. The dried sediment was stored in refrigeration for several weeks. OC and TN contents were then determined as above.

Statistical Testing

Statistical testing for all variables was made using one-way analysis of variance on $\log_{10}$-transformation data, followed by post-hoc multiple comparison testing with the Fisher's protected least squares difference test when the *F*-values were significant at $\alpha = 0.05$.

Results

Simulation Conditions

Physical properties associated with the road surface and adjacent areas are listed in Table 1. Antecedent soil moisture varied from 0.28 to 0.33 g (H_2O) g^{-1} (soil) over the course of the 10 days during which the simulations were conducted; no substantial rainfall occurred during this period. Differences in event-averaged simulated rainfall intensities (RF_{event}) and associated EFD values were not statistically significant among treatments (Table 3). RF_{event} ranged from 109 to 118 mm h^{-1}; and EFD varied from about 790 to 870 J m^{-2} $h^{-1.}$ This energy regime is equivalent to that produced by the following naturally occurring 1-h events in Hawaii: (1) a 75-mm storm, having 1.0-mm median

Table 3. Rainfall simulation summary statistics

	Treatment	n	RF_{event} (mm h^{-1})	EFD (J m^{-2} h^{-1})	D_{TORO} (mm)	Q_{total} (mm)	S_{total} (kg ha^{-1} mm^{-1})	C_{total} (kg m^{-3})
Pretraffic	Control	5	109 ± 17a	803 ± 123a	3.0 ± 0.9 a	111 ± 30b	35 ± 19b	5 ± 2b
	1xCoral	5	117 ± 27a	865 ± 202a	6.1 ± 1.9ab	111 ± 47ab	9 ± 04a	2 ± 1a
	2xCoral	5	112 ± 19a	824 ± 140a	8.9 ± 4.6b	92 ± 36 a	2 ± 05a	1 ± 1a
Posttraffic	Control	3	107 ± 5a	791 ± 35a	1.1 ± 0.4a	42 ± 3a	124 ± 89a	15 ± 9a
	1xCoral	3	118 ± 7a	872 ± 54a	2.1 ± 1.6a	37 ± 13a	62 ± 30a	6 ± 4a
	2xCoral	3	117 ± 21a	863 ± 154a	1.0 ± 0.2a	33 ± 2a	78 ± 31a	11 ± 6a

Simulation times for pre- and posttraffic simulation phases are 90 and 30 min after runoff generation; n = simulation replications; RF_{event} = event-averaged rainfall intensity; EFD = event energy flux density; D_{TORO} = depth of rainfall prior to time of runoff; Q_{total} = depth of total discharge from simulation plot; S_{total} = total sediment transported during the event normalized by area and total rainfall depth; C_{total} = event-average sediment concentration. Values are means ± 1 SD.

For each of the pre and posttraffic phases, values with the same letter in a column are *not* statistically distinguishable using one-way analysis of variance on $\log_{10}$-transformation data followed by post-hoc multiple comparison testing with the Fisher's protected least squares difference test when the *F*-values were significant at $\alpha = 0.05$.

drop size and 50-year return period; and (2) 40-mm storm, having a 2.0-mm median drop size and a 1–2 year return period. A 1-h, 118-mm h^{-1} event—our largest simulated event—would most likely resemble storms with return periods more than 100 years and EFD values ranging from approximately 1000–2500 J m^{-2} h^{-1} (i.e., for median drop sizes ranging from 1.0 to 2.5 mm). Thus, although the total energy of our simulated storms may be representative of 1-h storms in Hawaii, the total depth of simulated rainfall is high.

Effectiveness Related to Application Rate

Substantial differences were found in the runoff and sediment production variables for the three treatments differing in application rate of the coral surfacing material (Table 3). During the pretraffic phase, depth of rainfall prior to the time of runoff initiation (D_{TORO}) increased with application rate: control (3 mm) < 1xCoral (6 mm) < 2xCoral (9 mm). Only the 2xCoral D_{TORO} value was significantly different from that of the bare road control. Differences in D_{TORO} are, in part, proxies for differences in surface ponding depth, but they probably also reflect differences in water storage within the coral surfacing layer.

