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Sediment production from forest roads in western Oregon

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Abstract. Prevention and estimation of soil erosion from forest roads requires an understanding of how road design and maintenance affect sediment production. Seventy-four plots were installed on forest roads in the Oregon Coast Range to examine the relationship between sediment production and road attributes such as distance between culverts, road slope, soil texture, and cutslope height. An additional comparison was made between road segments with cutslopes and ditches freshly cleared of vegetation and segments with established vegetation on cutslopes and in ditches. All road segments were 5 m wide and insloped with aggregate surfacing, light traffic, and no overhanging forest cover. Sediment production was correlated to the product of segment length times road slope squared. Sediment production from aggregate covered roads on a silty clay loam was about 9 times greater than that from roads constructed on a gravelly loam. Sediment production was not correlated to the cutslope height. Road segments where vegetation was cleared from the cutslope and ditch produced about 7 times as much sediment as road segments where vegetation was retained, showing the potential reduction in erosion by revegetation following construction and the potential impact of ditch cleaning during maintenance. Relationships and estimates from this study provide a basis for improved erosion estimates by commonly used empirical procedures.

1. Introduction

Assessment of road contributions to sediment budgets generally relies on a summation of sediment production of each road segment multiplied by the fraction delivered to the stream [*Cline et al.*, 1984; *U.S. Department of Agriculture (USDA) Forest Service Northern Region*, 1991; *Washington Forest Practices Board*, 1995; *Dubé et al.*, 1998]. Predictions of the sediment production from road segments in these models are based on empirical observations [e.g., *Megahan and Kidd*, 1972; *Megahan*, 1974; *Reid and Dunne*, 1984; *Bilby et al.*, 1989; *Swift*, 1984], extension of rainfall simulation results [e.g., *Burroughs and King*, 1989; *Burroughs et al.*, 1992], and professional judgment. Recently, physically based modeling has been proposed as an alternative [*Elliot et al.*, 1995; *Tysdal et al.*, 1997]. The accumulated empirical evidence provides insight on how sediment yield is affected by traffic [*Reid and Dunne*, 1984; *Bilby et al.*, 1989; *Foltz*, 1999], surfacing [*Foltz*, 1999; *Foltz and Elliot*, 1997], and time following construction [*Megahan*, 1974]. There are a few limited observations on the effects of road slope [e.g., *Vincent*, 1985; *MacDonald et al.*, 1997] and cutslope height [e.g., *U.S. Department of Agriculture (USDA) Forest Service Intermountain Forest and Range Experiment Station*, 1981; *Boise State University Department of Geology and Geophysics*, 1984] on road sediment production. Data on the influence of road segment length, soil texture within a given climate, and maintenance practices on road segment sediment production are likewise limited or missing. These are important attributes of forest roads, and observations are needed to describe these effects in empirical models and verify predictions of physically based models. Here we describe how the sediment yield of a forest road segment (tread, cutslope, and ditch output through a culvert or crossdrain) relates to road segment length, road slope, cutslope height, soil texture, and maintenance practices.

2. Theory

Erosion is the result of the interplay between the ability of flowing water to remove sediment, transport capacity, and the availability of moveable sediment. There are two aspects to the concept of availability as applied to forest roads, material erodibility, and loose soil supply. The material with which road treads are built is generally well compacted during construction, reducing its erodibility. Road construction and maintenance practices, however, disturb a layer of soil on the road tread, ditch, and cutslope that is the source of the most easily eroded material [*Megahan*, 1974]. Both the erodibility and the supply of this "loose" material play a role in the sediment yield from a road segment. Using these concepts, we will develop specific hypotheses regarding the relationship of sediment yield to road segment length, slope, cutslope height, soil texture, and maintenance.

2.1. Length and Slope

Mass conservation dictates that

$$E = \nabla \cdot Q_s \tag{1}$$

where E is the change in storage of soil in an area (erosion) and Q_s is the sediment transport rate. For a small volume above a small area on the ground (infinitesimally small in both cases), the amount of sediment leaving the volume is the same as the amount flowing into the volume plus any erosion that occurs over the small area. For a small watershed, such as the cutslope, tread, and ditch of a road, (1) may be evaluated as

$$E = Q_{s(\text{out})} \tag{2}$$

The basin's sediment discharge, $Q_{s(\text{out})}$, depends on the transport capacity and incoming sediment to the exit point. To

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calculate the incoming sediment flux requires integrating detachment along the slope. Detachment at any point along the slope is not necessarily related to transport capacity. *Foster and Meyer* [1972, 1975] and *Lei et al.* [1998] describe methods to account for the difference between transport capacity and actual sediment flux. In general, however, on long plots with easily detached noncohesive materials (such as a ditch immediately following a grading operation), transport capacity at the end of a hillslope and the actual sediment discharge can be nearly equal [*Kirkby*, 1980; *Nearing et al.*, 1997]. Consequently, immediately following disturbance, we expect sediment production to be closely related to transport capacity.

