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CHANGES IN EROSION FROM GRAVEL SURFACED FOREST ROADS THROUGH TIME

by

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ABSTRACT: Annual erosion rates were measured for 2 years at experimental road plots in Western Oregon. Sediment production was compared between years on 16 plots with graded road treads, and bare cutslopes and ditches. Sediment production declined in the second year by 72%, indicating a substantial decline in sediment availability. The relative influences of precipitation, vegetation regrowth and surface armoring were examined. Precipitation differences between years were assessed by comparing annual erosion from 6 plots with vegetation removed from cutslopes and ditches before each transport season. Although precipitation and rainfall erosivity increased, erosion from these control plots did not vary significantly between years. Vegetation became established late in the second year following the most significant sediment transport events. The 10 percent vegetation coverage in the roadside ditch may account for less than 40 percent of the observed decline in erosion. Graded road surface plots declined to background levels in the second year due to surface armoring. Armoring of graded cutslopes and ditches was observed to be an important process resulting in surface stability and may account for more than half of the decline in erosion rates observed in the second year.

INTRODUCTION

Previous studies of erosion rates from forest roads have noted a substantial decline with time following construction (Megahan 1974, Swift 1984, Riley 1988 and Beschta 1978). Some would qualify this generality with the understanding that erosion is driven by climate and that variations in climate may interrupt the year to year decline in sediment production rates.

This time dependant decline in sediment production from forest roads is important to consider when estimating sediment budgets or managing a watershed within non-point source loading limits. When assessing the cumulative inputs of sediment from road segments of varying age, it is clear that one must know the age and have some idea as to the degree of recovery of each segment over time. When attempting to manage a road system to stay within sediment loading limits for a water body, one might be limited more in the number of new road miles constructed each year than in total road mileage. Faster and more complete recovery following construction would enable a greater road mileage to be constructed or maintained each year. An important question in examining the decline in sediment production over time is to understand the mechanisms.

Inter-annual variations in road surface sediment production can be ascribed to climate differences, vegetation growth, and armoring. If climate differences are the main source of variability in sediment yield over time, there is little hope in accelerating recovery or predicting sediment production from year to year. If vegetation growth were the primary influence in the decline in sediment production, then aggressive revegetation practices would be important for managers attempting to construct or maintain a large number of road miles. If armoring is the primary mechanism of recovery, then only time and such erosion will result in a stable surface and therefore a lower rate of recovery. The purpose of this study was to examine the changes in erosion over a 2-year period and relate them to these three processes

METHODS

We sampled sediment production from forest road segments over a 2-year period. Eighteen plots were used to examine the magnitude of change in sediment production between years. The influence of precipitation between years was assessed using an additional 6 plots along with 6 plots drawn from the sample of 18. Ten more plots were compared to 5 from the original 18 to assess the influence of road tread armoring.

Study Area

The study was conducted west of Eugene, Oregon in the Oregon Coast Range. The central Oregon Coast Range receives between 1800 and 3000 mm of rainfall annually, with drier portions being farther inland and wetter portions near the crest (Miller et al.). Winters are mild and wet while summers are warm and dry. Plots are located between 250 m and 600 m elevation, below elevations where snow commonly accumulates. Soils are derived from sedimentary geology through most of the Coast Range with some igneous dikes and sills. Sites are located on the deep, fine textured soils of the inner coast range. The soils are the Jory and Bellpine series, with silty clay loam textures.

Study Design

Two experiments were installed to examine the relationships between the variables of road length, slope, and road surface treatment to sediment production over time. In order to examine the response of the variables of interest we carefully selected and treated sites to control for the influence of other competing factors such as traffic level, construction standard, forest cover, and flow path geometry. Detailed description of the methods and site selection is available from Luce and Black (in press).

The first experiment examined the influence of road slope and length on sediment production on a fine textured soil. For this study segment length was divided into 3 general classes: Short (about 40 m), medium (about 60 m), and long (about 110 m). Road slope was also divided into 3 classes: Low (4-6%), medium (6-11%), and steep (11-13%). Road length and slope were varied so that there were 2 replications in each of the 9 combinations of length and slope, yielding 18 plots. This arrangement was used to assure that colinearity did not confound examination of the interaction term between length and slope during regression analysis. Plots in the length-slope experiment were selected with cut slope heights between 2 and 4 meters. The insloped roads were freshly bladed, and cut slopes and ditches were initially cleared of vegetation. A large storm event in 1996 damaged 2 of the 18 plots leaving 16 available for analysis.