Mean total discharge (Q_{total}) for the 2xCoral treatment was significantly lower than that of the bare road control. Q_{total} for the 1xCoral treatment was equally as high as the bare road, but it was not significantly different from the 2xCoral treatment because of high variability between individual runs. Thus, the 2xCoral application rate exhibited the ability to reduce runoff by storing water either on the surface via ponding or within the matrix of the material itself. Both normalized (by rainfall depth) sediment production (S_{total}) and total event concentration (C_{total}) on the bare road were significantly higher than for either the 1xCoral or the 2xCoral application rates (Table 3). Importantly, S_{total} on the 2xCoral treatment was about 95% lower than that on the bare road (2 versus 35 kg ha^{-1} mm^{-1}); S_{total} on the 1xCoral treatment was about 75% lower than the control (9 kg ha^{-1} mm^{-1}). No significant difference in sediment production, however, was indicated between the two coral treatments for S_{total} or C_{total} (Table 3). Absent in the instantaneous sediment concentration (C_t) time series for both the coral treatments is the initial flush of sediment within the first 10 min of simulated rainfall (Figure 2). Compared with the bare road control, sediment output is about 60% and 75% lower for 1xCoral and 2xCoral, respectively, during this period. Furthermore, sediment concentrations on the bare plot remained elevated over the duration of the 90-min pretraffic event, compared with those of the 1xCoral and 2xCoral treatments. After about 60 min, C_t values on the bare road control were approximately 3 g L^{-1}, compared with values less than about 1 g L^{-1} for both coral treatments (Figure 2). Again, event total sediment concentration was significantly higher for the control than for 1xCoral or 2xCoral treatments (Table 3).

Effectiveness Related to Trafficking

All three treatments showed elevated sediment output values during the posttraffic simulations, demonstrating the influence of trafficking in exacerbating sediment production on the wet road (Table 3). Peak concentration following the truck passes were 2, 3, and 13 times greater than the peaks during the pretraffic simulations on the control, 1xCoral, and 2xCoral treatments, respectively (Figure 2). These peaks were as much as two orders of magnitude greater than the concentration values at the end of the pretraffic simulations. Comparatively higher sediment production

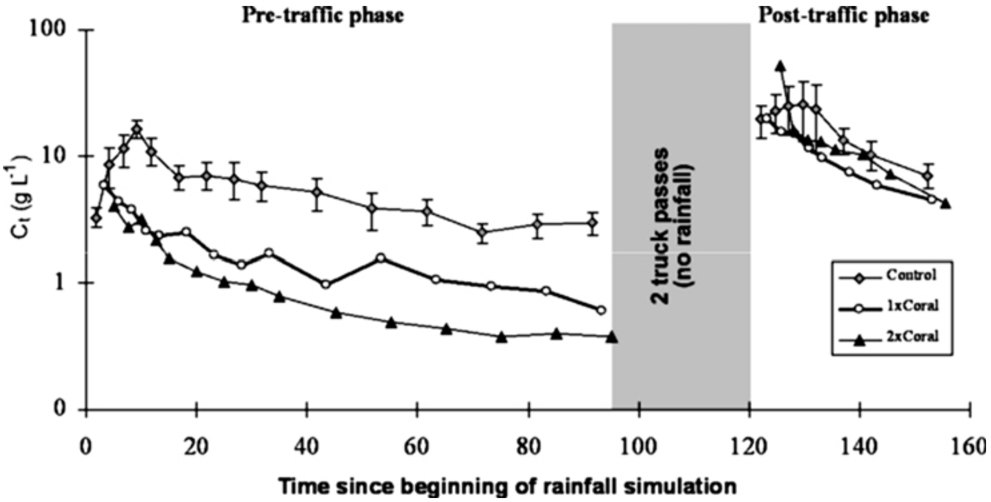

Figure 2. Mean instantaneous sediment concentration (C_t) for the 90-min pretraffic simulations and the 30-min posttraffic simulations. For visual clarity, error bars (standard errors) are shown for the bare control treatment only. The pretraffic values are means of five simulation replications; those for posttraffic are means of three replications.

rates per unit discharge depth were associated with the posttraffic phases, as compared with the pretraffic phases (Figure 3). Mean, normalized sediment output values for the three treatments were respectively about 3.5, 7, and 40 times higher during the posttraffic phase (Table 3). Although the 1xCoral and 2xCoral posttraffic S_{total} values were much lower than those on the bare control treatment, the differences were not statistically significant because of high variability among individual simulation runs and small sample number.

Road Sediment Sources

The nutrient data in Table 4 support the notion that the material mobilized during the simulations originated predominantly from the road surface. For example, organic carbon (OC) and total nitrogen (TN) values for sediment removed from the plots show only a slight enrichment over the values associated with the road surface material. In comparison, background OC and TN values collected on adjacent nonroad surfaces in a disturbed forest were an order of magnitude higher.

