Sediment Yield Response to Sediment Reduction Strategies Implemented for 10 Years in Watersheds Managed for Industrial Forestry in Northern California[1]

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Abstract

For the past decade, the productive forestlands now owned and operated by the Humboldt Redwood Company have been managed with low impact practices designed to reduce sediment delivery according to voluntary agreements and regulatory requirements of state and federal agencies. These timberlands located in the erosive sedimentary terrain of the northern coast of California have been extensively roaded and several generations of redwood dominated forests have been clear-cut logged since the 1860s. Intensive watershed and property-wide studies of sediment processes within the past 50 years when information is most reliable have created watershed sediment budgets and documented significant sediment impacts from past management activities. Forest operations now include geologic hazard avoidance and an extensive road upgrading and removal program to minimize the dominant sediment sources. Over the past 10 years, suspended sediment and streamflow have been continuously monitored at a number of locations in the mainstems and major tributaries of Freshwater Creek and Elk River. In this paper we explore the extent of sediment reduction in the watersheds and effects on water quality that may be evident in the relatively short monitoring record.

Key words: sediment yield, suspended sediment, water quality monitoring, logging effects

Introduction

Long-term research on logging effects in coastal California watersheds has found that sediment can be expected to increase concurrent with clearcut timber harvest for some duration, with effects diminishing with time (Lewis 1998, Ziemer 1998). Initial response levels vary with the type of erosion processes that are disturbed and the type of management practices applied (Lewis 1998). However, past effects may be persistent and contribute to sediment yield for decades (Klein et al. 2008, Lewis and Keppler 2007, Ziemer 1998).

The majority of timberlands in Elk River and Freshwater Creek were acquired by the Humboldt Redwood Company (HRC) after financial reorganization of the Pacific Lumber Company in 2008. The watersheds have been actively logged since the 1860s using clear-cut harvest as the primary logging method over the past several decades and has a road system built to various construction standards over the last 50 years. Since 1999, The Pacific Lumber Company and now HRC has been steadily

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working to reduce sediment with a combination of state-of-the-art road construction practices, a commitment to reconstruction and removal of older roads, and wet weather use limitations that prevent damage to roads and prevent sediment delivery to streams. Harvest related sediment is controlled through geologic hazard identification and geologist field investigation during timber harvest plan layout, rate of harvest limitations in these two watersheds, and practice of uneven-aged silviculture. Should we realistically expect sediment decline and has any occurred over the past decade?

Study area

Freshwater Creek and Elk River are adjacent watersheds that respectively drain to the north and south ends of Humboldt Bay on the coast of northern California (40°44’ N, 124°2’ W) (*fig.1*). The watershed area of Freshwater Creek is 80 km^2 and Elk River is 111 km^2. The region has warm to hot dry summers and mild wet winters with moderate storm intensities. The watersheds are predominantly forested with second-growth stands of various ages comprised of redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*).