The second experiment was an investigation of the influence of ditch and cut slope clearing. Three categories of road treatment were considered for this experiment: no treatment, road surface graded, and road graded with cleared ditch and cut slope. The 5 plots with no treatment had a range of slopes and lengths, and cut slope heights between 2 and 4 meters. Plots with the road treatment only were selected to have length, slope, and cutslope heights matching those of the no treatment group. The 5 graded plots with cleared ditches and cut slopes were selected from among the 18 lengths by slope experiment plots to match the lengths and slopes of the 5 no treatment plots. This amounted to a blocked Analysis of Variance (ANOVA) design that tested the main effect and treatment integrated over 5 plots with a range of slopes and lengths.

Precipitation variation between years was assessed by comparing sediment production on plots receiving identical treatment. Six road segments with medium lengths and slopes and typical cutslope heights were bladed and cleared of vegetation in the second year. These plots were compared to 6 similar plots treated identically in the first year to quantify changes in sediment production due to climatic differences.

Measurements

The field plots are installed along 2 stretches of insloped gravel surfaced forest road to capture the desired combinations of length, slope, and cut slope height required by the experimental design. Waterbars and cross drains were installed on the insloped road to hydrologically isolate each road segment. Waterbars directed flow off the road surface above each study segment and into the ditch below each measured segment where runoff was directed through an inlet structure and into a pipe.

Flow was transported through an 18.2 cm pipe below the road and discharged into a 1.5 m^3 settling basin where the material is collected. Sediment traps are weighed at the end of the transport season and as they filled halfway. Tanks were initially weighed using 4 load cells on hydraulic jacks. In the second year the tanks were changed from plastic to steel and were weighed using a single load cell mounted on a crane. When tanks are weighed to determine the mass of sediment, they are first filled with water to a predetermined level. Tanks are then emptied and cleaned and refilled with clean water to the same level. The mass of sediment is calculated as the difference between the two measurements adjusted for the difference between the particle density of the sediment and the density of water.

$$M_s = (M_{ts} - M_{tw})\, \rho_S/(\rho_S - \rho_W) \qquad (1)$$

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. ρ_S was estimated to be $2.65\rho_W$, based on the average density of feldspars, quartz, and mica particles that are the primary mineral fraction of the soils.

In order to quantify the differences between years, weather data was collected at a centrally located station within 2 km of each field plot. A Texas Electronics TE525 tipping bucket rain gauge with an inlet size of 152.44 mm was used to measure rainfall total and intensity with a resolution of .254 mm/tip.

In order to asses the influence of changes in vegetation cover on sediment production, cut slopes and ditches were surveyed in March of 1997 and again in July of 1997. The vegetation cover on cut slopes and the ditches was visually estimated on each meter of the treated road plots. Measurements were aggregated by plot and used as an index of cover conditions for that road element.

RESULTS

In the first year after treatment the mean sediment production value for 16 plots from the length and slope experiment was 491 kg per year. In the second year the mean was 136 kg, a 72 percent decline. There was substantial variability between plots in the first year and this variability carries forward into the following year. Figure 1 displays the trajectory of changes in sediment production rates between years. All but 2 plots showed a decrease in sediment production between years. Plots with high rates of sediment production in the first year tend to have high rates in the second year.

The 2 plots that had moderate rates in the first year and second year showed a minor increase averaging 12 percent between the years. The plot with higher than average sediment production had an unusually fine soil texture and average vegetation cover, while the second plot was more typical of the entire sample. These 2 plots were distinguished from the rest of the sample because they were located on concave slope positions. These locations may intercept more shallow ground water.

Sediment masses varied from 1 to 1844 kg per plot in the first year with a large percentage of transport mobilized in a single precipitation event that occurred on February 5-7, 1996. Two plots of the initial 18 were excluded from consideration because their upper boundaries were breached by high flows in this large event.

A regression approach was used regression to examine the variation between plots based on linear combinations of slope, S; length, L; slope squared, S^2; the square root of length $L^{1/2}$; and the 4 interaction terms, LS, LS^2, $L^{1/2}S$, and $L^{1/2}S^2$. The selection of these 8 variables is based on alternative theories of sediment transport, shear stress, and stream power. The interaction of length with the square of slope provided the best correlation to sediment production from among the models considered, as was found in Luce and Black (in press). The variation in sediment production in year one was best explained by the equation