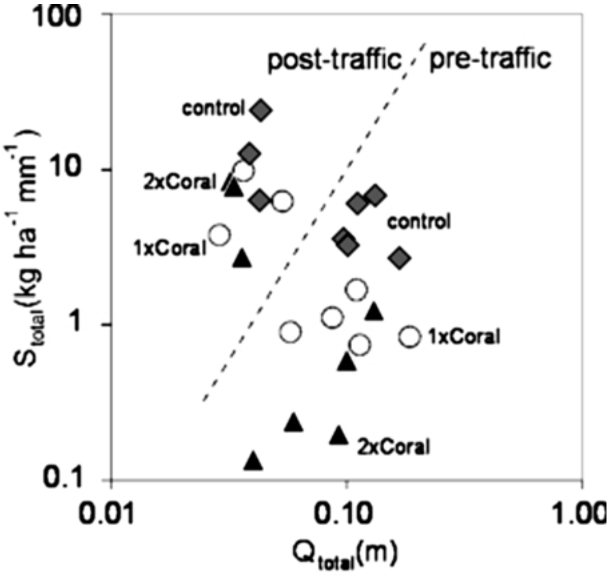

Figure 3. For both pre- and posttraffic simulation phases, total event discharge Q_{total} and normalized sediment output (S_{total}) are shown for the bare (diamonds), 1xCoral (circles), and 2xCoral (triangles) treatments. The dashed line serves only to separate the phases for clarity.

Discussion

Road Sediment Production

The observed 35 kg ha^{-1} mm^{-1} sediment production rate on the bare road treatment during the pretraffic phase is much less than the 197 kg ha^{-1} mm^{-1} rate determined during a prior rainfall simulation study on the same road section using a ''high-energy'' simulator (EFD = 803 versus 1860 J m^{-2} h^{-1}; Ziegler and others 2000). In other simulations conducted at a Thailand site, a sediment production rate of 190 kg ha^{-1} mm^{-1} was determined during similar high-energy experiments (1745 J m^{-2} h^{-1}) (Ziegler and others 2000). The prior experiments in Hawaii and Thailand showed that sediment production on unpaved roads

Table 4. Organic carbon and total nitrogen data for the simulated road surface, sediment transported during the simulations, and adjacent nonroaded lands

	Organic C (g kg^{-1})	Total N (g kg^{-1})	C/N ratio	n
Road surface	8.6 ± 1.0 a	0.7 ± 0.01 a	13.0	36
Transported sediment	10.6 ± 0.5 a	0.9 ± 0.01 a	11.6	18
Adjacent nonroad surfaces	44.2 ± 6.3 b	3.4 ± 0.40 b	13.2	9

Values are mean ± 1 SD; differences in sample number (n) reflect differences in collection protocols for related experiments. Values with the same letter in a column are *not* statistically distinguishable using one-way analysis of variance on $\log_{10}$-transformation data followed by post-hoc multiple comparison testing with the Fisher's protected least squares difference test when the *F*-values were significant at $\alpha = 0.05$.

originated from two primary sources: (1) loose surface material entrained by flowing water; and (2) material detached from the underlying road surface of relatively high erodibility (Ziegler and others 2001a). Compared with the prior high-energy simulations conducted in Hawaii, detachment of new material by rain splash during the LES simulations herein was reduced substantially (this is determined by comparing instantaneous sediment output rates after 60 min simulation time: 0.11 versus 0.35 g m^{-2} s^{-1} for LES and HES, respectively (Ziegler and others 2000). Thus, a high percentage of sediment removed from the plots during the pretraffic phase was that associated with the entrainment of already-detached material by overland flow.

Again, the nutrient comparisons indicate that the road surface was the primary source of material transported during the simulations (Table 4). Recognizing the predominance of this sediment source is important because of the presence of large ravel piles along the roadside margin. This material originates from slumping of the cutbank. The nutrient composition is therefore similar to that of the adjacent nonroad, vegetated surfaces. Ravel is a persistent source of loose surface sediment on the roadside margin that could potentially elevate sediment production on the entire road section. Although it did not appear to influence our experimental results, ravel may be mobilized during large natural runoff events, thereby exacerbating sediment production regardless of the presence of a surfacing material.

Reduction in Sediment Production by Resurfacing

The pretraffic rainfall simulations show that the coral-derived material reduced sediment production on the road during nontraffic conditions (Table 3, Figure 2). The erosion-mitigation effect provided by the coral-derived surfacing material is analogous to that shown in numerous nonroad, process-based studies (e.g., Summer 1982; Poesen 1992; Abrahams and Parsons 1994; Valentin 1994). For example, the presence of the relatively coarse coral material reduces splash detachment and transport by intercepting raindrops. In general, higher application rates provide greater surface coverage; and thus greater reduction in raindrop impact energy. In addition, the coral material increases surface roughness, which decreases flow velocity, thereby decreasing the shear stress and transport capacity of flowing water (cf. Lal 1990; Morgan 1995). Increased surface roughness also increases depth of surface ponding. Ponded water, after some critical threshold depth, mitigates raindrop erosion processes (Palmer 1964; Mutchler and Young 1975; Ghadiri and Payne 1979; Poessen 1981; Torri and Sfalanga 1986). Back-calculation using measured K_s and simulation discharge data indicate that ponding on the 1xCoral was about 3 mm greater than on the bare control, and ponding on 2xCoral was roughly 3 mm greater than that on 1xCoral. Some portion of this estimated ponding depth, however, might be water stored within the matrix of coral surfacing. If this storage is large, the effect of ponded water reducing rain splash detachment may not be important.