Sediment transport capacity can be defined by one of two models:

$$Q_s = k(\tau - \tau_c)^{n_\tau} \tag{3}$$

$$Q_s = k(\Omega - \Omega_c)^{n_\Omega} \tag{4}$$

where k is some index of mobility of the sediment, τ is shear stress, τ_c is the critical shear stress for incipient motion, n_τ is an exponent between 1 and 2 [*Foster and Meyer*, 1975; *Kirkby*, 1980], Ω is the stream power, Ω_c is the critical stream power for incipient motion, and n_Ω is an exponent between 1 and 1.5 [*Govers*, 1992; *Bagnold*, 1977]. Shear stress, τ, is given by

$$\tau = \rho_w g d S \tag{5}$$

where ρ_w is the density of water, g is gravity, d is the depth of flow (alternatively hydraulic radius), and S is the water surface slope, usually accepted to be the same as the bed slope. Stream power, Ω, is given by

$$\Omega = \rho_w g q S \tag{6}$$

where q is the flow per unit width. Bringing in a simple relationship for the hydrology of a particular event, considering a nearly impermeable forest road [*Luce and Cundy*, 1994] at steady state flow,

$$q \propto x \tag{7}$$

where x is distance downslope, and that depth is a square root function of flow [*Dunne and Dietrich*, 1980]

$$d \propto \sqrt{q} \tag{8}$$

that yields two approximations for sediment transport at the end of the ditch. By the argument stated earlier regarding the close relationship between transport capacity and sediment flux, road segment sediment production from a segment of length, L is

$$E \propto k(S\sqrt{L} - \tau_c)^{n_\tau} \tag{9}$$

$$E \propto k(SL - \Omega_c)^{n_\Omega} \tag{10}$$

In the model based on shear stress transport, erosion is proportional to the product of slope and the square root of length with an exponent slightly greater than 1. In the model based on stream power, it is proportional to the product of length and slope with an exponent slightly greater than 1. Both equations suggest a statistical interaction effect for length and slope. Because plots with higher slopes exceed the critical shear stress for a greater fraction of the plot, transport capacity may be more fully sated at the bottom of steeper plots yielding a slightly stronger effect on slope, S, than predicted solely from the transport capacity. For this reason, we also considered an increase in the exponent of slope relative to the exponent for length. The general form of an interaction between length and slope is supported by empirical erosion models developed on agricultural plots such as the Universal Soil Loss Equation (USLE) and the Revised Universal Loss Equation (RUSLE) [*Wischmeier and Smith*, 1978; *McCool et al.*, 1987, 1989; *Renard et al.*, 1994].

On the basis of the above discussion and the cited empirical observations, we hypothesize that sediment yield from road segments is related to plot length and slope according to a linear combination of L or $\sqrt{L}$, S or S^2, and one of the four interaction terms (LS, LS^2, $\sqrt{L}S$, and $\sqrt{L}S^2$). Arguments for why sediment yield should vary with L, $\sqrt{L}$, and S and their interactions are clear from (9) and (10). We also considered the increased role that slope might play in satisfying transport capacity at the end of the plot and the fact that n_τ can vary between 1 and 2 by considering a nonlinear slope term.

2.2. Cutslope Height

The effects of cutslope height on sediment production must be considered in light of the roles of transport capacity and loose sediment supply. Conceptually, flow and transport in the ditch control the sediment yield of an insloped road segment. Flow comes into the ditch from the road surface and the lower parts of the cutslope. The cutslope also contributes loose material to the ditch through a variety of processes, including soil creep, sheet wash, rilling, raveling, and slumping. Higher cutslopes produce more material [*USDA Forest Service Intermountain Forest and Range Experiment Station*, 1981; *Boise State University Department of Geology and Geophysics*, 1984]. If the initial loose sediment supply in the ditch is limiting, sediment yield over the course of a season should be higher on road segments with high cutslopes.

2.3. Soil Texture

Depths of flow and turbulence are not so great from a 100 m long road segment that all soil particles travel as suspended load. Larger particles move more slowly than smaller particles in saltating transport. *Burroughs et al.* [1992] describe soil erodibility as a function of soil texture and found that erodibility (for 0.6 m^2 plots under a rainfall simulator) was low in soils with high clay content (due to particle aggregation) and in soils with high sand content. The erodibility of soils with a high silt fraction was the greatest. Because the ditch is commonly set in the native soil, we expect that road segment sediment production will be greater on silty soils than on sandy soils.

2.4. Maintenance

Ditch maintenance removes vegetation that holds sediment in place and breaks up any armoring that may have occurred earlier. Effectively, this practice increases the supply of easy-to-transport loose sediment supply. The expectation is that ditch cleaning will increase sediment yields. Road grading should also increase yields but less dramatically because ditch vegetation is retained and aggregate surfacing is less erodible than the native soils in the ditches.

3. Methods

The general approach used to examine these questions and hypotheses was statistical inference based on sampling of sediment production from road segments. Sediment production was measured using sediment traps.

The study was conducted west of Eugene, Oregon, in the Oregon Coast Range (Figure 1). The central Oregon Coast Range receives between 1800 and 3000 mm of rainfall annually, with drier portions being further inland and wetter portions near the crest [*Miller et al.*, 1973]. Winters are mild and wet; summers are warm and dry. Plots are located between 250 and 600 m in elevation, below elevations where snow commonly accumulates. Soils are derived from sedimentary and metasedimentary rocks through most of the Coast Range with some igneous dikes in the inland foothills. The Tyee arkosic sandstone formation is the dominant bedrock throughout this part of the Coast Range. Douglas-fir and Western Hemlock forests cover much of the Coast Range.

Two field areas were used to examine sediment production on two soil textures. Many of the plots were located near Low Pass, Oregon. These sites were on the finer textured soils of the inner Coast Range. Soil series at Low Pass were Jory and Bellpine silty clay loams. The Jory soil is a clayey, mixed, active, mesic Palehumult; the Bellpine soil is a clayey, mixed, mesic Xeric Haplohumult. The other plots were located near Windy Peak, 15 km west of Low Pass and had coarser soils. The soils at Windy Peak were the Bohannon gravelly loam, a fine loamy, mixed, mesic Andic Haplumbrept, and the Digger gravelly loam, a loamy-skeletal, mixed, mesic Dystric Eutrochrept.