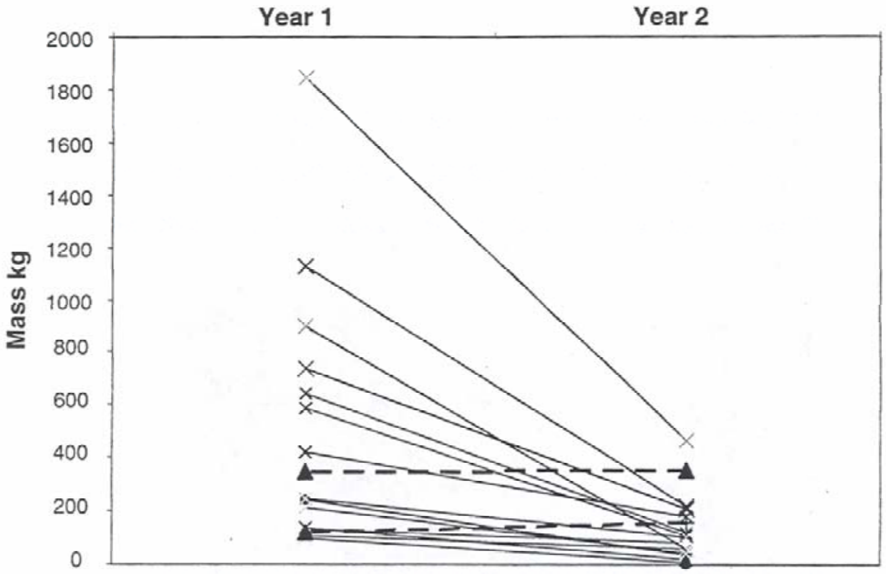

Figure 1. Mass of sediment from plots with road, cutslope, and ditch disturbed in the first year, and recovering in the second year. The average interannual decline is 72 percent. The two plots, which showed an increase of 12 percent, are shown with dashed lines.

$$E = 738\ LS^2 \quad (2)$$

Where E is erosion rate (kg m^{-2} year), L is the plot length (in meters), and S is the slope (in percent). The value of the constant is greater here than in Luce and Black (in press) because in that analysis only erosion through mid-February was considered. Sediment production from the first year is shown plotted against length and slope in Figure 2.

The same plots were revisited in July 1997 to examine the time-related changes in sediment production. Rates declined substantially in the second year on recovering plots with a range from 1 to 812 kg per plot. At the time of sediment sampling observations were made on vegetation cover on the cut slope and ditch. Vegetation recovery varied from plot to plot after being completely removed at the beginning of the study.

A plot of sediment production and percent vegetation cover in the ditch in March 1997 illustrates the initial regrowth of grass (Figure 3). The majority of the plots have a 10 percent or less cover while 6 plots have greater than 25 percent cover. The general trend shows a great deal of variation in sediment production from plots with 10 percent or less cover and generally less sediment production for plots with more than 25 percent cover. It was assumed that vegetation regrowth was probably a significant factor affecting the variation in sediment production between the 6 plots with high vegetation cover but with only 6 plots no further analysis could be done. The question of how to predict the differences between the other 12 plots with 10 percent

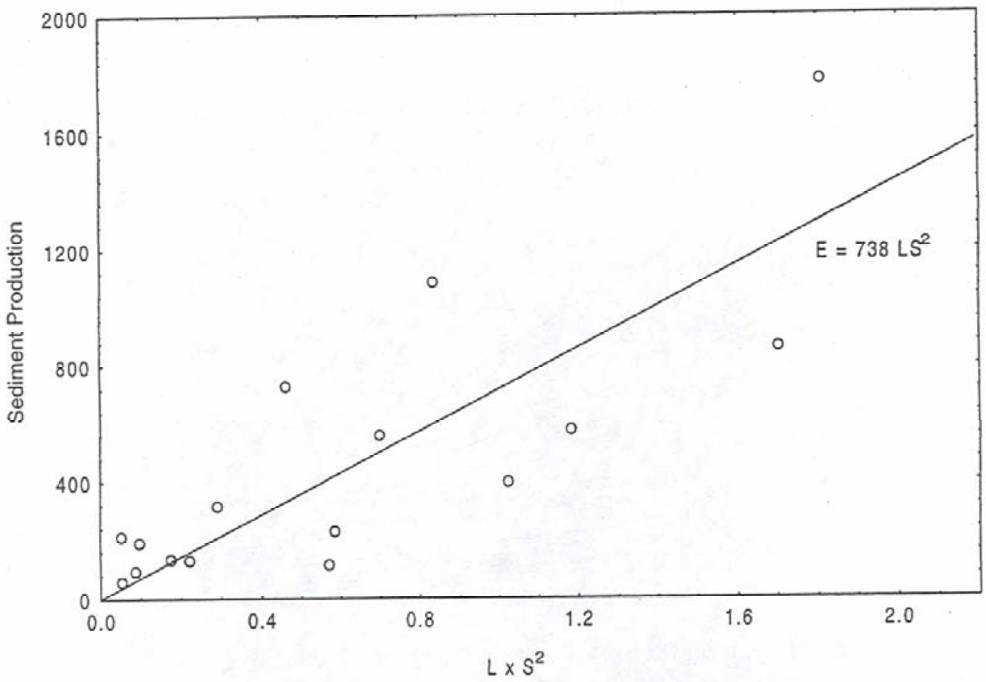

Figure 2. Sediment production in the first year plotted by length times the square of slope. The 16 treated cut slope and ditch plots were best described by the LS^2 relationship with an adjusted R^2 of .64. The value of 738 is a local constant encompassing soil, rainfall vegetation cover, and sediment availability factors, and will apply to only this year.

or less cover remained.