Effect of Trafficking

Despite demonstrating a general ability to reduce sediment production during simulated rainfall without traffic, the coral-derived surfacing material failed to reduce sediment production significantly after trafficking. This failure was likely related to the light application rates tested, which allowed the development of well-defined ruts that concentrated overland flow and increased runoff stream power (because of greater water depth, flow velocity, and shear stress). During the posttraffic simulation phases, runoff and sediment flowed from the plots exclusively in vehicle tracks.

Trafficking during wet conditions provided a mechanism by which additional sediment could be both detached and entrained after sediment output had reached equilibrium at the end of the pretraffic phase. Neither coral application rate was sufficient to counter these erosion processes. We expect that subsequent vehicle passes would produce additional spikes in sediment output (Coker and others 1993). Unfortunately, we cannot determine whether the magnitude of these spikes would eventually decline, thereby indicating that some degree of erosion protection was provided, relative to the bare road surface.

Negative evidence regarding the erosion-reduction performance of the coral surfacing material was also found on nearby road sections during a survey of runoff flowpaths. On one adjacent road of similar slope, for example, a deep rut had formed in the running surface (width = 20–40 cm; depth = 10–15 cm), despite prior resurfacing with a similarly thin layer of coral (Figure 1d). The presence of this type of rutting on many road sections demonstrates the ineffectiveness of the coral-derived material at the hillslope scale—at least for light application rates and the volume of traffic at the site (unknown). Similarly, Ziemer and Megahan (1991) found in the Federated States of Micronesia that when thin layers of crushed coral were applied without adequate subgrade preparation, traffic rapidly rutted the road, particularly during wet conditions. Swift (1984) determined that a thinly graveled road initially reduced sediment production relative to a bare road, but traffic quickly wore the surface layer down, thereby compromising its ability to reduce surface erosion and rut formation.

Application Rate and Aggregate Quality

Findings from other studies related to application rate and aggregate quality help explain the poor performance we observed both in our plot-scale simulations and on resurfaced roads at the test site (hillslope scale). Swift (1984) reported that a 15-cm layer of crushed rock and a 20-cm layer of large stones lowered sediment yields 92% and 97%, respectively; a 5-cm layer of crushed rock, however, produced no sediment yield reduction benefits. Kochenderfer and Helvey (1987) similarly reported reductions in sediment production of approximately 80–90% over a 4-yr period for 15-cm layers of gravels ranging in size from about 3.8 to 7.6 cm. In comparison, the material we tested was much finer and less durable (Table 2). In addition, our application rates produced an on-road surface layer <2-cm thick. Again, we chose these rates to bracket those already used at the military installation. Based on the experimental findings from other studies, these rates are probably not adequate to provide the strength required to mitigate erosion processes when trafficking occurs.

Foltz and Truebe (1995) showed via long-duration, high-intensity rainfall simulations on non-trafficked road plots that sediment production was exacerbated when surface aggregates were of marginal quality (also see Foltz and Truebe 2003). Burroughs and King (1984) suggested that erosion reduction on highly erodible subgrade materials is maximized by using ''hard'' crushed rock of appropriate thickness. Foltz and Truebe (2003) found that the percentage of particles passing through a 0.6-mm sieve was a good indicator of the ability of a surfacing material to reduce sediment production on roads. Briefly, they found that sediment production was directly proportional to the percentage of the surfacing material passing through the 0.6-mm sieve. Approximately 8% of the coral-derived material tested herein passed through the 0.6-mm sieve; this is comparable to the 8–12% found for the ''best performers'' in the Foltz and Truebe (2003) study. Thus, the general relationship between <0.6-mm material and sediment production found by Foltz and Truebe was not a good indicator of the effectiveness of the coral-derived material we tested. Again, this might be an artifact of applying too thin a surface layer, and not compacting it sufficiently (see below). Surfacings in the Foltz and Truebe (2003) study were 20-cm thick, and compacted with a 130-kg vibrating roller.

