Spatial and Temporal Patterns in Erosion from Forest Roads[1]

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ABSTRACT

Erosion from forest roads is an important contribution to the sediment budget of many forested basins, particularly over short time scales. Sediment production from 74 road segments was measured over three years to examine how road slope, segment length, cutslope height, and soil texture affect sediment production and how these relationships change with time. In the first year, differences in sediment production between plots could be explained by differences in sediment transport capacity of the plots. With time, differences between plots of different slope, length, cutslope height, and soil were reduced as all plots produced less and less sediment. Recovery was rapid with around 70% recovery between by the second year and 90% recovery by the third year.

1. INTRODUCTION

1.1 The Role of Road Surface Erosion in the Sediment Budget

Networks of forest roads traverse many mountain and forested regions in the western United States. Roads impose substantial local changes to soil properties and hydrologic behavior and commonly alter sediment budgets of the basins they pass through. The net effect of the changes is to increase the supply of sediment to streams through surface erosion on the bare road surfaces and mass erosion and gullying below the road.

Evaluation of the sediment budget is an important step in analyzing potential problems caused by the increased sediment supply from roads. Reid and Dunne [1984] suggest that the sediment budget be used to answer two questions with respect to forest roads ① "How much is contributed by surface erosion on roads?" and ② "How important is it relative to other sources?" The answers to these two questions do not well serve the purposes of managing and reducing sediment inputs from roads unless we also ask, ③ "Where is the contribution coming from?" and ④ "When is the sediment contributed?"

The question of the relative magnitude of sediment sources (② above) has been raised several times [Gilbert, 1917; Dietrich and Dunne, 1978; Reid, 1981; Reid and Dunne, 1996] and is one of the primary purposes for calculating a sediment budget. In some regions, roads may promote gully formation or headward channel migration and decrease slope stability through concentration of water [e.g. Fredriksen, 1970; Sidle et al., 1985; Furniss, 1991; Montgomery, 1994]. In other regions, surface erosion from the bare soil surfaces comprising roads is the dominant mode of sediment contribution from roads. The question of relative magnitude, ②, has several levels of importance. At one level it can assist in prioritizing erosion abatement practices; at another, it can assist in prioritizing information needs for constructing sediment budgets. Similarly, resources for acquiring information to improve sediment budgets would best be spent reducing uncertainty in estimates for the greatest contributors. Given these practical goals for sediment budgets, questions ① and ② should be answered in the context of clearly defined temporal and spatial scales.

We need to know the spatial (③ "from where") and temporal (④ "at what time") patterns of sediment production from forest roads relative to other sources for small areas and short time scales as well as for long time frames and whole watersheds. These questions suggest prioritization based on relative contributions in time and relative contributions from different locations. Reasons for prioritization of erosion abatement and information needs at small spatial scales (location) are considered "common sense"; they are practically oriented and based in part on budgets and the capability of human engineering.

Short time scales (on the order of one to a few years) may be important in constructing sediment budgets intended to identify and prioritize opportunities for erosion abatement. Long-term sediment budgets often have the aim of quantifying relative magnitudes of the various processes contributing to landscape evolution [Dietrich and Dunne, 1978]. Large-magnitude low-frequency sediment delivery events may well dominate the long-term sediment delivery to stream systems, and therefore landscape form and stream sediment volume and structure, in places like the Oregon Coast Range [Benda and Dunne, 1997; Benda et al., 1998]. These events are largely driven by large winter rainstorms with recurrence intervals on the order of one to a few decades. "Recovery" of streams in temperate regions following a major

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flood/erosion event may occur within a few years to two decades [Wolman and Gerson, 1978; Megahan et al., 1980]. If major mass wasting erosion events are sufficiently spaced in time that "recovery" occurs on shorter time scales, processes that introduce sediment on a more frequent basis, like road surface erosion, become important concerns in determining the most common stream condition in time. Changes to stream condition from these higher-frequency low-magnitude effects may include changes in the surface bed composition (e.g. cobble embeddedness, surface fines) and turbidity. Biologists refer to the large-magnitude low-frequency events as "pulsed" [Yount and Niemi, 1990] as opposed to the chronic (high-frequency) lesser magnitude "press" effects resulting from road erosion. While many aquatic species are adapted to large-scale infrequent disturbances, press disturbance above "natural" levels may pose special problems for species persistence.

1.2 Estimating the Contribution of Road Surface Erosion to the Sediment Budget.

Distributed modeling of sediment production and delivery from forest roads [e.g. Cline et al., 1984; USDA Forest Service Northern Region, 1991; Washington Forest Practices Board, 1995; Dubé et al., 1998] estimates sediment production from short segments of road based on characteristics of each segment. Estimates from individual segments are commonly based on traffic level and road use [Reid and Dunne, 1984; Bilby et al., 1989], soil texture, surfacing [Swift, 1984; Burroughs and King, 1989; Foltz and Elliot, 1997], time since construction [Megahan, 1974], and surface protection on cut and fill slopes [Burroughs and King, 1989; Megahan et al., 1992].

Technological advances in remote sensing, global positioning technology, and geographic information systems increase the ease with which we can collect and assimilate data about road networks. As information about the spatial distribution of road slope, cutslope height, cutslope condition, soil texture, maintenance practices, culvert location, become more readily available, it is important to understand their effects so that those effects may be described in distributed road erosion models. Because road segments with recently constructed or cleared ditches can produce so much more sediment than older roads [Megahan, 1974; Luce and Black, 1999], it is also important to understand how the effects of road characteristics such as slope, texture, and cutslope height may change over time.

Observations on the effects of road slope on sediment production [e.g. Vincent, 1985; Burroughs and King, 1989; MacDonald et al., 1997; Black and Luce, 1999; Luce and Black, 1999] are increasing in quantity and are beginning to note that the effect of slope on sediment production changes with time [Black and Luce, 1999]. Similarly, there are few publications on the effects of cutslope height, road segment length, soil texture, and maintenance practices and how those relationships change with time. These are important attributes of forest roads and observations are needed to describe these effects in distributed empirical models and verify predictions of physically based models such as ROSED [Simons et al., 1980], KINEROS [Woolhiser et al., 1990], or WEPP [Flanagan and Nearing, 1995; Tysdal et al., 1999].