We examined several potential combinations of road segment length and slope, as was done for the first year to explain the variation. The best model was

$$E = 235\ LS^2 \qquad (3)$$

Sediment production is plotted against LS^2 in Figure 4. From the scatterplot, it is clear that the road segment with the greatest LS^2 value strongly affects the fitted line, but that the fit is reasonable for all but one of the other points. The plot most poorly described by the LS^2 line was one of only two that increased in sediment production between years 1 and 2. From this analysis it is important to note that LS^2 provides the best fit for both years, and that the slope of the relationship for the second year is about 1/3 of the slope for the first year. This implies that for a given length and slope, sediment production from plots in the second year (with about 10 percent cover) was 30 percent of the sediment production from the previous year.

The decline in the slope of the LS^2 relationship between years can be attributed to 3 main sources: precipitation, vegetation, and armoring. First we will examine precipitation variation between years and consider if these differences contribute to the change in sediment production. Next we will consider the role of vegetation cover as

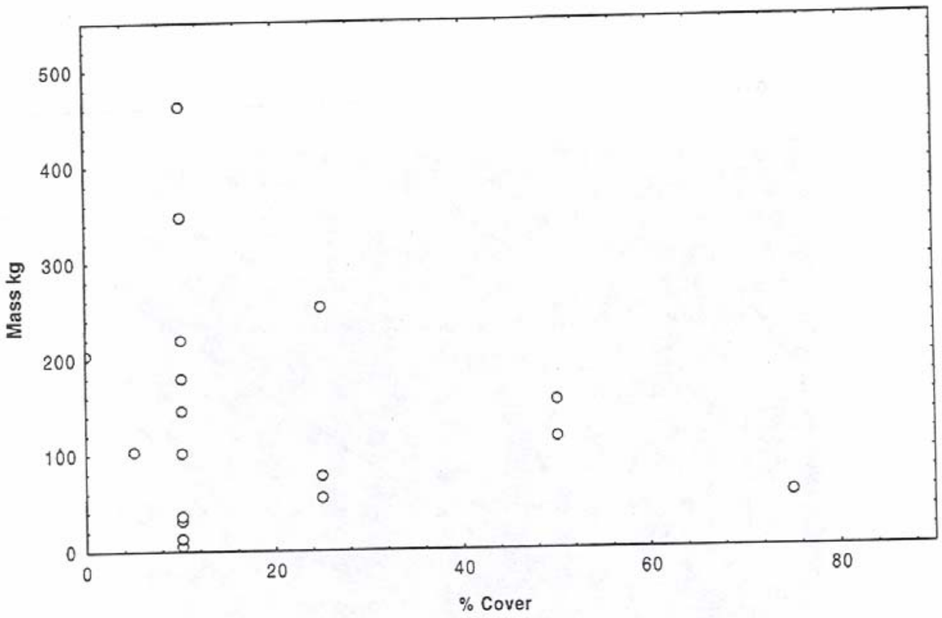

Figure 3. Ditch vegetation cover on March 7 in the second year and total mass of sediment in the second year on 18 plots with graded cut slopes and ditches.

it varied between years, leading to changes in surface stability. Finally we will examine changing sediment availability due to armoring of the cut slope and ditch and road surface.

Precipitation Differences between Years

Before we examine the processes leading to recovery between years it is necessary to assess the differences due exclusively to weather. We collected precipitation in a tipping bucket rain gauge near the plots and used the records to assess the differences in rainfall energy supplied to the plots between years.

Total precipitation was similar between years. Accumulation was 1944 mm in 1995/1996 and 2087 mm in 1996/1997. Cumulative rainfall is plotted in Figure 5 to show the seasonal distribution of precipitation for both years. Both years were noted for large storms that caused extensive flooding in the Pacific Northwest and produced substantial sediment from the road segments. In the first year significant rainfall events occurred on December 10-14, with 141 mm received in 108 hours with a maximum 30-minute intensity of 11.7mm hr^{-1} and on February 5-7 with a storm total of 164.1 mm in 59 hours with a maximum 30-minute intensity of 11.4mm hr^{-1}. The most prominent events of the second water year occurred on November 16-20 and December 29-31, 1996. The first event produced 218.7 mm in 95 hours with a maximum 30 minute intensity of 14.2 mm hr^{-1}. The second event produced 86.1 mm in 42 hours with a maximum 30 minute intensity of 23.4 mm hr^{-1}.