Comparison of aggregate fractions passing through several sieve sizes with two reported size specifications for road design indicates an overabundance of fractions greater than about 8 mm (Table 2). Using the Grading D and Base 1 specifications in Table 2 as metrics, the coral-derived material tested herein does not contain a desirable balance of aggregate fractions. Although too many fines may increase sediment production (Foltz and Truebe 2003), a good balance between all fractions is needed to fill the void spaces, thereby forming a stable, sealed surface (Skorseth and Selim 2000). During our rainfall simulations, a noticeable portion of the sediment transported from the plots was that associated with the coral material itself, probably because a sealed, stable surface was not present (also see next section). When applied on roads, the aggregate size distribution should become somewhat finer, because the medium and large fractions of these coral-based materials tend to break down during trafficking (column d, Table 2). Field evidence, however, suggests that such breakdown does not necessarily produce a more stable road surface: e.g., see the discussion above regarding rut formation. In addition, the presence of the fine ''dirty'' component in the coral material tended to make surfaced roads in the study area exceptionally muddy during rainfall events (Integrated Training Area Management staff, personal communication).

Experimental Bias

Finally, the poor performance of the coral-derived material during trafficking conditions was likely influenced by our plot preparation methods. For example, we did not compact the surfacing treatments in a manner that they would be when applied in most road surfacing applications. Improper compaction and surface preparation may have elevated sediment production rates during our experiments, particularly during the posttraffic phases. For example, Ziemer and Megahan (1991) reported that thin coatings of uncompacted coral dredgings are highly erosive. Failure to form a homogeneous compact surface layer may have contributed to disproportional ‘‘sediment pumping’’ on the small experimental plots, as coarse aggregates were forced into the road bed, thereby allowing finer material to rise to the surface where it was eroded easily by flowing water (cf. Reid and others 1981). In addition, we performed the vehicle passes during wet conditions when road surface shear strength was relatively low. A similar degree of trafficking during dry conditions probably would not have produced the well-defined ruts we observed in the coral treatment plots. Despite these experiment-related biases, we attribute the poor performance to the insufficient thickness of the surfacing layers tested, and in part, to the marginal quality of the coral-derived material.

Conclusion

The plot-scale rainfall simulation studies suggest that the coral-derived material applied at rates of 80 and 160 kg m^{-2} reduces sediment production on unpaved roads, but only during nontraffic conditions. Reduction in sediment production is related to an increase in surface cover/roughness that reduces both detachment and entrainment of road sediment. During rainfall simulations following two vehicle passes on wet plots, the two coral-derived treatments failed to reduce sediment production significantly, compared with the bare road plot. Road sediment and other materials associated with the coral material itself were transported in well-defined ruts that formed during the vehicle passes. In addition to serving as efficient pathways to channel runoff and sediment from the experimental plots, such ruts when formed on long, surfaced road sections would likely incise during subsequent overland flow events.

Literature comparisons suggest that any erosion benefits provided by these low application rates would be short-lived because the associated thicknesses (only 1–2 cm) fail to prevent rutting—particularly as the material breaks down over time in response to trafficking. These rates are probably also insufficient to counter erosion processes on long and/or steep road sections where concentrated overland flow develops. In addition, the composition of this material does not contain a balance of coarse, intermediate, and fine aggregates that facilitates the formation of a stable, erosion-resistant surface. Although our results are influenced by the small-scale of the test plots, the omission of proper compaction during application, and trafficking only during wet conditions, we believe the performance failure of this material results primarily from an insufficient application rate (i.e., surface thickness), and in part, to the marginal quality of the coral-based material itself. Literature comparison suggests that effective applications rates should be about 5–10 times higher than those we tested. The rates we used were in line with observed practices at the test site, where deep ruts had already formed on some road sections that had been resurfaced with this material in the past.

We agree with Bullen (2003) that this particular type of material is a subgrade alternative surfacing material for roads. Mixing with other good-quality aggregate may improve the strength and ability to form a resilient surface, as might proper compaction and subgrade preparation. Those wishing to use similar locally and economically available coral-derived materials for road surfacing, however, should perform additional long-term (multiseason) testing on representative road sections for a wide range of trafficking conditions and higher application rates. During testing, the probable application methods should be considered (namely, compaction, rolling, and multiple layering).

Acknowledgments

This project was funded in part by a National Science Foundation Award (no. 9614259) and a University of Hawaii (UH) Seed Money Grant to T.W. Giambelluca. Alan Ziegler was supported by an Environmental Protection Agency Star Fellowship and a Horton Hydrology Research Award (Hydrological Section, American Geophysical Union). We thank the following for their contributions: Thomas W. Giambelluca, T.T. Vana, C. Southern, R. Gouda; M. Nullet, J. Bussen, N. Thompson, J. Nagle, and M. Gilbeaux (UH Geography), Servillano Lamer (UH Agronomy and Soil Science); C.T. Lee (National Taiwan University); D. Ko, P. Malaspina, and E. Lind, Integrated Training

Area Management Division, Schoffield Barracks. Midwest Industrial Supply, Inc. freely provided Soil Sement. This paper benefited from comments by Dr. Randy Foltz.