This study was organized to collect observations on the relationships between sediment production and segment length, road slope, cutslope height, soil texture, and time since disturbance. Results from the first year of measurements are presented in Luce and Black [1999]. We also desired to explore changes of erosion from roads with time and test the applicability of Megahan's [1974] model.

In this paper we 1) Describe the relationship of sediment production to a few road characteristics (slope, cutslope height, length of drainage unit, and soil texture) that can be mapped on a road network, 2) Describe how these relationships change with time following disturbance for a short time period, and 3) Use insights gained from these examinations to suggest a conceptual model of the sediment "micro-budget" of the road-tread-ditch combination.

2. THEORY

Some expectations about the relative production of sediment from road segment to road segment and from time period to time period can be derived from our existing understanding of sediment transport and soil erosion processes. Mass conservation dictates

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

where E is the change in storage of soil in an area (Erosion) and Q_s is the sediment transport rate. This equation means that 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), equation 1 can be evaluated as

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

Where $Q_{s(in)}$ is 0, and $Q_{s(out)}$ depends on the transport capacity and supply to the exit point. If there is too much supply, material will be deposited before the exit point, and the output will match the transport capacity. If the supply does not meet the transport capacity at that point (the more common case) plot erosion is dictated by the amount that arrives at that point. Such a calculation requires estimating detachment along the slope. Detachment at some 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 non-cohesive materials (such as a ditch immediately following a grading operation), there is a close relation between transport capacity at the end of hillslope and the actual sediment discharge [Kirkby, 1980].

Consequently, immediately following disturbance, we would expect sediment production to be tied to transport capacity. Over time, processes of armoring, pavement formation, and vegetation growth reduce availability of fine sediments. We would expect to see relative sediment production tied to relative indexes of availability, such as vegetation growth or armoring [e.g. Megahan, 1974].

2.1 Length and Slope

At a point 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 1.5 and 1.9 [Foster and Meyer, 1975; Kirkby, 1980], Ω is the stream power and Ω_c is the critical stream power for incipient motion, and n_Ω is an exponent between 1.1 and 1.5 [Govers, 1992; Bagnold, 1977]. Shear stress, τ, is given by

$$\tau = \rho_w gds \tag{5}$$

where 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

$$\Omega = \rho_w gqs \tag{6}$$

where q is the flow per unit width. Bringing in a simple relationship for the hydrology of a particular event, considering a nearly impermeable road at steady state flow,

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

where x is distance downslope, and

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

[Dunne and Dietrich, 1980] 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:

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

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

In the first model, based on shear stress transport, erosion is roughly proportional to the slope times the square root of length, and the in the other it is proportional to slope times length. Both equations suggest a statistical interaction effect for length and slope. Luce and Black [1999] found that sediment production from recently disturbed plots (E) was proportional to length (L) times slope (S) squared,

$$E \propto LS^2 \tag{11}$$

which exhibits the interactive behavior suggested by theory and agrees well with observations [e.g. Wischmeier and Smith, 1978; McCool et al., 1987; Burroughs and King, 1985; Vincent, 1985; Renard et al., 1994].

Over time, as the initially available material is eroded and surface armoring and plant growth limit the availability of sediment, there is an expectation that transport capacity would be less important in determining sediment yield leaving the plot. Even when vegetation regrowth is slow, we would expect local particle size distributions to shift towards larger particles in locations with steeper slopes and larger contributing areas. After some period of erosion, then, contributing length and slope would not only affect local shear stress and stream power, but also the critical value required to initiate sediment movement.

2.2 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] attempted to describe forest soil erodibility as primarily a function of soil texture and found that erodibility (for 0.6-m^2 plots under a rainfall simulator in a laboratory) was low for both clay dominated and sand dominated soils and higher for soils with a high silt fraction. They also noted a dependence on clay minerology. Other authors [e.g. Carling et al., 1997] have seen similar behavior with respect to soil texture, and the general trend seems to be reflected in erodibility estimates published in soil surveys. Because the ditch is commonly set in the native soil, we expect that road segment sediment production would initially be greater on silty soils than on sandy soils. As discussed in the previous section selective transport in the ditch may reduce the importance of native soil texture with time.

2.3 Cutslope Height

The effects of cutslope height on sediment production must be considered in light of the relative roles of transport capacity and sediment supply. Conceptually, flow and transport in the ditch control the sediment yield of a road segment. Most of the water probably comes from the road tread, where infiltration capacities are low compared to most rainfall events. The cutslope contributes mostly loose material to the ditch through a variety of processes, including soil creep, sheet wash, rilling, raveling, and slumping, and we would expect more material to come from higher cutslopes. If the ditch already has a large loose sediment supply, separate from the cutslope contribution (for example from a recent ditch blading operation), we would expect that the cutslope height would make little difference. Once armoring begins in the ditch, material added from the cutslope should become an important contribution to the loose material supply. So initially, following disturbance to the ditch and cutslope, we would expect little difference in sediment production from plots with different cutslope heights. In later years, however we would expect to see some effect from cutslope height.

2.4 Time Following Construction or Disturbance

Megahan [1974] describes a model of erosion over time following disturbance, t [days], based on the idea of an initially available amount of soil, S_0 [tons/mi^2], a rate constant, k [day^{-1}], and a long term constant erosion rate, ε_n.

$$\varepsilon(t) = \varepsilon_n + kS_0e^{-kt} \tag{12}$$

from this, we can see that the initial erosion rate

$$\varepsilon_0 = \varepsilon_n + kS_0 \tag{13}$$

and that the total soil eroded in increase over the long term rate is S_0. The S_0 parameter should relate to soil characteristics like the volume fraction taken by non-transportable rock fragments. S_0 should also related to the transport capacity, as more strongly flowing water has access to a greater portion of the particle size distribution of the soil. The k parameter describes how quickly erosion rates move from high initial rates toward the background rate. It may, in part, be a function of transport capacity. With a high k, the initial rate will be high, and armoring will occur rapidly. Lower k values predict a longer decay period with overall lower erosion rates.