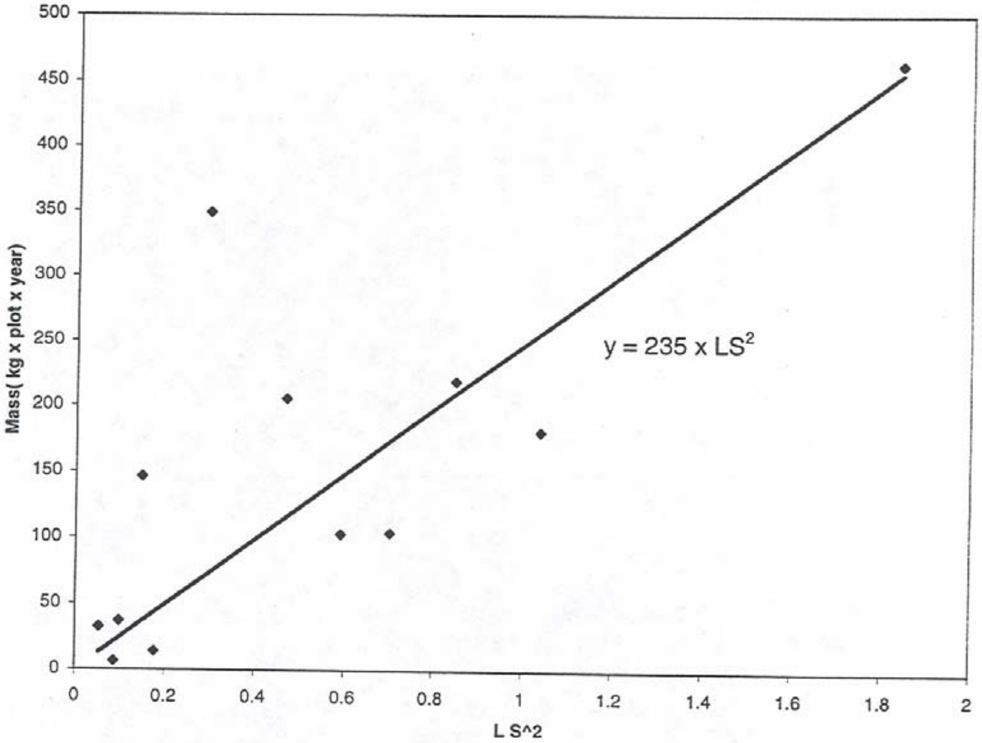

Figure 4. Sediment production in kg per plot and LS^2 in the second year. The constant of 235 in the second year two indicates a shift to lower levels of sediment product while the LS^2 proportionality remained unchanged from the first year.

In order to compare the influence of rainfall differences between years, a rainfall erosion index (EI) (Wischmeier and Smith 1978) was calculated to compared the seasonal total values and the maximum storm values. The EI was tested as a predictor of rainfall induced erosion because it incorporates a measure of both total rainfall kinetic energy input and a measure of rainfall intensity. Particle detachment and peak discharge are related to high intensity rainfall while stream power may be more closely related to total precipitation depth.

Wischmeier and Smith (1978) defined a storm as a precipitation event accumulating at least 12.7 mm without a 6-hour rain free period, unless the rainfall exceeds 6.4 mm in 15 minutes. EI is a measure that combines the kinetic energy of a storm (E) with the peak 30 minute intensity of a storm (I_{30}), and is calculated as;

$$E = 916 + 331 \log_{10} I \qquad (4)$$

$$EI = E \times I_{30} \qquad (5)$$

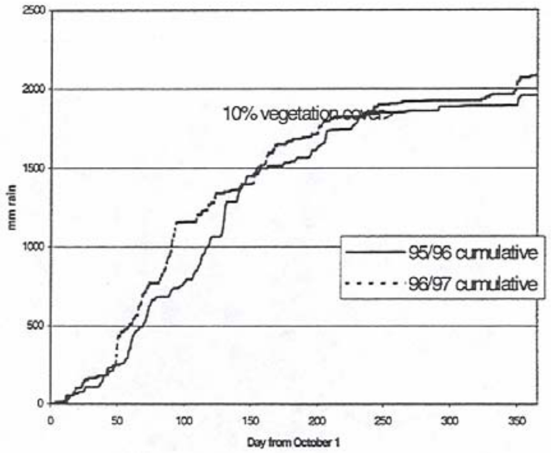

Figure 5. Cumulative precipitation in water the first year as a solid line, in the second year as a dashed line. Total accumulation differed by less than 10 percent. Most vegetation colonization began in March of the second year.