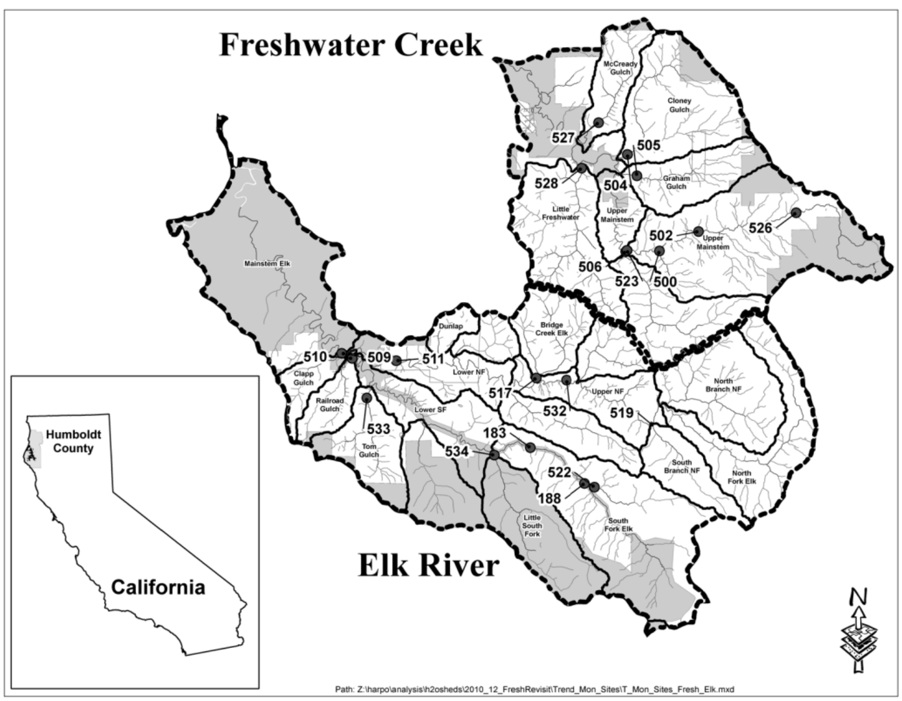

Figure 1—Overview of study watersheds in Humboldt County with the location of hydrologic monitoring stations.

Unlike the controlled experiment at Caspar Creek, this water quality monitoring project can only be described as a messy experiment. There was no pre-measurement period—the experiment was joined in progress along with whatever past impacts and possible recovery may have occurred from high sedimentation documented in the sediment budget from a significant storm that occurred in 1997. Management is ongoing throughout the study period and multiple activities that could either increase or decrease sediment happen simultaneously. Most of the tributary basins have experienced both harvest and road construction or deconstruction during the 8 year monitoring period, often in the same year. As the experiment proceeds, timber management objectives dictate where, when and what activities occur. All of the current management activities are designed to prevent and minimize new sediment input while restoration activities remove existing sources. Is the net effect of the system as a whole leading to a reduction in the sediment yield? An extensive water quality monitoring project was initiated in 2002 to answer these questions.

Watershed sediment budgets

Sediment sources have been extensively studied in Watershed Analysis projects sponsored by the Pacific Lumber Company (PWA 1998, 1999) and in support of TMDL related projects (Manka 2005, NCRWQCB 2011; PWA 2006, 2008). The erosion studies have characterized past and current sediment discharges and compiled sediment budgets (Reid and Dunne 1996) using remote sensing and aerial photography, extensive field surveys, and empirical physical modeling. Although the details within the sediment budgets vary somewhat among the various studies, and remain a topic of debate (NCRWQCB 2011), the general level of sediment as shown in *figure 2* is similar among the studies. HRC updates the budgets based on ongoing landslide inventories and other adjustments with monitoring projects and restoration work. The current estimated budget is also shown in *figure 2* along with the average sediment yield described in the next section. There has been reduction in sediment sources in each watershed over the decade, largely due to significantly reduced landslide rates and road improvements.

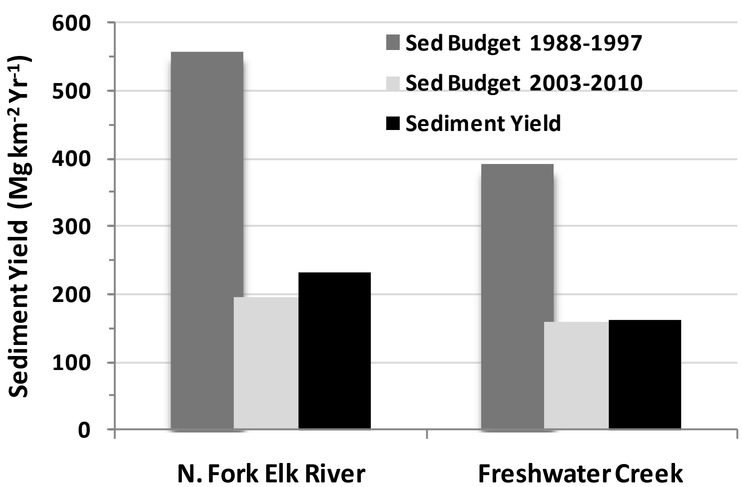

Figure 2—Sediment budget estimates for the period prior to (1988 to 1997) and following adoption of new management practices in the watersheds (2003 to 2010).