Literature Cited

Abrahams, A. D., and A. J. Parsons. 1994. Hydraulics of interrill overland flow on stone-covered desert surfaces. *Catena* 23:111–140.

Bearkley, B. R. 1984. Report on coral testing: Faleolo Airport extension, western Samoa. Internal report 84-170/P106 on Faleolo Airport extension. Cameron McNamara Pty. Ltd. Consultants.

Beschta, R. L. 1978. Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range. *Water Resources Research* 14:1011–1016.

Bilby, R. E., K. Sullivan, and S. H. Duncan. 1989. The generation and fate of road-surface sediment in forested watersheds in southwestern Washington. *Forest Science* 35:453–468.

Bofinger, H. E., and J. Rolt. 1976. The design of road pavements for tropical countries. Presentation at regional seminar on low cost roads, Badung, Indonesia.

Bowers N. A. 1944. Coral airstrips on Pacific islands. *Engineering News Record* July:80–85.

Bradford, J. M. 1986. Penetrability. Pages 463–478 *in* A. Klute (ed.), Methods of Soil Analysis, Part 1. Physical and mineralogical method, agronomy monograph no. 9, second edition. American Society of Agronomy-Soil Science Society of America, Madison, Wisconsin.

Burroughs, E. R. Jr., F. J. Watts, and D. F. Haber. 1984. Surfacing to reduce erosion of forest roads built in granitic soils. Pages 255–264 *in* C. L. O'Loughlin and A. J. Pierce (eds.), Proceedings of a symposium on effects of forest land use on erosion and slope stability, 7-11 May 1998. East-West Center, University of Hawaii, Honolulu.

Bullen, F. 2003. Use of coral-derived aggregates for construction of low-volume roads. Transportation Research Record 1819 (LVR8-1115):134–142.

Bullen, F., and B. Heaton. 1986. Evaluation of coronus pavement materials. Conference proceedings of the 13th ARRB and 5th REAAA 13(2):63–75.

Cederholm, C. J., L. M. Reid, and E. O. Salo. 1981. Cumulative effects of logging road sediment on salmonoid populations in the Clearwater River, Jefferson County, Washington. Pages 38–74 *in* Salmon-spawning gravel, a renewable resource in the Pacific Northwest, paper 39. Washington Water Research Center, Pullman, Washington.

Coker, R. J., B. D. Fahey, and J. Payne. 1993. Fine sediment production from truck traffic, Queen Charlotte Forest, Marlborough Sounds, New Zealand. *Journal of Hydrology (NZ)* 31:56–64.

Corradi, P. 1945. Reconstruction of Japanese air base on Peleliu Island. *Military Engineer* 37(234):143–148.

Croke, J., and S. Mockler. 2001. Gully initiation and road-to-stream linkage in a forest catchment, southeastern Australia. *Earth Surface Processes and Landforms* 26:205–217.

Dunne, T., and Dietrich, W. 1982. Sediment sources in tropical drainage basins. Pages 41–55 *in* Soil erosion and conservation in the tropids, ASA special publication no. 43. American Society of Agrononmy, Soil Science Society of America, Madison, Wisconsin.

Dyrness, C. T. 1967. Mass soil movements in the H.J. Andrews Experimental Forest. USDA Forest Service res. pap. PNW-42. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, 12 pp.

Fahey, B. D., and R. J. Coker. 1992. Sediment production from forest roads in Queen Charlotte Forest and potential impact on water quality, Marlborough Sounds, New Zealand. *New Zealand Journal of Marine and Freshwater Research* 26:187–195.

Foltz, R. B. 1996. Traffic and no-traffic on an aggregate surfaced road, sediment production differences. Pages 195–204 in Proceedings of the Food and Agriculture Organization (FAO) seminar on ''Environmentally Sound Forest Road and Wood Transport,'' 17-22 June, Sinaia, Romania, FAO, Rome.

Foltz, R. B., and M. A. Truebe. 1995. Effect of aggregate quality on sediment production from a forest road. In Conference proceedings 6, Sixth International Conference on Low-Volume Roads, vol. 1. TRB, National Research Council, Washington, D.C.

Foltz, R.B., and Truebe, M. 2003. Locally available aggregate and sediment production. Transportation Research Record 1819, paper no. LVR8-1050:185–193.

Forman, R. T. T., and L. E. Alexander. 1998. Roads and their major ecological effects. *Annual Review of Ecology and Systematics* 29:207–231.