The EI has proven to be a useful predictor of erosion from road fill slopes when snow melt generated runoff is not a significant component (Megahan et al. 1991). The annual EI was calculated as the sum of the individual storm EI values for the water year. In the first year the annual EI value was 2067 MJ mm $(\text{ha hr})^{-1}$ and the storm maximum of 328 MJ mm $(\text{ha hr})^{-1}$ occurred on February 7, 1996.

In the second year the annual EI value was 2717 MJ mm $(\text{ha hr})^{-1}$ and the storm maximum EI of 535 MJ mm $(\text{ha hr})^{-1}$ occurred on November 18, 1996. The predicted 22-year average annual EI is expected to exceed 851 MJ mm $(\text{ha hr})^{-1}$ for western Oregon (Dissmeyer and Foster 1984) although this prediction is extrapolated from limited data.

In order to test the EI as a predictor of sediment production and to examine the differences between years due to weather, 6 control plots with similar physical parameters were treated before the start of precipitation each season. These plots measure the sum of the effects of all the sources of inter-annual variability, including precipitation total and intensity, frost heave, and dry ravel. No appreciable snowfall occurred during the 2 years. A comparison of these control plots for the 2 years (Figure 6) indicates that there was no significant change in sediment production between years. A T-test indicates the probability that the samples, which had means of 6.7 kg/m in year 1 and 7.7 kg/m in year 2, were not significantly different $(M_{yr1}=M_{yr2})=.7127$. A comparison between the mean of 16 treated plots and the mean of 6 precipitation control plots indicates that they are not significantly different in the first year.

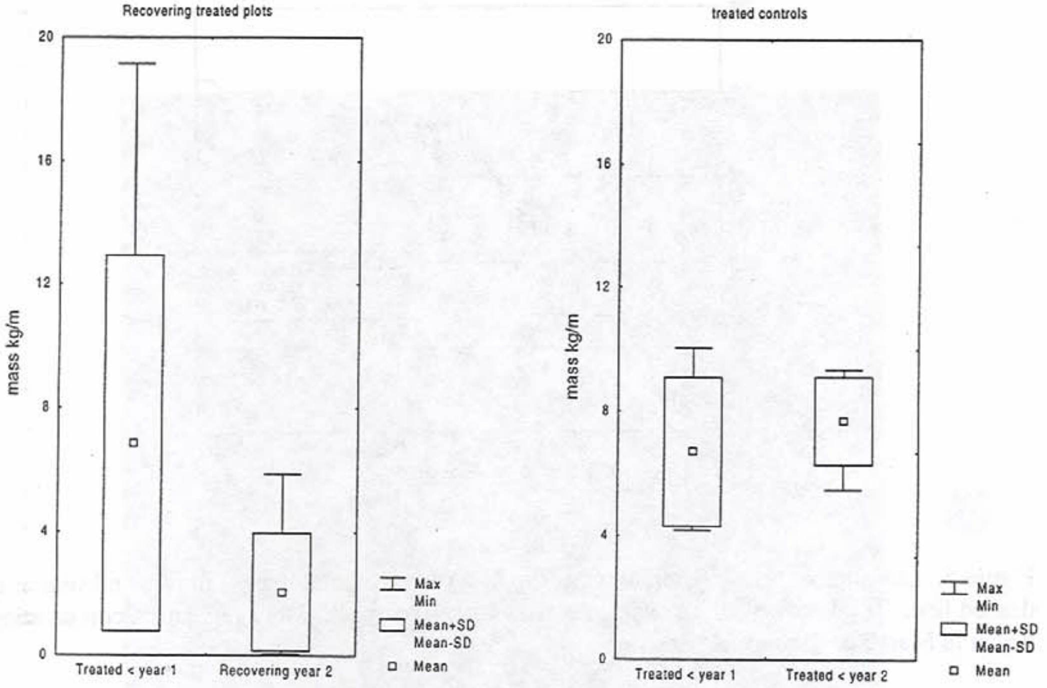

Figure 6. The graph on the left compares sediment production (in kg/m) on 16 treated cut slope and ditch plots treated in the first year and left untreated in the second year. Sediment production was not significantly different on 6 similar plots (in kg/m) with cut slopes and ditches treated before the first year and before the second year. Climatic variation between the years did not have a detectable impact on sediment production and was not responsible for the differences shown in the recovering plots.

Although the annual EI was 30 percent greater and the maximum storm EI was 63 percent greater in the second year, total precipitation increased by only 7.4 percent. The observed 15 percent increase in sediment production was not statistically significant. A 72% decrease in erosion rates at the 16 recovering plots was measured, however none of this decrease can be attributed to precipitation differences between years. The decrease in sediment production must therefore be attributed to decreases in sediment availability caused by vegetation growth and surface armoring.