Table 1. Factors Considered in the Study Design and How They Were Treated

Variable	Treatment
Soil Type	two soils selected: silty clay loam and gravelly loam
Segment length	three levels used: 40, 60, and 110 m
Road slope	varied from 3 to 12%
Cut-slope height	varied from 0.5 to 4 m
Time since construction	0 years and 15 years
Degree of rutting	all plots bladed at beginning
Inslope/crown/outslope	all plots bladed to inslope at beginning
Aspect	not controlled
Cut-slope slope	not controlled: higher cutslopes tend to be steeper
Slope position	all in upper third of hillslope
Road width	all roughly 5 m
Rainfall	differs between soils; recorded at both sites after 1st year
Forest cover	all plots in clearcut areas
Surfacing	basalt aggregate existing at all sites
Road use	all have light recreational and administrative traffic

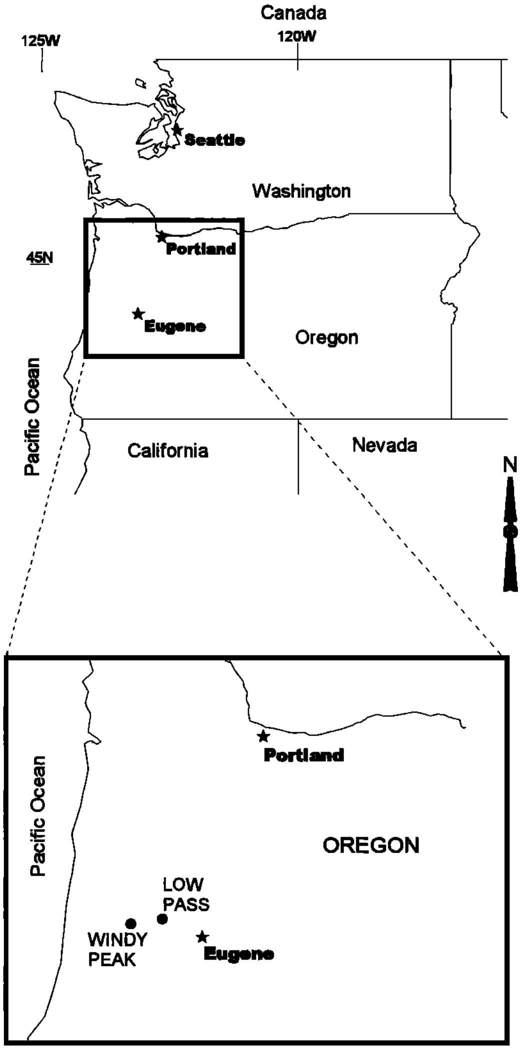

Figure 1. Location map with inset of northwestern Oregon showing the location of the two study areas, Low Pass and Windy Peak.

3.1. Study Design

Major factors affecting sediment production from a forest road are (1) inherent erodibility and runoff producing capacity of the soil and running surface, (2) road segment length, (3) road gradient, (4) amount of cutslope and running surface, typically a function of road width and side slope, (5) treatments of cutslope, running surface, and fillslope, such as surfacing, straw, or jute mat, (6) flowpath geometry as embodied in insloping and outsloping and degree of rut development, (7) slope position and aspect in so far as they affect soil moisture, (8) forest cover, (9) time since construction, (10) road use, and (11) weather at the site, as indexed by rainfall erosivity. This study was designed to evaluate only a few of these factors. We attempted to control the other factors. Table 1 lists the variables embodied by these 11 factors and how each was treated in the study.

Three experiments were conducted. The first experiment was set up to examine the effects of road segment length and road slope or gradient. The second experiment was directed toward the effect of cutslope height on different soils. The third experiment focused on the effect of vegetation removal from the cutslope and ditch.

The study examining the effects of road segment length and road slope was carried out at the Low Pass site. Segment length was divided into three general classes: short (~40 m), medium (~60 m), and long (~110 m). Road slope was also divided into three general classes: low (4–6%), medium (6–11%), and steep (11–13%). Road length and slope were varied so that there were two replications in each of the nine combinations of length and slope, yielding 18 plots. This arrangement was used to assure that multicollinearity did not prevent examination of the interaction term between length and slope during regression analysis. Plots in the length-slope experiment were selected with cutslope heights in the medium category (2–4 m). Roads were freshly bladed, and cutslopes and ditches were cleared of vegetation.

The cutslope height experiment was carried out at both sites to introduce variability due to soils. Plots in the cutslope height experiment had cutslope heights in three classes determined by the slope length of the cutslope: low (0–2 m), medium (2–4 m), and high (>4 m). These classes were used for plot selection to ensure that a comparable range and set of cutslopes were used at each study area. Two replications of each class for each soil yielded an additional 12 plots. This design allowed an analysis of covariance with the continuous cutslope height variable and the categorical soil variable. All cutslope height plots had medium lengths and medium slopes. Roads were freshly bladed, and cutslopes and ditches were cleared of vegetation.

The ditch and cutslope clearing experiment was also conducted at Low Pass. Three classifications of road treatment were considered for this experiment: no treatment, road tread graded, and road tread graded with cleared ditch and cutslope. The five plots with no treatment were installed 1 year earlier and had a range of slopes, and lengths, all with medium cutslope heights. Plots with the road treatment only were selected to have a matching set of plots. The five plots with road grading and cleared ditches and cutslopes were selected from among the length slope experiment plots to match the lengths and slopes of the five no-treatment plots.

In addition to the 40 plots required for these experiments, 34 more plots were installed in the area for replacement plots (in case of failure or vandalism) and for the later examination of temporal trends. Vandalism was widespread and regular but consisted mostly of shot sediment traps that were easily repaired. Ditch dams used to hydrologically isolate individual road segments were breached upslope of five plots during a large precipitation event. Those data were removed from examination.