In some situations, the effect of varying transport capacity from plot to plot will appear more strongly in the k parameter and in others more strongly in the S_0 parameter. If the volume of transportable material is entirely transportable by all flows regardless of the transport capacity, the variation will manifest in the k parameter, with high k values and rapid declines associated with higher transport capacities and low k values and gentle declines associated with low transport capacity. An example of this might be if uniform fine sand were the material to be transported. Alternatively, if the material to be transported were heterogeneous in character, the volume to be transported, S_0, would also be a function of the transport capacity. Variations in S_0 do not alter the relative timing of the recovery. It is important to know how these two parameters might change with changing transport capacity (segment length or slope) on forest roads.

3. FIELD MEASUREMENTS

3.1 Description of Study Sites

We measured annual sediment production from 74 road segments in the Oregon Coast range (Figure 1) over three years to test these expectations. 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 m 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; and 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.

All road segments were selected in clearcut areas to prevent differences in precipitation due to variable interception by forest cover. All segments had high quality basalt aggregate surfacing and received infrequent administrative and recreational traffic from light vehicles.

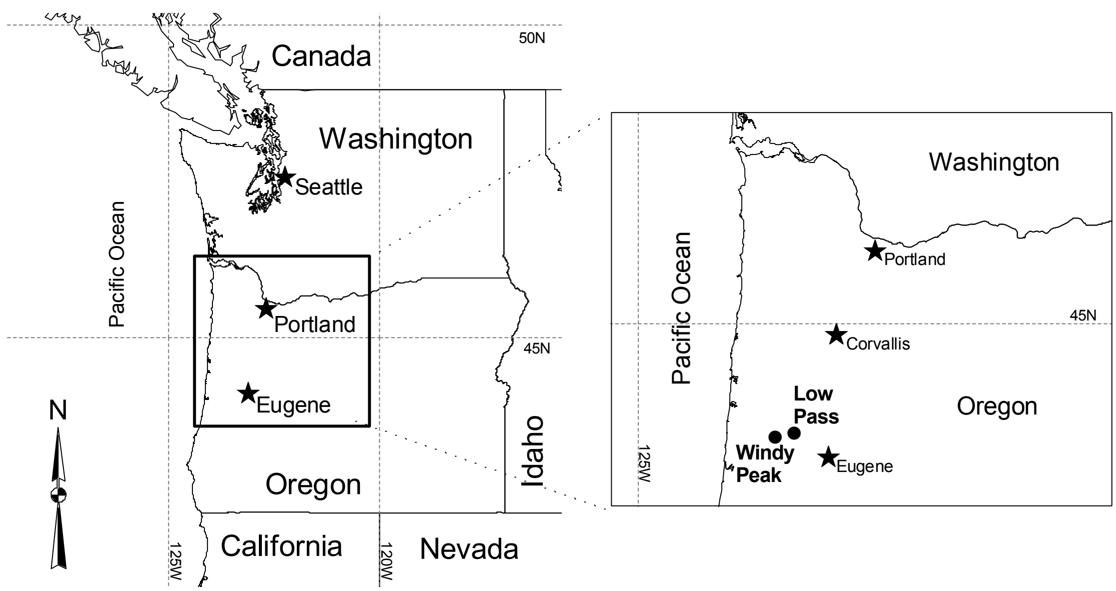

Figure 1. Location map with inset of northwestern Oregon showing the location of the two study areas, Low Pass and Windy Peak.

3.2 Measurement Procedures

Large tank style sediment traps (~1.5 m^3) similar to those described by Ice [1996] collected sediment produced from insloped road segments with rubber-flap waterbars bounding the top and the bottom on the road surface (Figure 2). The plots were installed
in the summer of 1995. Measurements of erosion were taken on a water year (beginning October 1) basis, so they cover Water Years 1996, 1997, and 1998.

At the end of each water year, we weighed the sediment traps containing sediment (M_{ts}) and again filled with just clean water (M_{tw}). For both weighings, the tank was topped off with water so that the volume was always the same. These weights reflect the contents of the tank:

$$M_{ts} = M_t + V_s\rho_s + V_w\rho_w \quad (14)$$
$$M_{tw} = M_t + \rho_w(V_s + V_w) \quad (15)$$

where M_t is the mass of the tank, V_s is volume of soil solids, ρ_s is the density of soil solids (we assumed a value of 2.65 Mg/m^3), ρ_w is the density of water (1.0 Mg/m3), and V_w is the volume of water in the tank. Note that $V_s + V_w$ is the volume of the tank. The difference in weight between the tank containing sediment and the tank full of clean water is the submerged weight of sediment.

$$M_{ts}-M_{tw} = V_s(\rho_s-\rho_w) \quad (16)$$

and the mass of sediment (M_s) is just $\rho_s V_s$, yielding

$$M_s = (M_{ts}-M_{tw})\rho_s/(\rho_s-\rho_w) \quad 17)$$

A few measurements and modeling indicated that for the range of flows we observed and soil particle size distributions of the sites measured that the traps probably caught at least 90% of the sediment entering [Luce and Black, 1999]. Three tanks were overtopped by sediment in the first year; we estimated volumes of two of them from local deposits on the concrete pads holding the tanks.

We also measured climate variables at two weather stations near the plots. Data collected included precipitation, temperature, humidity, incoming solar radiation, wind speed, and wind direction. Precipitation was measured in a 0.01-inch-per-tip tipping bucket gage. Half-hourly binned data were used to estimate the annual Erosivity Index (EI) [Wischmeier and Smith, 1978] values for each of the three years.