Vegetation Influences on Sediment Production

At the start of the study vegetation cover was removed mechanically by blading. The surface had not stabilized sufficiently to allow plants to recolonize in the following spring; therefore, cover was not a factor in the first year. A survey of vegetation in March of the second year indicated that grass was becoming established and provided cover by July when the sediment measurements were collected. Median vegetation cover in the ditch was 10 percent in March and increased to 72 percent by

July. The cut slopes were slower to revegetate and averaged 20 percent cover by July. Ditch and cut slope cover were not significantly correlated (p=0.4162). Cutslope vegetation cover was not correlated with sediment production in the second year. Ditch vegetation cover from March in the second year is plotted against mass in the second year in Figure 3 and were not well correlated as discussed earlier.

We chose to use the March measurement of vegetative cover to represent the typical conditions of the plots for the year because this measurement was made closer to the period when transport was observed to be most active. The 2 largest storm events of the season occurred in November and December of the second year. Vegetation conditions in the ditch changed rapidly between the March and the July measurements, and plants were just beginning to develop in early winter. It is possible that some of the plots were essentially bare when the main precipitation events occurred in the second year.

Vegetation cover provides protection from erosion by mitigating the force of raindrop impact and by providing physical reinforcement of the soil surface. A recent study of natural erosion rates on undisturbed granitic soil surfaces found surface cover was the best predictor of surface stability (Clayton and Megahan 1997). The influence of vegetation cover has been examined extensively in the agricultural literature where it has been used to predict erosion from tilled fields. A change in surface cover from 0 to 10 percent without canopy interception is predicted to decrease erosion about 20 percent based on results from erosion plots on tilled soils with a 9 percent slope and 22.12m length planted with grain crops (Wischmeier and Smith 1978). Burroughs and King (1989) summarize a number of studies relating erosion treatments and vegetation cover on road cut slopes and fill slopes to sediment production. Using a groundcover to sediment reduction relationship developed from observations of straw with asphalt tackifier on cut slopes, a change from 0-10 percent cover would produce a 40 percent reduction in sediment. This evidence indicates that a small change in vegetation cover on cut slopes may have a large impact and can result in a substantial reduction in the sediment entering the ditch. It may be inexact to compare erosion prediction methods developed from cut slopes and apply them to both cut slopes and ditches which act as both a potential source of sediment and as a transport element. Assuming that an average vegetation cover of 10 percent describes the conditions at the plots when erosion was occurring, a 20-40 percent decline would be expected based on previous studies. Given that a 72 percent decrease in erosion was observed and that vegetation recovery explains only part of the sediment decline, the role of armoring will also be considered as an explanation for the rest of the sediment reduction.

Armoring

We define armoring as a process that generates a relatively coarse surface layer through selective mobilization of fine material from a mixed matrix (Gomez 1994). The exponential decay of sediment production presented by Megahan (1974) has been loosely compared to decreases in sediment production from the cutslope and road tread under repeated rainfall simulation (Burroughs and King 1989, Foltz and Burroughs 1990). During these experiments, vegetation and precipitation influences do not change, giving strong evidence that armoring can be an important process in road recovery from disturbance. Reid and Dunne (1984) observed rapid, (one or two day) decreases in sediment production on heavy traffic roads following cessation of traffic, demonstrating that armoring of the road surface may be particularly important.

Observations of cutslopes showed formation of pedestals during rain events, where fine material was removed from around larger particles. Observations of ditches in the second year showed a change from a soil surface with mixed fines and gravel to a surface dominated by gravel sized soil aggregates and sandstone clasts. This trend toward physical armoring was seasonally interrupted when ice-needle formation would increase soil creep on the cutslope or when small slumps would fall from the cutslope. Both processes occurred during winter months on wet cutslopes and would disrupt the armor on the cutslope while burying the armor in the ditch. By the second year, reduction in slumping from the cutslope greatly diminished this effect.

Results from the road treatment experiment are used to examine the role of armoring in reduction of sediment production with time. Three levels of treatment were applied to plots with similar lengths, slopes, and cut slope heights, and observed these plots over 2 years. Each group of 5 plots was constructed on fine textured silty clay loam soils and received light vehicle traffic. The first group received no road grading treatment and represents typical conditions on a 20-year old road system. The second group received road surface grading at the start of the study and none thereafter.