Sediment budgets have been a helpful tool that adds insight into expected sediment sediment yield and management effects, especially when available at the level of detailed study performed in these watersheds. Current sediment budgets match observed average sediment yield adjusted for bedload fairly well (*fig. 2*). The study has benefited from a wide range of rainfall during the short 8-year study period that has produced a representative average.

Stream sediment measurement methods

An extensive water quality monitoring program was installed by The Pacific Lumber Company in Elk River and Freshwater Creek in October 2002 and sites are currently operated by HRC. Sites are located in a number of subwatersheds and in the mainstems (*fig. 1*). Sediment and streamflow are measured at nine sites in the Freshwater and 11 sites in the Elk River watersheds. Contributing basin areas range from 0.13 to 112 km^2. The project includes the basin containing the Headwaters Forest Reserve in the Little South Fork Elk River (534). This watershed has an undisturbed old growth forest with only a very minor management impact. This site was initially installed by Humboldt State University (HSU) on Bureau of Land Management Property (Manka 2005) and has been maintained by HRC since 2007.

All sites are run of the river installations. Streams are equipped with continuous measuring turbidimeters and depth recorders that sample every 15 minutes from October to June. Physical sediment samples are collected and streamflow is measured. This combination of measures allows the continuously recorded turbidity and depth to be translated to streamflow (m^3s^{-1}) and sediment load. These are summed to produce annual sediment load, expressed in metric tons (Mg), or sediment yield per unit watershed area expressed as Mg km^{-2}.

Results

A comprehensive presentation of results for all stations and parameters of interest is beyond the scope of this paper. The focus is trends of annual sediment yield within the 8-year period from 2003 to 2010. There is a wide and typical range in sediment yield among sites as illustrated for an average rainfall year (hydrologic year 2010) in *figure 3A*. The old growth watershed in the headwaters of Elk River (534) had sediment yield of 5.9 Mg km^{-2}. Sediment yield is similar among the Freshwater sites, averaging about 50 Mg km^{-2}. This is about 10 times greater than the export from the old growth watershed. Sediment yield is more variable in Elk River reflecting a variety of factors. The old growth site has no management influence, subwatershed 519 has substantial bank erosion and streamside landslides from legacy channel filling (PWA 2008), and stations 510 and 511 are the mouths of the large river basins (drainage areas 50 and 57 km^2, respectively). The relationship between sediment yield and watershed size is shown in *figure 3B*. Site 533 is found in the westernmost portion of the watershed within the Hookton geology, a spatially minor but particularly erosive formation with considerable soil disturbance from past logging.

Data from four sites is used to illustrate the annual pattern of sediment yield for the period from 2003 to 2010 widely observed among most of the sub watersheds in the study (*fig. 4*).

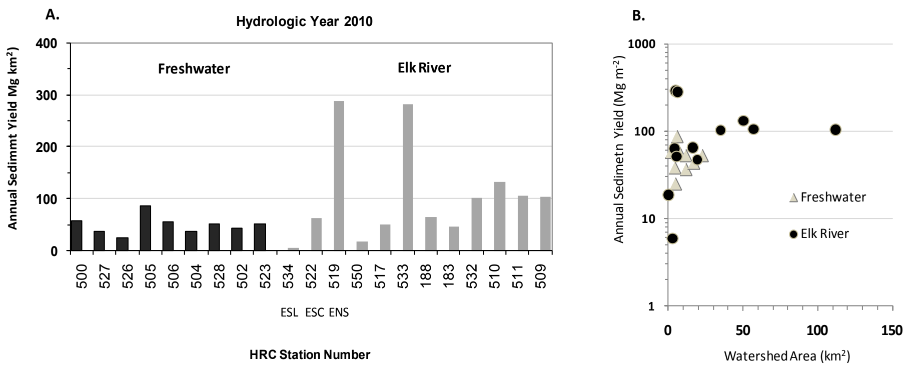

Figure 3—A) Sediment yield in hydrologic year 2010 (Oct 2009-Sept 2010) at each of the hydrologic stations. Original HSU labels for three sites discussed in Manka 2005 are indicated. B) Sediment yield as a function of basin area.