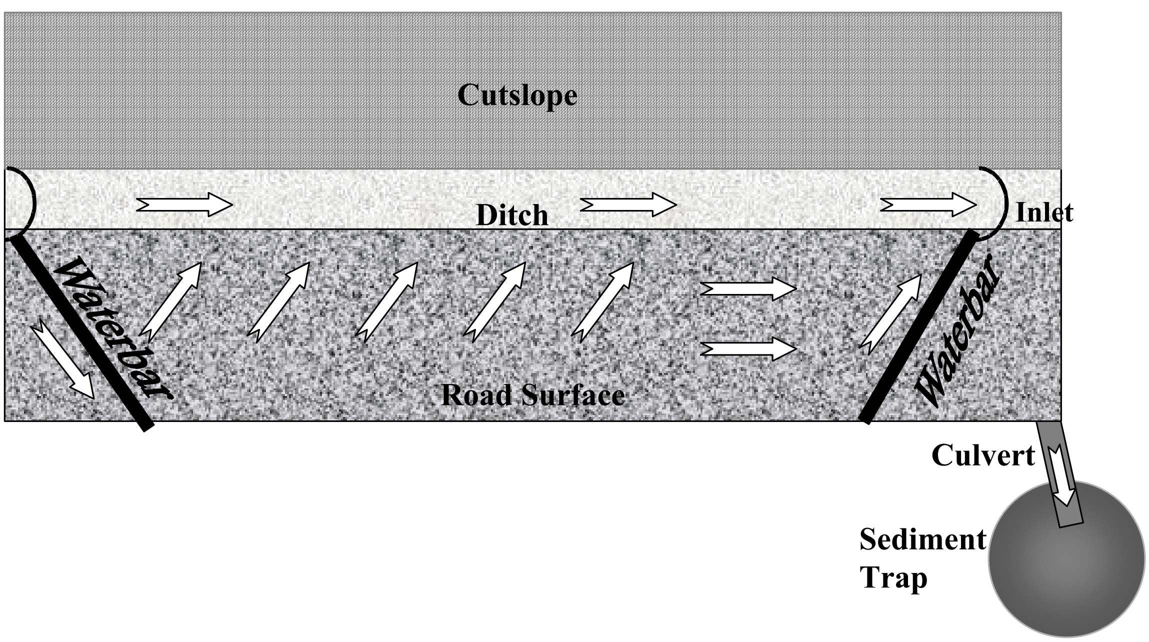

Figure 2. Typical plot layout. Water flows through 8-inch plastic pipe under road surface from inlet to sediment trap. Arrows indicate approximate patterns of water flow.

4. EXPERIMENTAL DESIGN AND DATA ANALYSIS

The plots were managed in 5 groups according to type and timing of disturbance to observe how erosion changed with time following disturbance.

Group I:	No Treatment. (N=5, All at Low Pass)
Group II:	Road surface graded at beginning of WY 1996. No treatment thereafter. (N=18, 9 at Low Pass, 9 at Windy Peak).
Group III:	Road surface graded and ditch and cutslope scraped clear of vegetation at the beginning of WY 1996, no treatment thereafter. (N=31, 22 at Low Pass, 9 at Windy Peak)
Group IV:	Road surface graded at beginning of WY 1996. Road surface graded and ditch and cutslope scraped clear of vegetation at the beginning of WY 1997, no treatment thereafter. (N=15, 10 at Low Pass, 5 at Windy Peak)
Group V:	Road surface graded at beginning of WY 1996. Road surface graded and cutslope scraped clear of vegetation at the beginning of WY 1997, and again at beginning of WY 1998. (N=5, All at Low Pass)

This organization of plots was designed to isolate the effects of clearing the ditch and cutslope from the effects of changes in weather between years. The effect of weather alone is reflected in the comparison between years for a subsample of five plots from Group III for WY 1996 and the five plots in Group V for WY 1997 and 1998. Although the plots changed between WY 1996 and WY 1997, all five plots in Group V had the same length-slope combinations as the subsample of five plots from Group III. This set of plots was used for examination of weather effects so that changes in sediment availability caused by site recovery would not affect the year to year changes in sediment production. All rainfall plots were on the finer soils at Low Pass. There is some variation in slope and length among the five plots, so erosion was normalized for length and slope variation among the plots (LS^2) using the results of Luce and Black [1999] for recently disturbed plots. Remaining comparisons between groups over time were done graphically. No normalization for length or slope was done for the other groups because per unit length and slope adjustments valid in the initial year may not be valid in later years. As a consequence, only comparisons between temporal trends are logically sound.

The plots in Group III had a special purpose beyond looking at the effects of ditch clearing. These plots were organized into two experiments:

Experiment 1.	To test the effects of changing length and slope on sediment production.
Experiment 2.	To test the effects of changing soil texture and cutslope height on sediment production.

Experiment 1 was arranged with 18 plots, all at Low Pass. For these plots, length was varied between 40 and 120 m. Six plots were close to 40 m in length; six others were close to 60 m; and the other six were about 120 m long. Slope was varied between 3 and 12 %, again broken down with equal numbers of plots in each of three classes (3-6%, 6-11%, and 11-13%). Plots were constructed and selected so that there were two plots within each length and slope class combination to remove colinearity effects between length and slope. All of these plots had cutslope heights in the range of 2-4 m. These data were examined by multiple regression in a manner similar to that in Luce and Black [1999] for comparison to equations 9 and 10. We also estimated the k parameter from the Megahan [1974] model by dividing the WY 1997 and WY 1998 sediment production by the WY 1996 sediment production and back calculating the k parameter from

$$k_{97} = -\ln(E_{97}/E_{96}) \quad (18)$$

$$k_{98} = -\tfrac{1}{2}\ln(E_{98}/E_{96}) \quad (19)$$

where k is the time decay constant in equation 11 and E is the sediment production. Subscripts indicate respective water years.