Ghadiri, H., and D Payne. 1979. Raindrop impact and soil splash. Pages 95–104 *in* R. Lal and D. J. Greenland (eds.), Soil physical properties and crop production in the tropics. John Wiley & Sons, Chichester.

Grayson, R. B., S. R. Haydon, M. D. A. Jayasuriya, and B. L. Finlayson. 1993. Water quality in mountain ash forests—separating the impacts of roads from those of logging operations. *Journal of Hydrology* 150:459–480.

Gucinski, H., Furniss, M. J., Ziemer, R. R., and Brookes, M. H. (eds). 2001. Forest roads: A synthesis of scientific information. General technical report PNW-GTR-509. USDA Forest Service, Portland, Oregon, 117 pp.

Hafley, W. L. 1975. Rural road systems as a source of sediment pollution—a case study. Pages 393–405 *in* Watershed management: symposium conducted by the Committee on Watershed Management of the Irrigation & Drainage Division of the American Society of Civil Engineers Utah Section, ASCE. Proceedings held at Utah State University, Logan, Utah, August 11–13, 1975. American Society of Civil Engineers, Committee of Watershed Management, New York.

Jones, J. A., F. J. Swanson, B. C. Wemple, and K. U. Snyder. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. *Conservation Biology* 14:76–85.

Kochenderfer, J. N., and J. D. Helvey. 1987. Using gravel to reduce soil losses from minimum standard forest roads. *Journal of Soil and Water Conservation* 42:46–50.

Lal, R. 1990. Soil erosion in the tropics—Principles and management. McGraw-Hill, New York 580 pp.

Lee, D. C., J. R. Sedell, B. E. Rieman, R. F. Thurow, J. E. Williams, D. Burns, J. Clayton, L. Decker, R. Gresswell, R. House, P. Howell, K. M. Lee, K. MacDonald, J. McIntyre, S. McKinney, T. Noel, J. E. O'Connor, C. K. Overton, D. Perkinson, K. Tu, and P. Van Eimeren. 1997. Broadscale assessment of aquatic species and habitats. Vol. III, Chapter 4 *in* T. M. Quigley, S. J. Arbelbide (eds.), An assessment of ecosystem components in the interior Columbia basin and portions of the Klamath and Great Basins. Gen. Tech. Rep. PNW-405. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon.

Luce, C. H., and T. W. Cundy. 1994. Parameter identification for a runoff model for forest roads. *Water Resources Research* 30:1057–1069.

MacDonald, L. H., D. M. Anderson, and W. E. Dietrich. 1997. Paradise threatened, land use and erosion on St John, US Virgin Islands. *Environmental Management* 21: 851–863.

Megahan, W. F. 1972. Subsurface flow interception by a logging road in mountains of central Idaho. Pages 350–356 *in* C. Csallany, T. G. McLaughlin, and W. D. Striffler (eds.), Proceedings of a symposium on watersheds in transition, series 14, 19-22 June, Fort Collins, Colorado. American Water Resources Association, Herndon, Virginia.

Megahan, W. F., and J. L. Clayton. 1983. Tracing subsurface flow on roadcuts on steep, forested slopes. *Soil Science Society of America Journal* 47:1063–1067.

Megahan, W. F., and W. J. Kidd. 1972. Effect of logging roads on sediment production rates in the Idaho batholith. Res. pap. INT-123. USDA, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, 14 pp.

Megahan, W. F. 1984. Erosion over time on severly disturbed granitic soils, a model. Res. pap. INT-156. USDA, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, 14 pp.

Montgomery, D. R. 1994. Road surface drainage, channel initiation, and slope instability. *Water Resources Research* 30:1925–1932.

Morgan, R. P. C. 1995. Soil erosion and conservation, 2nd ed. Longman Group Ltd, Essex, 198 pp.

Motha, J. A., P. J. Wallbrink, P. B. Hairsine, and R. B. Grayson. 2004. Unsealed roads as suspended sediment sources in an agricultural catchment in south-eastern Australia. *Journal of Hydrology* 286:1–18.

Mutchler, C. K., and R. A. Young. 1975. Soil detachment by raindrops. Pages 113–117 *in* Present and prospective technology for prediction sediment yields and sources. USDA-ARS publication ARS-S-40.

Palmer, R. S. 1964. The influence of a thin water layer on water-drop impact forces. *International Association of Scientific Hydrology Publication* 65:141–148.

Poessen, J. 1981. Rainwash experiments on the erodibility of loose sediments. *Earth Surface Processes and Landforms* 6:285–307.

Poesen, J. W. 1992. Mechanisms of overland flow generation and sediment production on loamy and sandy soils with and without rock fragments. Pages 275–305 *in* A. Parsons Abrahams (ed.), Overland flow hydraulics and erosion mechanics. U.C.L. Press, London.