General road characteristics common to the plots are 5 m width, basalt aggregate surfacing, insloped with ditch and crossdrains, recreational and administrative (light) traffic, and no forest cover. Aggregate for most of the roads came from two basalt quarries. Nelson Mountain quarry had a coarse durability of 78, a fine durability of 48, LA abrasion of 21%, and sulfate soundness of 7% loss [*American Association of State Highway and Transportation Officials*, 1995]. Conser quarry igneous intrusives had a coarse durability of 66, a fine durability of 76, and an LA abrasion of 19%.

The degree of rutting in the road has been cited as an important factor in sediment production of the road surface [*Foltz and Burroughs*, 1990]. Initial rutting was removed on all but five plots by grading the roads. The relatively equal surfacing and levels of traffic are expected to yield similar levels of rutting on the graded plots over time. All roads were insloped with water bars and crossdrains to make the contributing area for each sediment trap constant over time. With an insloped road and waterbars, all runoff and sediment generated on the road surface eventually reached the ditch.

Megahan [1974] demonstrated that time since construction is an important determinant in road erosion. In this study, we used roads that have been in place between 10 and 25 years. For the cutslope height and length-slope experiments, we bladed the road surface and scraped all vegetation from the cutslopes to simulate the effects of new road construction. At the time that the data presented in this paper were collected, the plots had been in operation for 1 year. Three more years of study are planned to measure the variation in sediment production over time. Five plots at the Low Pass site were left in the original, ungraded, vegetated condition for comparison to the experimentally treated plots.

The steepness of the cutslope may affect how much sediment is produced by a cutslope. In general, the cutslope gradient is designed when the road is engineered and constructed and depends on soil properties. It is also, in practice, a function of cutslope height. Low cutslopes are built in weaker surface soils and therefore have shallower gradients. Higher cutslopes intersect lower soil horizons and sometimes bedrock. Typical low cutslopes had gradients of 3:1, and medium cutslopes were around 2:1 on both soils. Higher cutslopes were between 2:1 and 1:1, generally steeper at the Windy Peak sites.

As constructed, forest roads do not have neatly defined segments with relatively constant slopes or cutslope heights. We installed waterbars and crossdrains (Figure 2) to hydrologically isolate relatively homogeneous road segments with the characteristics we wished to investigate. Cement inlet structures were placed to collect flow from the ditches, and runoff was routed under the road through 15.24 cm (6 inch) plastic pipe crossdrains to the sediment traps. Only sediment carried through this crossdrain was measured. The results of *Megahan and Ketcheson* [1996] showed that most sediment from roads and the sediment that is carried the farthest downslope is carried through crossdrains.

3.2. Sediment Traps

Sediment traps were 1.5 m^3 plastic bins placed below the outlets of the crossdrains. Tanks were weighed with four load cells on jacks; the water was level across the top of the tank with the tank overflowing. These tanks have since been replaced by steel tanks of similar dimension (Figure 3) that can be weighed with a crane. The mass of the tank was measured with sediment and water and with water only. The mass of sediment was calculated from

$$M_s = (M_{ts} - M_{tw})\rho_s/(\rho_s - \rho_w) \qquad (11)$$

where M_s is the mass of sediment, M_{ts} is the mass of the tank, sediment, and water, M_{tw} is the mass of the tank with water only, ρ_s is the particle density of the sediment, and ρ_w is the density of water (1000 kg/m^3). Here ρ_s was estimated to be $2.65\rho_w$ (2650 kg/m^3).

The attributes of several types of sediment traps were explored by *Ice* [1986]. This type of trap had the best trap efficiency of the several Ice explored. *Foltz* [1999] used a much smaller sediment trap for shorter road segments and estimated efficiencies for silt and finer fractions to be 40–60%. The few measurements of trap efficiency that we have taken indicate that an overflowing tank with 1/3 of its volume filled with sediment captures 70–80% of the fraction finer than silt (50 μm) and all of the larger fractions during a 12 mm/hr storm. At Low Pass, where the soil is finer, an average of 8% of the soil fraction finer than 2 mm was finer than 0.05 mm based on aggregate particle size analysis as described by *Kemper and Rosenau* [1986]. Three traps filled with sediment during the largest event of the measuring period. Fortunately, the overflow from two of the traps deposited on large flat benches below the traps and the bypassed volumes were estimated from those deposits.

3.3. Climate Measurements

Climate observations were made in an open area at the Low Pass site. Precipitation was measured with a 0.254 mm/tip tipping bucket gage with 152.4 mm orifice. Temperature, relative humidity, wind speed, and direction were also measured.

