Sediment Yield From First-Order Streams in Managed Redwood Forests: Effects of Recent Harvests and Legacy Management Practices[1]

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Abstract

According to the State of California, most of North Coast's watersheds are impaired by sediment. This study quantified sediment yield from watersheds under different management conditions. Temporary sedimentation basins were installed in 30 randomly chosen first-order streams in two watersheds in Humboldt County, California. Most treatment sites were clearcuts, but two types of clearcut harvest occurred: sites harvested under strict regulations of a Habitat Conservation Plan (HCP) and sites harvested prior to implementation of the HCP. Second-growth stands not recently entered served as the control. Neither geologic substrate nor management were significant predictors of sediment yield. The pre-HCP sites contributed more sediment, but some control sites had sediment yields comparable to these sites. The possible management effect on sediment yield may be influenced by the fact that the HCP sites have experienced only one or two post-harvest winters, while the pre-HCP sites had sediment mobilized in relatively severe winters over a longer post-harvest period. The mean sediment yield from control sites was higher than from HCP sites suggesting that legacy effects of management may be important.

Key words: erosion and sedimentation, forest management, headwater channels

Introduction

Headwater stream channels with ephemeral flow represent a narrow band of fluvial process that occurs on a portion of the landscape dominated by hillslope processes. The proximity of hillslopes (particularly steep ones) to a relatively dense stream channel network creates a zone in which hillslope materials may be readily transferred to the channel network (Swanson and others 1982, Vannote and others 1980). Although channel morphology is recognizable in headwater areas, it is often discontinuous and weakly expressed over channel lengths of up to a hundred meters or more. A discrete channel head may or may not be present. The strength of fluvial process may also vary temporally as well as spatially, so the channel head migrates up or down slope depending on climate and landscape disturbance (Dietrich and Dunne 1993). The size distribution of sediment in these channels reveals weak fluvial

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sorting (Dietrich and Dunne 1978) leading to geomorphic classification of these channels as "colluvial" (Montgomery and Buffington 1997). Moving down-slope and increasing contributing area, the fluvial process domain becomes more fully established, manifested by a continuous channel with well-defined channel banks and increased fluvial sorting of sediment.

These areas at the head of the watershed channel network are referred to as zero-order basins. In mountain landscapes where debris flows are the dominant erosion process, fluvial processes in headwater channels are thought to be of little significance in the long-term sediment budget (Benda and Dunne 1987, 1997). These hillslope hollows are evacuated by debris flow and then gradually refill by colluvial processes before failing again (Reneau and Dietrich 1991). Not all mountain landscapes, however, are dominated by debris flow processes. There has been relatively little investigation of morphological or fluvial sediment routing characteristics of colluvial headwater streams (O'Connor 1993). In such areas, the magnitude and frequency of fluvial processes in colluvial headwater channels may be relatively important in long-term sediment routing from low-order basins.

The northern California Coast Range is well known for high sediment yield (Lisle 1990) and deeply weathered soil and bedrock profiles (McLaughlin and others 2000). Although not unknown in the region, debris flow processes are less prevalent than large-scale deep-seated landslides and debris slides on inner gorge slopes. Consequently, the role of colluvial headwater channels in sediment routing and watershed scale sediment budgets may be better characterized by weak fluvial processes than episodic mass wasting processes. In addition, the California Coast Range supports extensive redwood *(Sequoia sempervirens)* forests that have been intensively logged over the last century, and most areas are in their second or third harvest rotation. Early clearcut logging was followed with fire to clear small debris prior to log yarding. Soil disturbance occurred on the surface and in draws and stream channels. Harvest techniques following World War II relied increasingly on bulldozers to yard logs by ground skidding and resulted in extensive soil disturbance to greater depth. Since the State of California began to regulate timber harvest practices in 1974, the permissible extent of disturbance to stream channels has declined.

Under the California Forest Practice Rules, colluvial headwater streams are typically categorized as Class III waters for regulatory purposes. The primary definition of a Class III channel is the ability or potential to transport sediment downstream, consistent with the geomorphic concept of channels. Determination of the headward extent of Class III channels and the boundary with Class II channels (defined as supporting non-fish aquatic life and loosely defined by the extent of intermittent or perennial stream flow) is more problematic and integral to the determination of the extent of Class III channels.

According to present regulations, Class III channels are protected from widespread mechanical disturbance by heavy equipment. In addition, retention of at least 50 percent of the understory vegetation present before timber operations is required (California Department of Forestry and Fire Protection 2004, §916.5). The efficacy of these and related regulatory protections with respect to erosion has been investigated through monitoring programs (Cafferata and Munn 2002) and experimental studies at Caspar Creek (Henry 1998). The Caspar Creek study compared sediment yield from clearcut-logged second-growth and unlogged second-growth redwood forest over a six-year post-logging period (Lewis 1998). Suspended sediment yield increased between 123 and 203 percent in three 10- to 25-ha clearcut watersheds. Observed peak flow increases of about 25 percent for two-year recurrence interval storms (Ziemer 1998) attributed to reduced canopy interception and evapotranspiration in clearcuts may have induced surface erosion and accelerated channel erosion to produce the observed increase in sediment yield (Lewis 1998).