Reid, L. M., T. Dunne, and C. J. Cederholm. 1981. Application of sediment budget studies to the evaluation of logging road impact. *Journal of Hydrology (NZ)* 20:49–62.

Reid, L. M., and T. Dunne. 1984. Sediment production from forest road surfaces. *Water Resources Research* 20:1753–1761.

Sidle, R. C., A. J. Pearce, and C. L. O'Loughlin. 1985. Hillslope stability and land use. Water resour. monogr., vol. 11. American Geophys. Union, Washington, D.C.

Sidle, R. C., S. Sasaki, M. Otsuki, S. Noguchi, and A. R. Nik. 2004. Sediment pathways in a tropical forest: effects of logging roads and skid trails. *Hydrological Processes* 18:703–720.

Skorseth, K., and A. A. Selim. 2000. Gravel roads: maintenance and design manual. Report for the US Federal Highway Administration (FHWA) by the South Dakota Local Transportation Assistance Program (SD LTAP). 64 pp.

Soil Conservation Service. 1981. Erosion and sediment control, guide for Hawaii. USDA. Soil Conservation Service, Honolulu, Hawaii 178 pp.

Sullivan, K.O., and S. H. Duncan. 1981. Sediment yield from road surfaces in response to truck traffic and rainfall. Weyerhaeuser research report. Weyerhaeuser, Western Forestry Research Center, Centralia, Washington, 46 pp.

Summer, R. 1982. Field and laboratory studies on alpine soil erodibility, southern Rocky Mountains, Colorado. *Earth Surface Processes and Landforms* 7:253–256.

Swift, L.W. Jr. 1984. Gravel and grass surfacing reduces soil loss from mountain roads. *Forest Science* 30:657–670.

Swift, L.W. Jr. 1988. Forest access roads, design, maintenance, and soil loss. Pages 313–324 *in* W. T. Swank and D. A. Crossley Jr. (eds.), Forest hydrology and ecology at Coweeta. Ecological studies, vol. 66. Springer-Verlag, New York.

Torri, D., and M. Sfalanga. 1986. Some problems on soil eosion modeling. Pages 161–171 *in* A. Giorgini and F. Zingales (eds.), Agricultural nonpoint source pollution, model selection and applications. Elsevier, Amsterdam.

Trimble, G. R., and R. S. Sartz. 1957. How far from a stream should a logging road be located? *Journal of Forestry* 55:339–341.

TRRL. 1997. Road note 31, A guide to the structural design of bitumen-surface roads in tropical and sub-tropical countries. Transport and Road Research Laboratory, Crowthorne, United Kingdom.

Valentin, D. 1994. Surface sealing as affected by various rock fragment covers in West Africa. *Catena* 23:87–97.

Wemple, B. C., and J. A. Jones. 2003. Runoff production on forest roads in a steep, mountain catchment. *Water Resources Research* 39:1–17.

Wemple, B. C., F. J. Swanson, and J. A. Jones. 2001. Forest roads and geomorphic process interactions, Cascade Range, Oregon. *Earth Surface Processes and Landforms* 26:191–204.

Ziegler, A. D., and T. W. Giambelluca. 1997. Importance of rural roads as source areas for runoff in mountainous areas of northern Thailand. *Journal of Hydrology* 196:204–229.

Ziegler, A. D., T. W. Giambelluca, and R. A. Sutherland. 2001a. Erosion prediction on unpaved mountain roads in Northern Thailand, I. Validation of dynamic erodibility modeling using KINEROS2. *Hydrological Processes* 15:337–358.

Ziegler, A. D., R. A. Sutherland, and T. W. Giambelluca. 2000. Partitioning total erosion on unpaved roads into splash and hydraulic components, the roles of inter-storm surface preparation and dynamic erodibility. *Water Resources Research* 36:2787–2791.

Ziegler, A. D., R. A. Sutherland, and T. W. Giambelluca. 2001b. Interstorm surface preparation and sediment detachment by vehicle traffic on unpaved mountain roads. *Earth Surface Processes and Landforms* 26:235–250.

Ziegler, A. D., T. W. Giambelluca, R. A. Sutherland, M. A. Nullet, S. Yarnasarn, J. Pinthong, P. Preechapanya, and S. Jaiarree. 2004. Toward understanding the cumulative impacts of roads in agricultural watersheds of montane mainland Southeast Asia. *Agriculture, Ecosystems, and Environment* 104:145–158.

Ziemer, R. R., and W. R. Megahan. 1991. Erosion and sedimentation control on roads and construction sites in the Federated States of Micronesia. Report for the Environmental and Policy Institute, East-West Center, Honolulu, Hawaii. (note: unpublished report found via www search).