The Low Pass site is 15 km farther inland and is 300 m lower

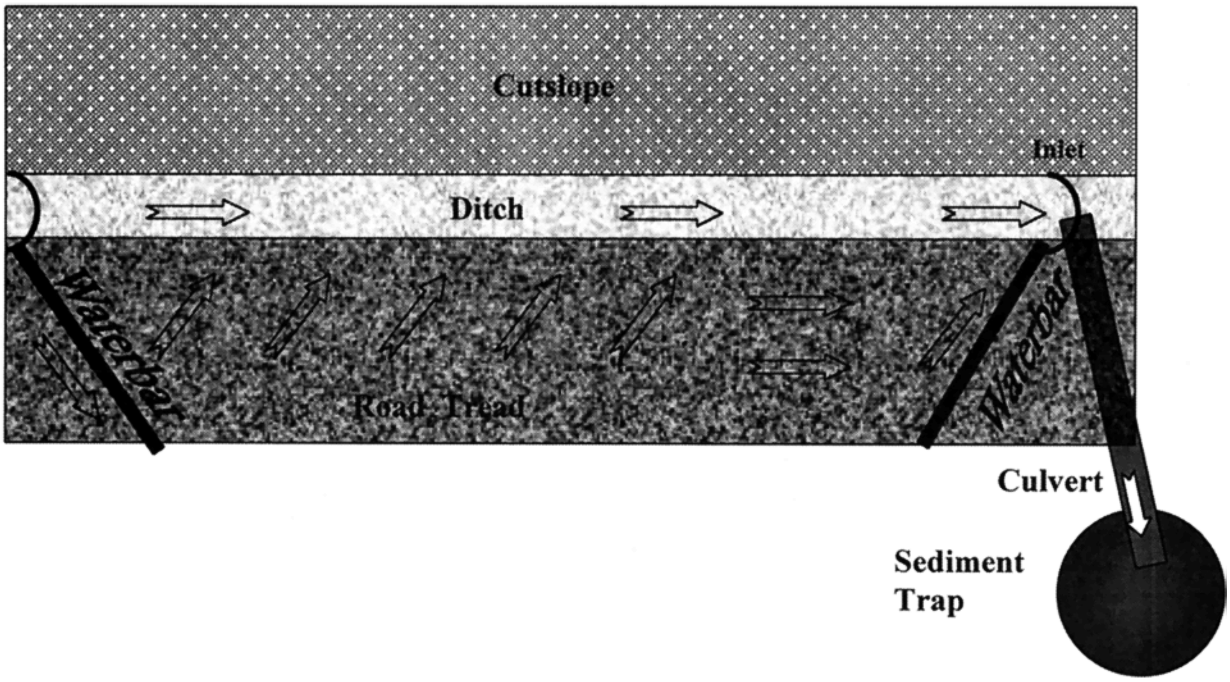

Figure 2. Typical plot layout.

in elevation than the Windy Peak site, so it almost certainly receives less precipitation. This difference is implicit in any comparisons between soils. All plots on a particular soil are within 2 km of each other.

For the period of study, November 1995 to February 1996, 1017 mm of rain fell at Low Pass. While the entire period was wetter than normal, the storm of February 6–7, 1996, was responsible for the greatest amount of runoff and sediment production. Peak hourly rainfall intensities for this storm were in the range of 10 mm/hr (Figure 4).

3.4. Statistical Analyses

Road segment length and slope data were analyzed by linear regression. Sediment yield data were regressed against multiple combinations of the variables listed in the theory section (L, $\sqrt{L}$, S, S^2, and their interaction terms) to determine the best linear combination of these variables using fit, significance, and parsimony as criteria. For the better fitting models where the intercept was not significant, the prediction sum of squares (PRESS) statistic was used as a criterion. The PRESS

Figure 3. Photograph of sediment trap with crossdrain outlet.

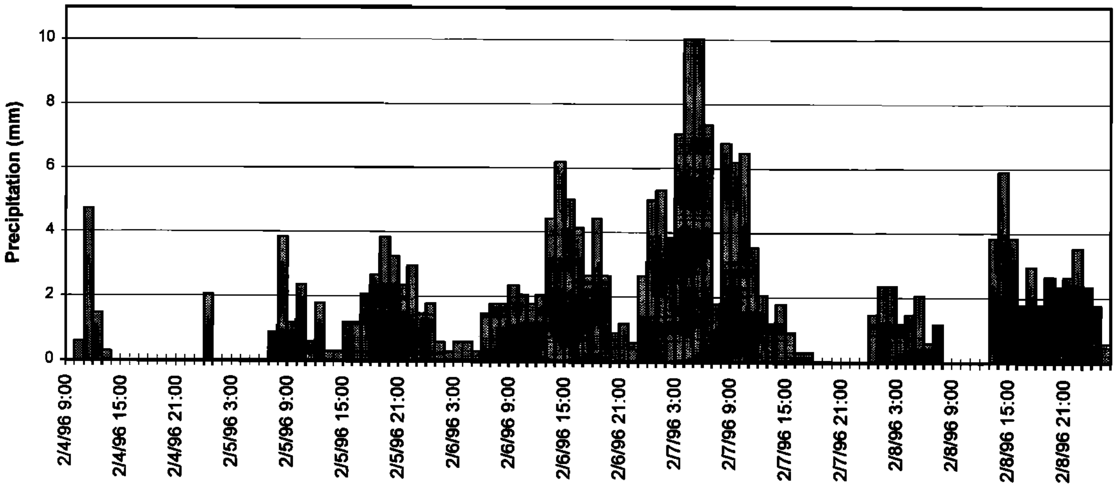

Figure 4. Hourly hyetograph for early February 1996, when the largest runoff event of the study period occurred.

statistic is calculated through a cross-validation procedure where the error for a point is found from the difference between the point and a line regressed through all of the other points. These are prediction errors of the model, which are summed and squared to yield PRESS. Normalizing the PRESS statistic by the variance times $(n - 1)$ yields the R_{pred} statistic, which gives an impression of how well the model can be used for prediction. Because plot length was a regression variable, we did not normalize by length to estimate per-unit-length or per-unit-area sediment production. Part of the purpose of the regression study on length was to determine whether unit area scaling is appropriate for road erosion.

Analysis of covariance was used to analyze the difference in sediment production between soils given the variation in cutslope height among plots, and separate regressions were done for each soil to estimate the effect of cutslope height on sediment production. Analysis of variance was used to compare the three maintenance treatments.

4. Results and Discussion

From November 1995 to February 1996, varying amounts of sediment were collected in the 68 surviving sediment traps (Figure 5). The most striking feature of these observations is the large range of sediment masses collected. In general, most road segments produced little sediment, but a few produced a large amount. This shows that substantial amounts of sediment can come from relatively standard roads with little use and that it may be possible to substantially reduce road erosion by targeting those few sections with the greatest sediment production. Given the wide range of characteristics for these roads, it is important to understand the sources of variability.