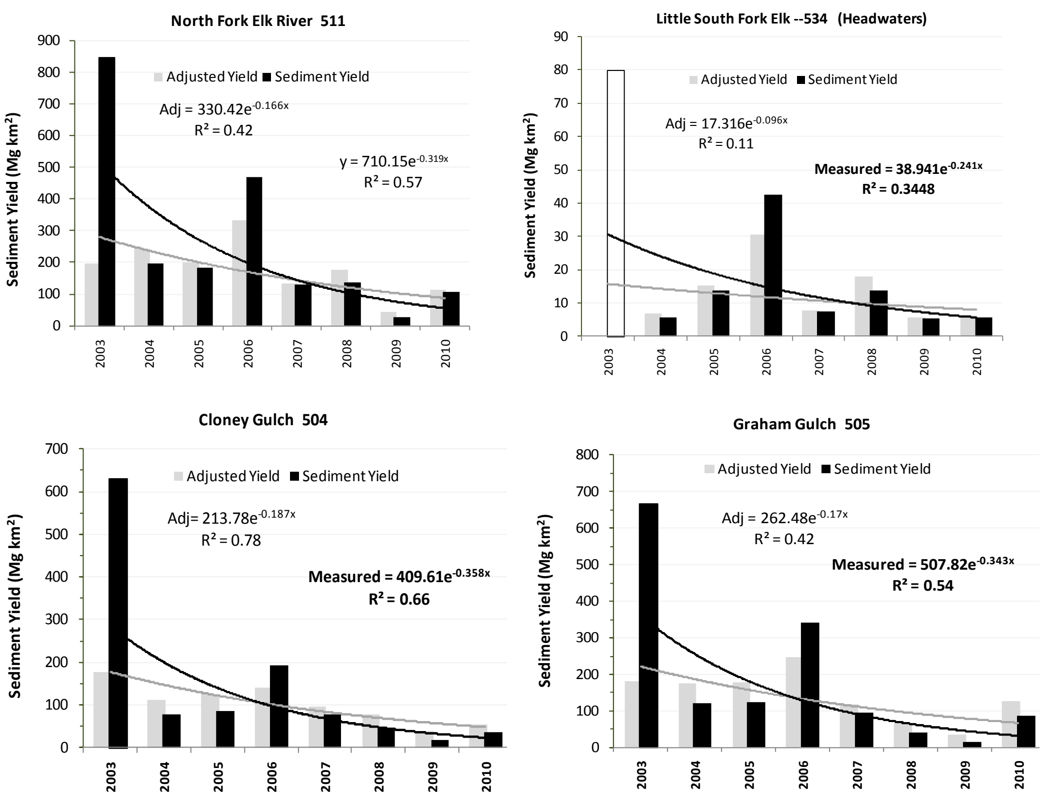

Figure 4—Annual sediment yield at four stations in the study area. A value for site 534 for 2003 has been estimated. The adjusted sediment yield has been normalized for annual climate characteristics using the erosivity index.

The four sites were selected to include a large river (511), the old growth unmanaged site (534), and two moderate sized subwatersheds, each of which had timber harvest and road reconstruction work during the interval (504 and 505). Other stations not shown follow a similar pattern evident at these four.

There is a clear decreasing trend in sediment yield during the measurement period. This largely follows the rainfall and storm pattern experienced during the period. The study period began in hydrologic year 2003. A storm in December 2002 set a number of rainfall records for the 122-yr record at the National Weather Service site in Eureka, including maximum daily rainfall, and caused an estimated 60-yr return interval flood in the study area (Dhakal and Sullivan 2005). Hydrologic year 2009 was a dry year with rainfall at 75 percent of normal and no large storms. Note that site 534 was not yet operative in 2003 and a value for that year has been estimated for illustrative purposes in this figure only.