Experiment 2 was arranged with 15 plots to test the effects of cutslope height and soil texture. Soil was treated as a categorical variable with two values, and cutslope height was varied between 0 and 6 m. Plots were placed so that the plot-average cutslope heights were evenly distributed through three classes (0-2 m, 2-4 m, and 4-6 m) on each soil texture. Six plots at Low Pass (fine texture) and nine plots at Windy Peak (coarse texture) were analyzed in the cutslope height and soil texture experiment. Because all plots in the study had basalt aggregate surfacing, we expected to see increasing differences between soils with increasing cutslope height. Analysis of the cutslope height data was done using analysis of covariance (MANCOVA) with soil as a categorical variable and cutslope height as a covariate for each of the three years. This tested both the significance of the differences between soils with cutslope height effects removed and the regression of sediment production against cutslope height.

5. CHANGES IN EROSION WITH TIME FOLLOWING DISTURBANCE

5.1 Effects of Rainfall Differences

Water year 1997 showed the greatest normalized erosion from the rainfall plots; water year 1998 showed the least, and WY 1996 was intermediate (Figure 3, Table 1). Indexes of erosion based on precipitation data, including maximum single storm EI, total EI for season, and total precipitation for the water year all show the same ranking among the three years (Table 1). Water years 1996 and 1997 are known for the particularly large flood events in the Willamette River and streams in the Oregon Coast Range. WY 1998 had no particularly notable events and had close to the annual average precipitation for this area.

5.2 Effects of Site Recovery

The average erosion volumes for each of the treatment Groups (I-V) at Low Pass do not follow this same trend (Figure 4). The general behavior seen is a dramatic increase in

TABLE 1. Several indexes of the relative contribution of weather to the erosion from each water year. EI is calculated from ½ hour binned precipitation data by method of Wischmeier and Smith (1978). Erosion from five plots disturbed at beginning of each year is normalized by dividing by length times slope squared.

Water Year	Annual Precipitation (mm)	Erosivity Index (EI) Annual (MJ mm ha^{-1} hr^{-1})	Erosivity Index (EI) 1-Storm Maximum (MJ mm ha^{-1} hr^{-1})	Normalized Erosion Median (kg/m)	Normalized Erosion Average (kg/m)
1996	1955	1574	274	524	685
1997	2086	2060	425	1265	1149
1998	1496	1033	116	410	507

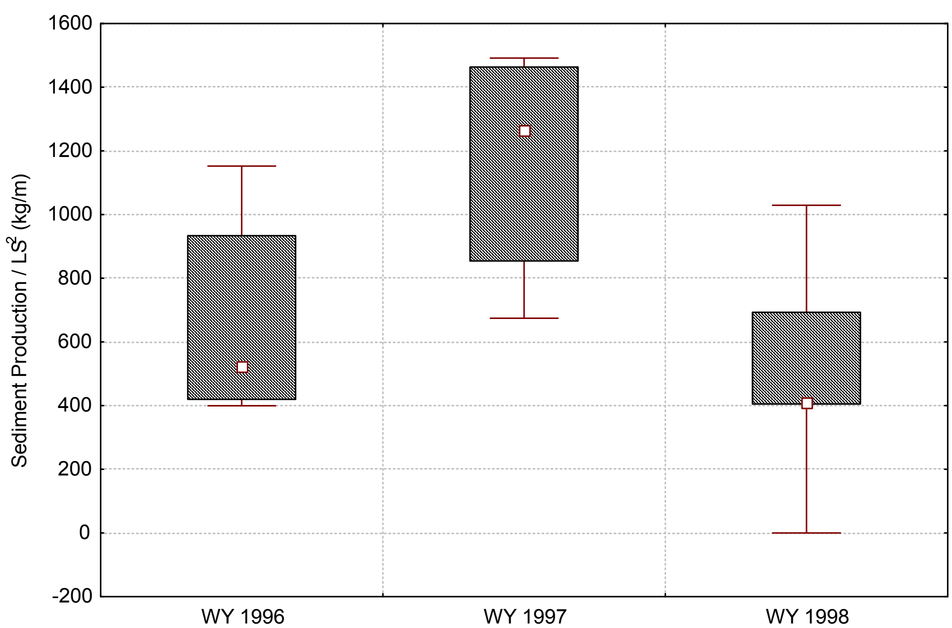

Figure 3. Differences in erosion induced by differences in weather from year to year. Sediment production was normalized by length x slope squared to account for differences in slope and length among the five plots. Whiskers indicate the minimum and maximum; the top and bottom of the box are at the 75th and 25th percentile, and the square is at the median.

erosion immediately following disturbance followed by a swift reduction in erosion the following year. Group III saw a 70% reduction between WY 1996 and WY 1997 and an 87% reduction between WY 1996 and WY 1998. Erosion from Group IV was 78% less in WY 1998 than WY 1997. Differences between lines approximately follow expected behavior and echo the results of Luce and Black [1999] for the first year showing that grading only the road tread gives no statistically significant increase in erosion, whereas clearing the ditch and cutslope yields a seven-fold increase in sediment production. The Group V plots which were disturbed at the beginning of WY 1997 and 1998 are the same plots shown in Figure 3, so echo the decline in erosion caused by weather changes. The road segments with no treatment or with only the road surface treated show a steady decline through time as do the more fully treated plots of Group III. We interpret this to mean that interannual differences caused by disturbance and recovery may be greater than interannual differences caused by differences in weather. However, it must be noted that we have not seen a full range of variability in climatic driving during these three years. Recovery for each disturbance set is rapid. We see tremendous decreases in sediment yields within one to two years. This is similar to Megahan's [1974] results for small watersheds and for plots on fillslopes.