4.1. Relationship of Sediment Production to Segment Length and Slope

Figure 6a shows the relationship of sediment production to segment length by slope class, and Figure 6b shows the relationship of sediment production to slope by segment length class. The figures show that increases in both road length and gradient can lead to increased erosion. The interaction between length and gradient is strong in both figures. For example, increasing length has little effect if the gradient is low but has a great deal of effect on roads with high gradients. The difference in how sediment production relates to gradient for different length classes in Figure 6b seems mostly to be change in slope of the graphs as opposed to a shift in position. This indicates that the interaction term in a regression would be potentially more important than either length or road slope alone.

The r^2, adjusted r^2 (includes a penalty for increased number of parameters), and p value (indicates significance of relationship) for several combinations of length, slope, and interaction terms are reported in Table 2. The best models, given the criteria of fit and parsimony, appeared to be those that included only one of the four interaction terms. For each of these, the intercept was not statistically different from zero, and because we believe that for zero length or slope the erosion would be nominally zero, regressions with the intercept set to zero were tested. Table 3 shows a comparison of the four interaction-only models with zero intercept using the prediction sum of squares (PRESS). On the basis of this analysis, the model

$$E = 717\ LS^2 \tag{12}$$

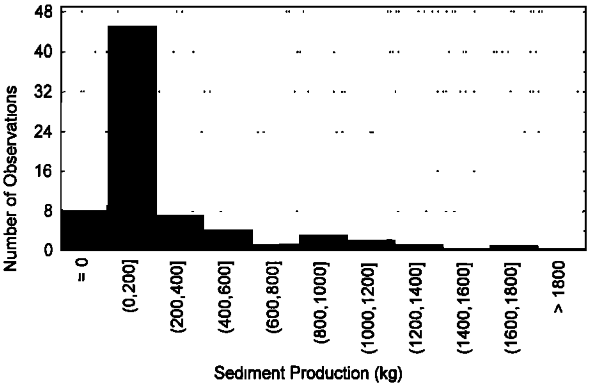

Figure 5. Histogram of sediment production from all plots. The range (x-axis) and relative frequency (y-axis) of sediment produced during the study period from a large variety of road plots are shown.

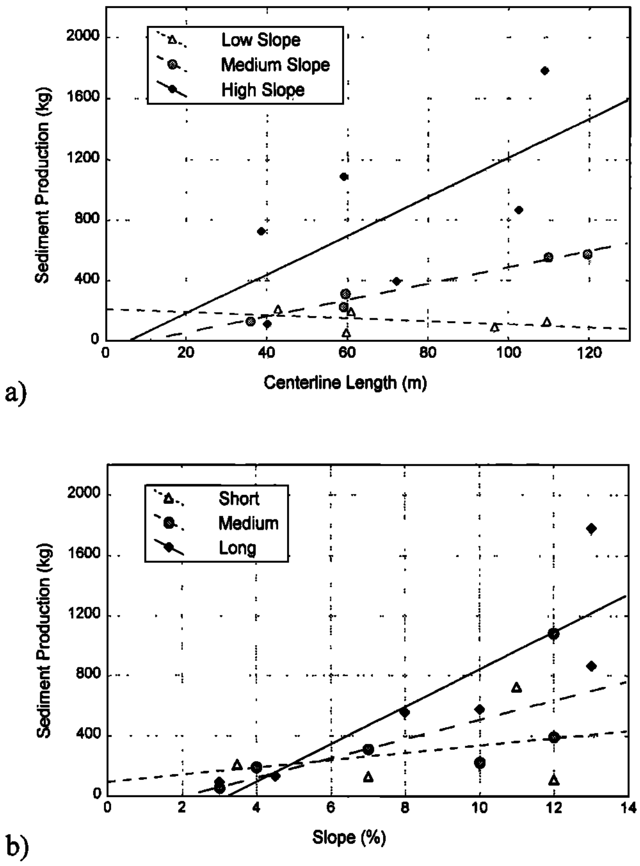

Figure 6. Sediment production as a function of (a) segment length lumped by three slope classes and (b) road slope lumped by three length classes.

Table 3. R_{pred} Scores for the Four Zero-Intercept Models

Model	R_{pred}	SE_{est}	F	p
$E = aLS$	0.43	302.75	58.2	0.000001
$E = aLS^2$	0.51	273.92	74.41	<0.000001
$E = aL^{1/2}S$	0.42	310.36	54.65	0.000002
$E = aL^{1/2}S^2$	0.49	282.22	69.23	0.000001

had the best predictive ability. Erosion is plotted against LS^2 in Figure 7.

Embodied within the constant obtained from this regression is information on soil erodibility, the runoff producing capability of the road and ditch, the rainfall erosivity experienced in this period of time, and the antecedent moisture conditions for a given rainfall event. This constant may well be meaningless outside of this context, and the more useful relationship is the general

$$E \alpha LS^2 \qquad (13)$$

On the basis of this relationship, measurements from a road with known slope and length for a soil and climate of interest can be extrapolated to apply to roads with differing slopes and lengths but otherwise similar characteristics. The exponent for slope agrees well with observations by *Vincent* [1985] and *McCool et al.* [1987], who found nonlinear, concave-upward, relationships between slope and erosion. The exponent for L disagrees with the square-root relationship identified by *Wischmeier and Smith* [1978], although the difference in fit is small (Table 3). *McCool et al.* [1989] suggested that the exponent should be closer to one for situations where rill erosion dominates over rainsplash in delivery of sediment. Given the uncertainty in the literature about exponents for (9) and (10) and the similarity in fit for LS^2 and $\sqrt{L}S^2$, it is difficult to say whether the shear stress model or the stream power model is better supported by these data. However, the best fit to the data agrees well with the basic model form derived from consideration of either a shear stress or stream power conceptualization. This physical basis lends credence to this model form for use in other soils and climates.