Beginning the monitoring project coincident with the large storm assures a decreasing trend in sediment yield and related turbidity measures within the record. Hydrologic analysis of water quality trends often requires some method for removing the influence of climate (Helsel and Hirsch 2002). This paper introduces a climate detrending parameter that can be simply calculated with standard reported rainfall data to represent the climate influence, referred to here as the erosivity index. It is calculated as:

Erosivity Index = Annual Rainfall (in.) x Maximum Daily Rainfall (in.)

The index is very efficient at explaining sediment yields in the study area as shown for one representative site in *figure 5*. Sediment yield is highly correlated with the annual maximum peak flow (*fig. 5A*). This storm typically carries between 40 and 80 percent of the annual load each year. Although only rainfall is used in the calculation of this index, it is highly correlated with the annual peak flow (*fig 5B*.) Thus the index shares the same high correlation with sediment yield as the annual peak flow (*fig. 5C*). It is clear from *fig. 5* that one could also use the annual peak flow to index storm effects on sediment yield. One could also fine tune the short-term rainfall metric if the weather records are available. For comparing many stations, the erosion index has the advantage of applying commonly to all sites and it is surprisingly effective at capturing the elements of rainfall that lead to the observed sediment load.

This method based on rainfall was conceived with the goal to meaningfully characterize storm conditions that explain the erosiveness of storms with one simple parameter. The method helps create historical perspective on the relative sediment generating capacity of past storms based on climate records that may exist when long-term flow records may not. This is a question that arises often when constructing sediment budgets backwards in time or even in creating context for modern storms. The historical erosion index reflecting the 125-year rainfall record at the nearby Eureka NWS weather station is shown in *fig. 5D*. The record setting conditions of 2003 were equaled only in 1890. This storm generated at least a 60-year flood event at the hydrology stations in the study area. The period from 1997 to 1999 was a period of significantly higher than average erosivity. With the exception of 2003, the index has been at or below the long-term average during the monitoring period. This index would not effectively represent rain-on-snow events, but these type of events are rare in these watersheds due to low elevation and coastal proximity and have not occurred in the recent monitoring period.

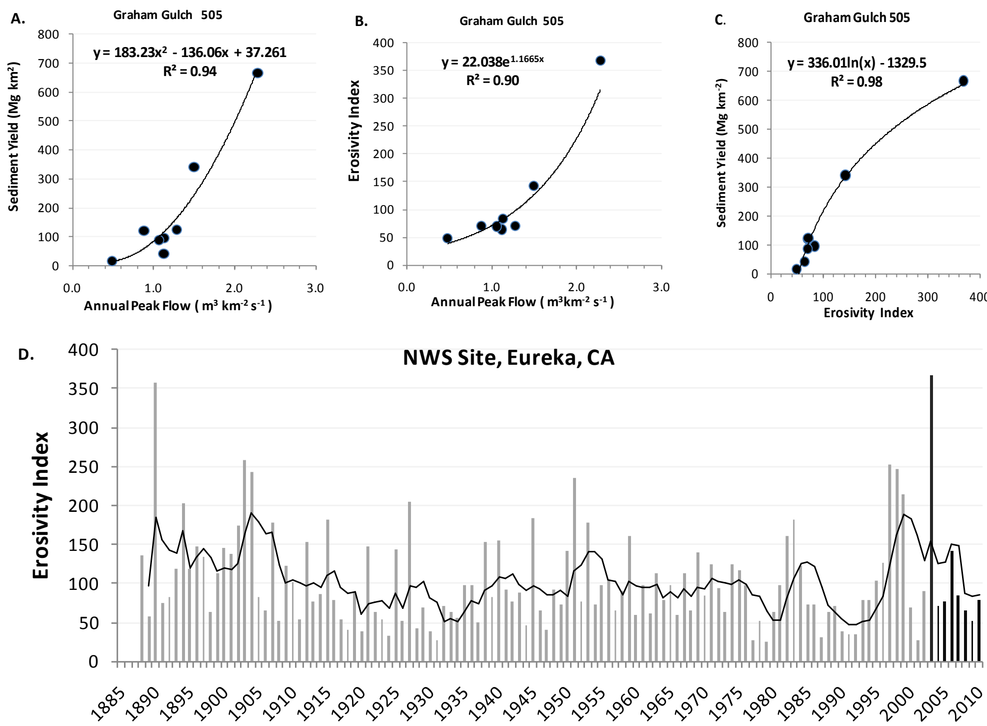

Figure 5—Erosivity index as a detrending variable. Relationships between A). annual peak flow and sediment yield, B) erosivity index and annual peak flow, C) erosivity index and sediment yield. D). Annual erosivity index of Eureka rainfall. Five-year moving average is also traced.