6. SEDIMENT PRODUCTION OVER TIME FROM THE LENGTH-SLOPE EXPERIMENT

6.1 How Variations in Transport Capacity are Represented by the Exponential Recovery Model

The plots used to estimate the effects of segment length and slope on erosion show the same general decrease over time shown by the average of all Group III plots at Low Pass and the general form of Megahan's [1974] model of exponential recovery (Figure 5). The trajectory of individual plots, however, may differ from the trend. Those plots not following the recovery trend follow a pattern similar to the precipitation effects in Figure 3 suggesting that armoring may not have occurred on those plots. Visual observation of minor gullying and bare soil in the ditch of these plots confirms the suspicion, although there are no other plot characteristics that separate them from the remainder of the group. Sediment production is not high on these plots in spite of the abnormal activity (Figure 5).

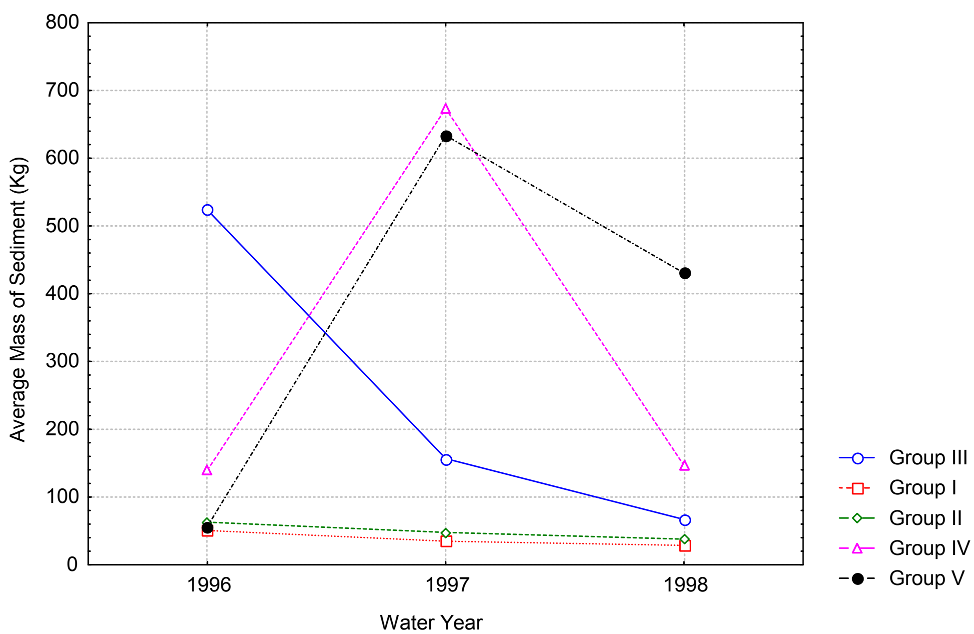

Figure 4. Average erosion from each of the five groups over the three year study:
Group I: No Treatment.
Group II: Road surface graded at beginning of WY 1996, no treatment thereafter.
Group III: Road graded & ditch and cutslope cleared before WY 1996, no treatment thereafter.
Group IV: Road graded before WY 1996, Road graded, ditch and cutslope cleared before WY 1997, no treatment thereafter.
Group V: Road graded before WY 1996, Road graded, ditch and cutslope cleared before WYs 1997 and 1998.

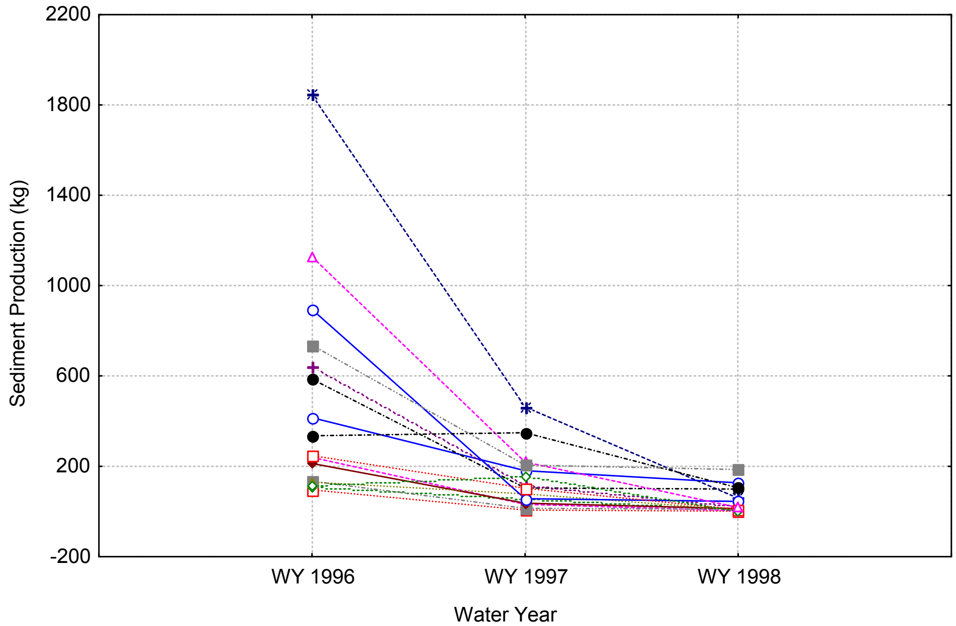

Figure 5. Erosion over the three-year study from each of the plots in Experiment 1 (length and slope) that operated all three years (N=14). All plots were treated at the beginning of WY 1996 by clearing the ditch and cutslope and grading the road surface. In WY 1996 differences are related to length times slope squared.

The remaining 14 segments (data from two segments was lost in the first year of the study) were used to examine the relative role of k and S_0 in the model of Megahan [1974]. If the dominant effect in changing transport capacity from plot to plot is in changing the k parameter (high transport capacity yields high k) we would expect to see the curves in Figure 5 crossing. Because they are somewhat parallel in their decline and the initial erosion rate scales with transport capacity (LS^2) [Luce and Black, 1999], we can conclude that the main effect of changing transport capacity is in changing the amount of available material for transport between ditch disturbances, S_0. We can also examine this problem by estimating k values implicit in the change between years from equations 18 and 19. We found no correlation between the first year sediment production and the estimated k for WY 1997 or WY 1998 (r = 0.07 for both), confirming the visual analysis above. The relative dominance of the S_0 parameter highlights the role of particle size heterogeneity in the sediment supply and the importance of armoring as a process in recovery over time.