4.2. Relationship of Sediment Production to Underlying Soil and Cutslope Height

Examination of data from the cutslope height and soil texture experiment shows a strong relationship with soil texture and a weak relationship with cutslope height (Figure 8). Average sediment production was 473 kg for the Low Pass plots and 51 kg at Windy Peak, a factor of 9.3 times greater. Analysis of covariance showed that this difference was statistically sig-

Table 2. Statistics of Selected Models Used to Fit the Length and Slope Versus Sediment Production Data

Model	R^2	Adjusted R^2	p
$E = aL + b$	0.131	0.068	1.7E-01
$E = aS + b$	0.452	0.413	4.3E-03
$E = aL^{1/2} + b$	0.126	0.064	1.8E-01
$E = aS^2 + b$	0.494	0.458	2.4E-03
$E = aLS + b$	0.580	0.550	6.1E-04
$E = aLS^2 + b$	0.658	0.638	1.4E-04
$E = aL^{1/2}S + b$	0.600	0.571	4.3E-04
$E = aL^{1/2}S^2 + b$	0.629	0.603	2.5E-04
$E = aL + bS + c$	0.543	0.473	6.1E-03
$E = aL + bS^2 + c$	0.577	0.512	3.6E-03
$E = aL + bLS^2 + c$	0.662	0.610	8.7E-04
$E = aS + bLS^2 + c$	0.658	0.605	9.0E-04
$E = aS^2 + bLS^2 + c$	0.659	0.606	9.0E-04
$E = aL + bS + cLS^2 + d$	0.671	0.589	3.1E-03
$E = aL + bS + cLS + dLS^2 + e$	0.676	0.558	9.0E-03
$E = aL^{1/2} + bL^{1/2}S + cL^{1/2}S^2 + d$ (USLE)	0.646	0.558	4.8E-03

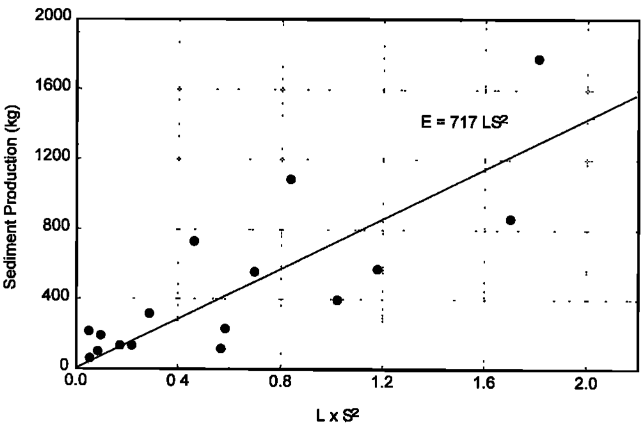

Figure 7. Erosion versus LS^2. Note that 717 is a constant that would apply only for this study period and for these soils. The more general relationship is $E \propto LS^2$.

nificant [$p(M_{LP} = M_{WP}) = 0.002$]. This agrees with general theory in sediment transport and erosion that larger clasts and sediments are more difficult to move. Infiltration capacity may also be greater in the coarser soil. In general, Windy Peak would be expected to receive more rainfall than Low Pass because it is closer to the coast and has a higher elevation, emphasizing the role of soil in the difference between Low Pass and Windy Peak sediment production.

The slope of the relationship between cutslope height and sediment production at both sites is not significantly different from zero [$p(\beta_{LP} = 0) = 0.25$, $p(\beta_{WP} = 0) = 0.74$], although generally trending in the expected direction. From these data, cutslope height appears to have no effect on whole plot sediment production for freshly disturbed roads and ditches. On the basis of the concept of availability as discussed in the theory section, this finding suggests that loose sediment was available in all ditches throughout the study.

We observed abundant loose soil in the ditches at the beginning of the season, so this is a reasonable possibility. High cutslopes may be a more important source of sediment in later years when sediment availability in the ditch of segments with stable noneroding cutslopes is reduced, implying that the time scale considered in this study is too short to show the effects of sediment depletion and vegetation regrowth in the ditch. This observation is supported by the results of the length and slope experiment.

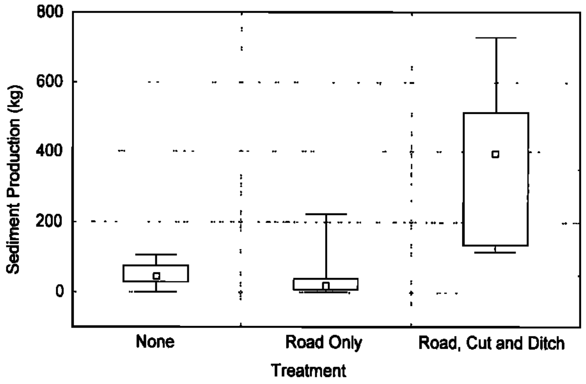

Figure 9. Sediment production versus road treatment for a subset of plots.

4.3. Relationship of Sediment Production to Ditch and Cutslope Treatment

Cleaning ditches and removing the cutslope vegetation caused a dramatic increase in sediment production. Three groups of plots at Low Pass were used to measure the effect. The first group received no treatment and presents a 20 year old road with vegetated cutbank and ditch. The second group had only the road surface graded. The third group had the road graded, the ditch cleaned, and the cutslope stripped of vegetation. Figure 9 shows the range of values for each of the three treatments, with the mean sediment production at 50 kg for the untreated road, at 57 kg for the treated road tread, and at 377