Correlation and multiple regression analysis was applied to the annual sediment yield to determine whether trends exist and whether there are effects of ongoing management activities. *Figure 6* shows the correlation (Pearson's) between various factors and annual sediment yield at individual sites and for all sites combined. The erosivity index as a surrogate for weather factors explains 89 to 99 percent of the variation in sediment yield and turbidity parameters during the study period and is highly significant at each individual site and for all sites combined. The correlation of the other factors was computed controlling for the erosivity index. There is a negative correlation between sediment yield and year at all sites. The correlation is strong but is statistically significant only at site 504 and when all sites are combined ($p < .05$). The trend is weak at site 502. This result suggests a generally decreasing trend in sediment yield with time independent of the climate but varying by watershed.

The correlation of sediment yield with several management related parameters is also shown in *fig. 6* for seven sites. These sites were selected because all data was available for the full monitoring period and to represent the range of watershed size and activity. For these variables, the correlation was controlled for both erosivity index and year. The correlation of annual harvest rate with sediment yield is quite mixed. At several sites the correlation is positive and at others it is negative. Overall, the annual harvest rate is not highly correlated with sediment yield. Klein et al. (2008) used the annual average harvest rate of the previous 10 or 15 years as an index of harvest effects. This parameter tends to have a negative correlation with sediment yield in most watersheds but is positive in several. The correlation is not statistically significant. Finally, the annual sediment removal is the sum of sediment saved at each road sediment source site in each watershed and it is used here as a measure of the amount of disturbance from road construction and deconstruction conducted in the preceding summer. This work potentially generates sediment with post construction site adjustment. This management activity generally has an increasing influence on sediment yield, and was statistically significant for all sites combined.

A multivariate linear regression on the combined data for all the parameters discussed was highly statistically significant and a backward stepping algorithm selected the same 3 significant variables for the combined group as the correlation analysis shown in *fig. 6* (F = 158.65, p< .000). The variables are erosivity index, year, and sediment removal.

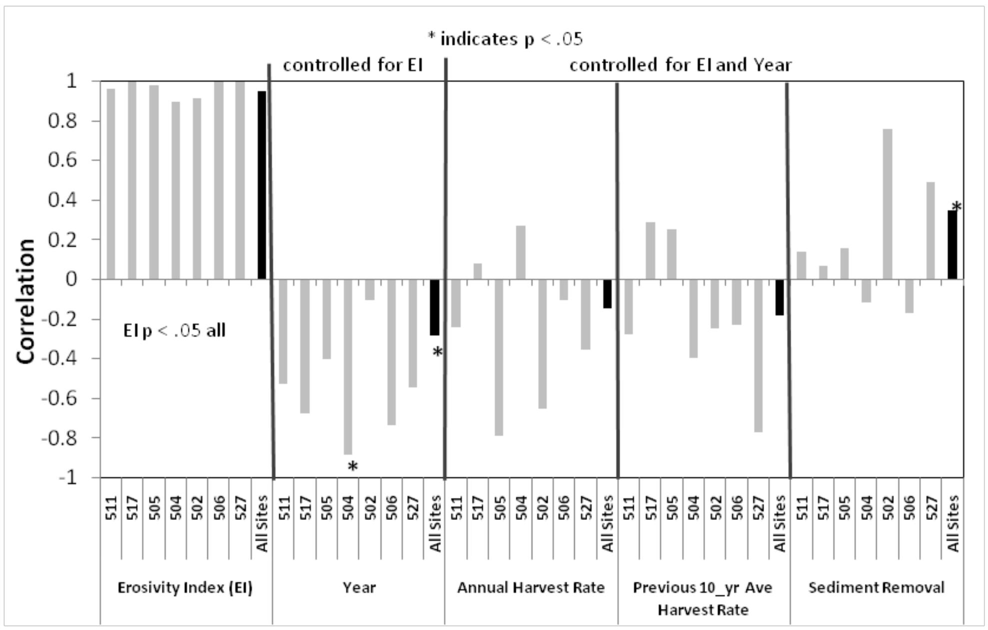

Figure 6—Correlations between annual sediment yield and various weather, time trend and management factors. Management factor correlations were computed by controlling for the erosivity index and year.