Figure 7 reports the means and distributions of these treatment groups after one and two years. Undisturbed roads produced the least sediment, 51 kg in the first year and 35 kg per plot in the second year. Plots that were graded produced 100 kg in the first year and 56 kg in the second year. A one-way analysis of variance indicates that plots that were left undisturbed for at least 3 years were not significantly different between the 2 measurement years P (Mnyr1 = Mnyr2) = 0.5117. Sediment production from the 5 plots with a graded road surface declined in the second year by 44 percent P (Mroyr1 = Mroyr2) = .0864. Interestingly, the mass produced in the second year on treated road surface plots was not significantly different than that produced from undisturbed plots during the second year, P (Mro = Mnyr2) = 0.2900. This indicates that road surface grading causes elevated fine sediment production rates as the fine material washes from the gravel, but that rates decline within the second year to a background rate. This agrees again with the rapid armoring observed by Reid and Dunne (1984) following disturbance of the road tread by heavy truck traffic.

CONCLUSIONS

Vegetation growth and armoring caused a rapid decrease in sediment availability in the second year of this study. Erosion decreased by 72 percent on 16 plots with cutslopes, road surfaces, and ditches treated to simulate new road construction. The annual erosion index (EI) increased while erosion decreased. There was no significant difference in sediment production from control plots treated in both years. Vegetation recovery accounted for part of the observed sediment reduction. During the main storm events of the second year, less

Station and the Eugene District of the Bureau of Land Management. This study was cooperatively funded by the Oregon State Office of the USDI Bureau of Land Management, the National Council of the Pulp and Paper Industry for Air and Stream Improvement, and the USDA Forest Service Rocky Mountain Research Station.

Mass in Kg

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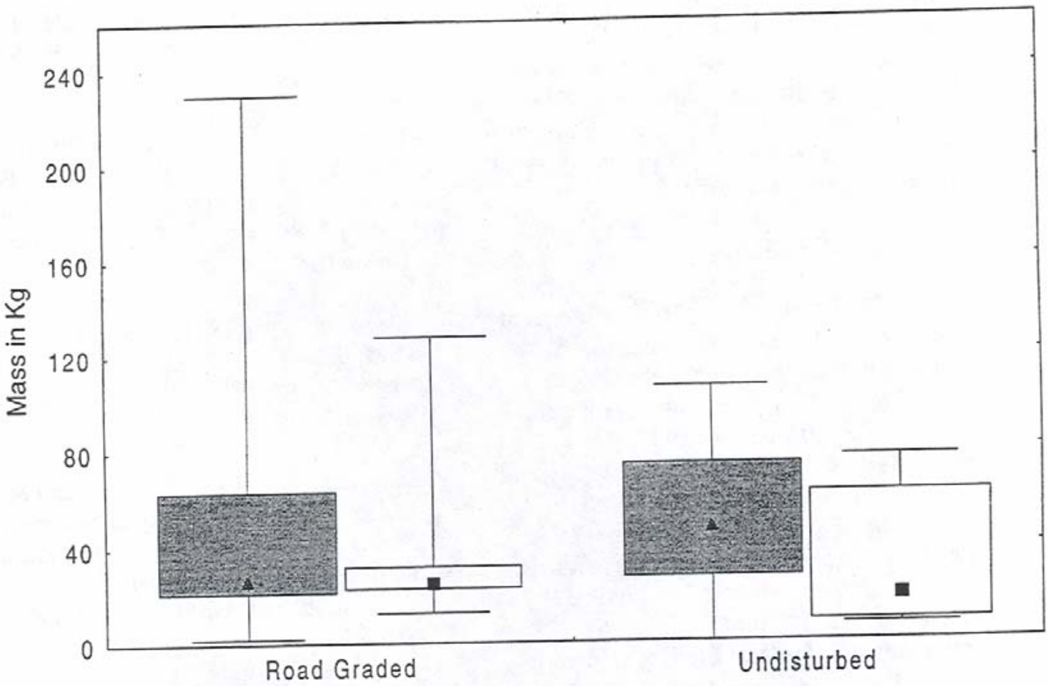

Figure 7. Road treatment and median sediment production and from 2 groups of 5 plots. The road graded group had road treads bladed in the first year, and not in the second year. The undisturbed group has remained ungraded for at least 3 years. The dark boxes indicate the first year inter-quartile range. The light boxes indicate the second year interquartile ranges. Whiskers indicate maxima and minima.

40 percent decrease in erosion from a 10 percent vegetation cover. Armoring of the newly graded surfaces accounted for the rest of the reduction in the erosion from the plots. Measurements of the impact of road surface grading indicate that sediment production declined to pre-disturbance levels due to armoring in the second year following road grading. While this study was unable to precisely apportion the observed recovery to vegetation influences or armoring, we were able to distinguish between the effects of weather and sediment availability. Future work is warranted to quantify the relative influence of armoring and vegetation cover as mechanisms of recovery.

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