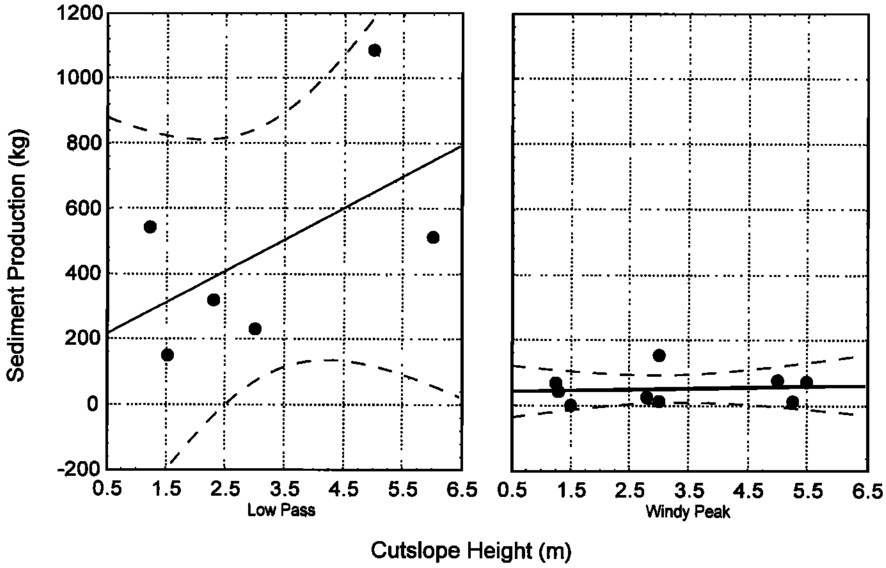

Figure 8. Sediment production versus cutslope height on each of the two soils. Soils at Low Pass are a silty clay loam, and soils at Windy Peak are a gravelly loam. The relationship between cutslope height and sediment production is not significant for either soil.

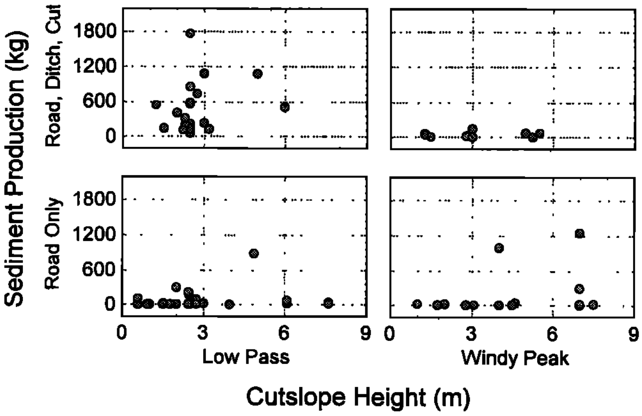

Figure 10. Sediment versus cutslope height for four different cases. The top graphs are for plots used in the experiments that were freshly bladed and with vegetation cleared on the cutslope and ditch. The bottom two graphs use "validation" plots that only received a treatment of the road surface. The data from the fine-grained soils at Low Pass from the coarser soils at Windy Peak are shown.

kg for the treated ditch and cutslope. Analysis of variance showed that the difference in sediment production among the three classifications was significant [$p(Mu = Mr = Mrc) = 0.0110$]. The difference between no treatment and roadway treatment was not significant [$p(Mu = Mr) = 0.95$], and the difference between either of those sets of plots and plots where the ditch and cutslope were treated was significant [$p(Mu = Mrc) = 0.008, p(Mr = Mrc) = 0.008$]. In these fine-grained soils, removing vegetation from the ditch and cutslope increased sediment production by a factor of 7.4 relative to no treatment and by a factor of 6.6 over treatment of the road surface only.

The question remains whether the differences in erosion are due to the cutslope contribution or the ditch contribution. Figure 10 shows four graphs of sediment production versus cutslope height. Two of the three anomalous points for plots with treated roadways only (the two lower plots) are cutslopes with unusual soil and bedrock conditions leading to a naturally bare cutslope and ditch, and the third anomalous point is a 250 m long 15% grade plot with a gullied ditch. None of the four scatterplots show any significant relationship between sediment production and cutslope height. At the same time there is a large difference between treated and untreated cut/ditch at Low Pass and a lesser but still noticeable difference at Windy Peak. From this, it can be concluded that the treatment of the ditch is probably a more important factor in the increased sediment production than the treatment of the cutslope, although, this may only be true for a short period following treatment of the ditch.

5. Summary and Conclusions

Sediment production by a forest road through surface erosion clearly depends on several factors. The data presented in this paper provide important insights into some of these dependencies. First, the variability in sediment production from road segment to road segment is high. Most segments produce little sediment, while only a few produce a great deal, implying that managing the sediment production of the few highest risk segments would be the most efficient. Second, sediment production is proportional to the product of road segment length and the square of the slope (LS^2). The nonlinearity in the effect of slope is important to consider and demonstrates that road slope is an important attribute to consider in the assessment of sediment budgets. The use of a linear scaling of sediment yield by length (e.g., tons/mile) is supported by this relationship for road segments with lengths on the scale of tenths of kilometers. Third, soil texture has a strong effect on sediment yield, with coarser soils producing much less sediment than finer soils. This is a key area of uncertainty in most road erosion assessments. It is clear that measurements that show the relative erodibility of soils in the context of the entire road prism should yield significant improvement of these assessments. Finally, sediment yields from older roads with undisturbed ditchlines are much smaller than sediment yields from newer roads or roads with disturbed ditchlines. Disturbance of the road surface alone through grading showed less effect.

The results of this study give insights that are valuable when considering two important questions remaining unanswered by this study; the effects of time and of traffic. It is clear that time in a nominal sense, old and new, is important. Answers to the questions of how rapidly the changes occur and through what mechanisms would be useful when seeking the integrated sediment yield over some time period. In addition, the role of traffic in forming ruts and disturbing the tread surface is effective in interaction with processes occurring in the ditch. Previous studies suggest that rut formation and disturbance to the tread increases tread erosion. This study suggests that it is also important to consider the degree to which the rutting captures water that would otherwise be ditchflow and whether the increased erosion due to tread disturbance results in an increase to the total erosion from a road segment with a recently disturbed ditch.

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