6.2 How the Relationship Between Length, Slope, and Sediment Production Changes with Recovery

In the first year, the proportionality between sediment production and LS^2 [Luce and Black, 1999], suggested a close relationship between sediment transport capacity and sediment yield. The expectation was that as sediment availability decreased (Group III, Figure 4), the proportionality based on sediment transport would become a poorer approximation.

In year two, we found through a cross validation procedure that the proportionality of equation 11 was still the best predictive relationship for plots with less than 10% vegetation (Figure 6). While the cross validation procedure reduces the influence of the point in the upper right, its influence is still noticeable, and inspection of the scatter around the regression excepting this point reveals that the relationship is not strong. The constant of proportionality was much lower in WY 1997 than WY 1996, in spite of a very small increase in vegetation cover and a slight increase in rainfall erosivity, suggesting that armoring may be an important factor in the general trend from WY 1996 to WY 1997. Because detachment capacity equations are similar in nature to transport capacity [e.g. Nearing, 1991; Govers, 1992] and net erosion is a convolution of the transport and detachment capacity down the plot [Kirkby, 1980; Lei et al., 1998] it may not be possible to tell whether sediment production is transport limited or detachment limited from the fact that factors controlling transport capacity and net erosion are correlated. Erosion from plots with > 10% vegetation in WY 1997 and erosion from plots in WY 1998 (all plots > 80% vegetation) show no correlation between LS^2 and sediment production. There were too few plots with > 10% vegetation in WY 1997 (and little variation in cover among them) to separate the relative effects of vegetation and LS^2.

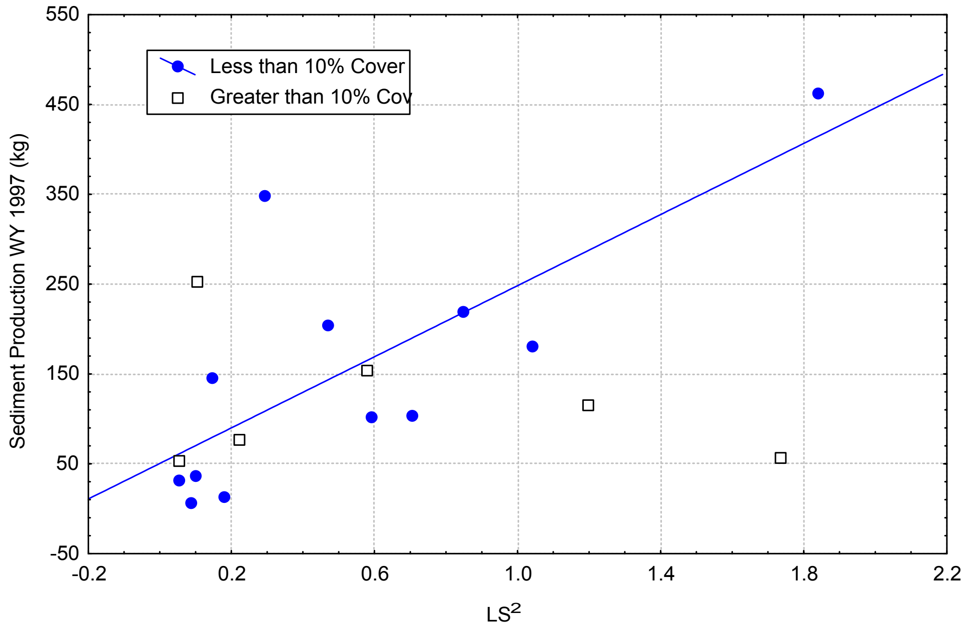

Figure 6. Sediment production versus Length X Slope Squared for WY 1997. Plots are separated into those that have greater than 10% vegetation cover and those that have less.

These results do not seem to be helpful in establishing guidelines for waterbar spacing. On recently disturbed segments, sediment production is proportional to length; so the per-unit-length sediment production is the same on a 40-m segment as it is on a 120-m segment. On "recovered" segments there is no scaling with length, and per-unit-length sediment yield may actually decrease as length increases. From this data, there is no clear threshold of length and slope beyond which erosion will become unacceptable, so the decision must be based on other information. Megahan and Ketcheson [1996] show that runoff leaving the road prism at concentrated points, such as cross-drains, is more likely to deliver sediment to streams than diffuse drainage. Montgomery [1994] argues that concentration of drainage by roads is the primary reason for gully development and landsliding below roads. Given these insights, we can see that total per-segment sediment and water outputs of the road may be as important as the per-unit-length outputs. A greater segment length leads to greater runoff, greater sediment yield at the outlet, a higher probability of delivering eroded material to streams, and a greater likelihood of inducing gullies or landslides below the road. Montgomery [1994] recommends limiting road segment length based on slope of the hillside to which the segment drains. Megahan and Ketcheson [1996] suggest spacing to limit delivery distance across hillslopes above streams.