Comparison of the sediment yield from the managed sub-basins with the old growth basin (534) confirms that there has been a decreasing trend in sediment yield with time. One of the relationships between a managed basin and 534 is illustrated in *fig. 7A*. This relationship was computed for all sites and the residuals from this regression at each site are plotted in relation to time in *fig. 7B*. This analysis includes 2004 to 2010 when the old growth site (534) was operative. A check of the one high value evident in *figure 7A* did not appear to exert leverage on the results.

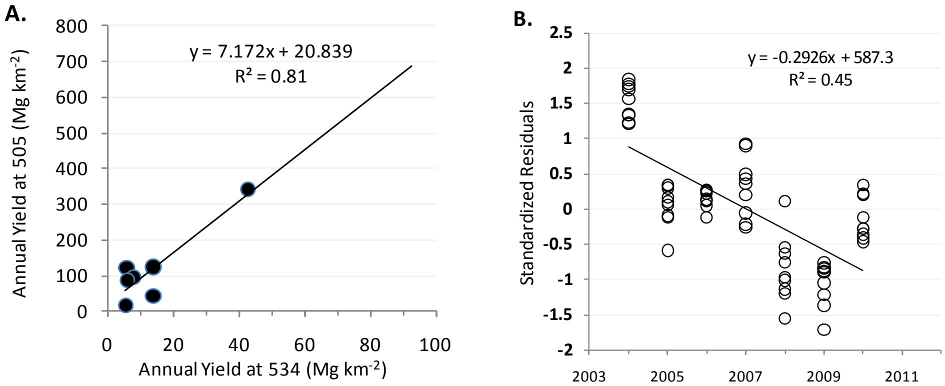

Figure 7—A. Relationship between annual yield in a managed watershed (505) with the old growth watershed (534). B. Residuals of the same comparison with eight managed watersheds as a function of year.

To visually see the effect of climate normalization, climate adjusted sediment yield is shown at the four sites in *figure 4*. This is computed by dividing the observed annual yield by the normalized erosivity index relative to the long-term median value. For example, in 2003 the erosivity index was 4.3 times the long-term median and the sediment yield was adjusted downward accordingly. Years with below median yield are adjusted upward. A negative exponential curve fit to the adjusted yield at the old growth site shows a decline of about 10 percent per year. The decline in slope averages about 18 to 20 percent for many of the managed watersheds but is higher in some. The difference in slope between the control and managed sites suggests that the sediment yields in many of the subwatersheds have declined at least 10 percent and perhaps as high as 18 percent per year during the 8 year study period.

Discussion and conclusions

There has been a small but persistent decline in sediment yield in most of the subwatersheds independent of climate and management factors from 2003 to 2010. The effect of ongoing management activities on annual sediment yield vary with subwatershed. Most have negative correlation suggesting that effects are not large enough to prevent observable recovery. Sediment yield in a few basins is positively correlated with ongoing activities. None are statistically significant.

It is questionable whether this rate of decline can continue. The sediment budgets indicate that roads and landslides were a large part of the sediment sources in the past. A large part of the road system has now been upgraded and landslides have been rare for a number of years. The forest on the landscape continues to mature, especially in steep streamside higher hazard areas that are now off limits to logging. The sediment budgets indicate that legacy sediment sources are now an increasing portion of the annual sediment load. These include such features as old skid trail crossings which are abundant in the two watersheds and eroding banks left from the initial logging (PWA 1999), both of which continue to contribute sediment on an annual basis. Finding solutions for these sources will be challenging.

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