7. SEDIMENT PRODUCTION OVER TIME FROM THE CUTSLOPE HEIGHT AND SOIL EXPERIMENT.

The first year of sediment production data showed no correlation between cutslope height and sediment yield. Based on the idea of the plots being transport limited, this was a reasonable expectation. Given that by WY 1997, erosion was no longer transport limited we expected some effect of greater availability of sediment from higher cutslopes. No relationship was found between sediment production and cutslope height for either soil in any of the three years of the study. Logic and other observations [e.g. Megahan et al., 1983] suggest that erosion from cutslopes is a large contributor to road sediment production, particularly in the long term. There may be several reasons that variations in cutslope height from nearly zero to more than 4 m produced no systematic variation in sediment yield for road segments. The simplest explanation may be that sediment production from cutslopes is not a function of cutslope length. [Megahan et al., 1999] found no correlation between cutslope length and cutslope sediment production on decomposed granite cutslopes and reasoned that most sediment production came from the A and B horizons, not the less erodible C horizon. The effect is magnified by the fact that the A and B soil horizons tend to be thinner where roads intersect ridges, and this is also where the cutslopes are highest. It may also be that for these soils, the signal strength is smaller than other sources of noise in our data. One avenue that we did not explore is the possibility that much of the reduction observed between years is due to stream capture by the ruts in the road surface. This would take runoff that is bound for the relatively erodible ditch (into which the cutslope contributes material) and run it down shallow ruts in the aggregate road surface, which on our roads was nearly non-erodible. If much of the runoff produced in storms comes from the nearly impermeable road surface, this effect might be sufficient to reduce or mask cutslope effects.

Differences in erosion between the two soil textures were large in WY 1996 and declined with time (Figure 7). Initially there is higher erosion from the silty clay loam and there is a larger decline in erosion over time on the finer soil. Our results follow the general expectation that armoring of the soil surface and growth of vegetation will make the two soil surfaces more similar with time.

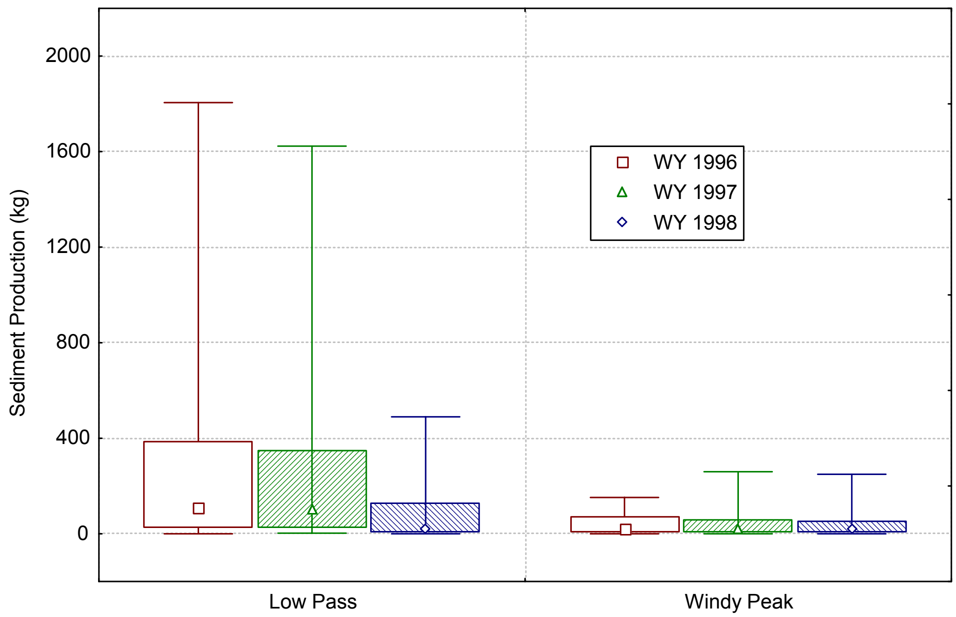

Figure 7. Sediment production over three years from plots in Experiment 2, Cutslope Height and Soil Effects. Low pass has silty clay loam soils, and Windy Peak has gravelly loam soils. Whiskers indicate the minimum and maximum; the top and bottom of the box are at the 75th and 25th percentile, and the symbol (square, triangle, or diamond) is at the median.

8. CONCLUSIONS

This paper addressed questions ③ and ④ about "where" and "when" road surface erosion occurs in a basin. The basis was observations from 74 road segments in the Oregon Coast Range monitored for three years.

With respect to question ③ (where), sediment production is greater where slope is greater in proportion to the square of the slope of the road segment; longer segments produce more sediment individually, but no more per unit length; and segments on more erodible soils produce more sediment. Segments with higher cutslopes did not produce more sediment.

With respect to question ④ (when), erosion is greatest immediately after disturbance, and there is a decline in erosion following initial disturbance that is exponential in shape, consistent with Megahan [1974]. Recovery is rapid; within 1 to 2 years most plots experienced at least a 50% percent reduction in erosion. On recently disturbed roads, there is more erosion in years with more precipitation and with higher single storm or total EI values.

More interesting results address both ③ and ④ together – the where of the when. The dependence of erosion on length and slope is only important for the first two years following disturbance. Initially, sediment production can be tied to indexes of transport or detachment capacity of flowing water, but the dependence seems to vanish with increasing vegetation cover and armoring. Similarly, the importance of the soil properties in determining erosion is reduced with increased armoring and vegetation. The initial availability parameter, S_0, of Megahan's [1974] exponential decay model varies more strongly with transport capacity than the rate parameter, k, indicating that selective transport of finer sediments from heterogeneous soils may be an important process in reduced erosion with time.

There were a few "odd" plots in this study that did not follow the general rules outlined above. We can develop and fit process-based and empirical models to fit the answers to questions ③ and ④ outlined above, but those models will not predict the "exceptions" to the rule. The rule sets above and earlier findings on cutslopes suggest that roads that do not recover become the greatest contributors of sediment in the long run. We need to learn what road characteristics increase the risk of non-recovery.

Erosion from forest roads is a large component of the sediment budget in some forested basins. Because of its frequency in time, it is probably an important component with respect to aquatic habitat quality in many basins. Road erosion varies on short time scales and over short distances, creating a challenge for agencies and companies managing a large road mileage. Rules that increase our ability to estimate the variation in road erosion at small time and space scales will improve prioritization of erosion abatement, information gathering, and watershed planning. The rules examined in this study relate directly to simple information that can, in many cases, be obtained through existing maps and record keeping. In addition, the methods of this study can be used with relative ease in other locations for understanding local soils and climate.

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