Habitat Conservation Plans (HCPs) to protect endangered aquatic species either in effect or being developed under the authority of the Federal Endangered Species Act include increased regulatory protections for Class III channels in portions of the redwood region. The Pacific Lumber Company (PALCO) has operated under an HCP since 1998 that provides for a minimum 10-m-wide equipment exclusion and limited harvest zone adjacent to Class III channels. It also requires a 3-m-wide no-harvest zone adjacent to each bank of the channel. Given the limited information on headwater colluvial (Class III) channels and the significant harvest restrictions under its HCP, PALCO initiated this pilot study to develop additional data on sediment yield from Class III channels and to test whether HCP regulations accomplished the desired goal of reducing sediment yield.

Methods

Study Design

The erosion processes of interest in this study were surface erosion and channel erosion that could reasonably be modified by the presence or absence of riparian forest cover. We designed our study to exclude the direct influence by roads and landslides that would introduce excess runoff or sediment that would be expected to be of much larger magnitude than the effect on the erosion and runoff processes of interest. We focused particularly on comparing management practices under PALCO's HCP with recent pre-HCP harvest practices. Our fundamental hypothesis was stated as follows:

H_0: There is no effect of geology or management on sediment yield, and

H_a: There is an effect of geology and/or management on sediment yield.

A randomized block design was developed to test our hypothesis. The design included four geologic types (Franciscan units `co1` and `co2`, Yager unit `y1`, and Wildcat unit `Qtw`), and three forest management categories; these include clearcut areas harvested after implementation of the HCP in 2000 and 2001, clearcut areas harvested prior to adoption of the HCP typically between 1994 and 1997, and a group of control sites where no harvest had occurred since at least 1985. We attempted to locate at least five sites in these management categories distributed across each of the four geologic types, for a desired total sample size of sixty sites.

Study Area

This study was conducted on PALCO timberlands in Humboldt County in the lower Van Duzen River and lower Eel River watersheds. These study areas correspond to watershed analysis units developed by PALCO for its HCP. Watersheds drained by mapped Class III channels in the study area are small, with a median contributing area of five ha (n = 350). About 80 percent of Class III streams drains watersheds smaller than 10 ha.

The three most common bedrock formations underlying Class III channels in these areas are the Franciscan, the Wildcat and the Yager (McLaughlin and others 2000). The Franciscan is generally characterized as deformed and sheared sedimentary rocks of Tertiary to Cretaceous age. McLaughlin and others (2000) re-mapped the Franciscan according to topographic criteria and subdivided it into four units. Our study sites in the Franciscan were ultimately located in map unit `co2` which is described as Coastal Belt Franciscan rocks with roughly equal parts sandstone and clay-rich mélange lacking well-incised side hill drainage systems. This unit also comprised the largest acreage of the four subunits of the Franciscan in the study area. The Yager is of similar age and sedimentary composition, and varies widely locally in strength; McLaughlin and others (2000) describe map unit `y1` as relatively well-lithified sedimentary rocks of the Yager terrane. The Wildcat Group is of sedimentary origin, of Pliocene-Miocene age, and is more uniformly weak; it is denoted as map unit `Qtw` and described as weakly lithified sedimentary rock (McLaughlin and others 2000). All of these rocks weather to form soils rich in silt and clay; the Wildcat generally does not produce competent gravel that withstands fluvial transport (Pacific Lumber Company 2003).

Site Selection Procedure

A map of potential field sites was developed from PALCO's geographic information system to identify areas of recent harvest and to exclude sites likely to receive direct runoff from roads. Potential sites were grouped according to geologic types. Field crews were given reconnaissance assignments selected by a random draw. These field visits determined whether a sediment basin could be installed and, if so, confirmed the forest management treatment. When treatment sites were identified, a nearby control site was also identified. Field reconnaissance continued until the necessary number of sites was identified or until the pool of potential sites was exhausted.

We found a large number of sites where sediment basins could not be installed. This was primarily a result of small channel size, discontinuous channels, or extensive woody debris. Some sites were easily accessible by road while others were reached by a combination of ATV and hiking. Ultimately, it was not possible to maintain equal sample size in each of the combinations of geology and management class. Sites in Franciscan map unit `co1` were so few that this geologic type was removed from the study.

Sedimentation Basins

We established sedimentation basins to capture sediment transported in ephemeral colluvial headwater drainages. Sedimentation data was collected over the 2002 and 2003 water years.

A simple sedimentation basin formula using basin surface area and estimated discharge was applied to provide a target for basin dimensions and to impose some uniformity of trapping efficiency (Goldman and others 1986, p 8.15). We expected the basins to retain sediment about 0.5 mm and coarser.

Sedimentation basins were constructed in channels by installing a flashboard dam of marine plywood with a trapezoidal notch to control spilling stream flow. The floor of the sedimentation basin was covered with plastic sheeting in the first year; this was replaced by a porous erosion control fabric for the second year of the study to reduce ponding. These liners provided a sampling surface upon which sediment in transport could settle and be positively distinguished from material on the channel floor and banks.

Most dams were composed of 2.4-m wide plywood with the base of the notch about 0.75 m above the channel floor. The basins typically extended three to four m upstream, but the shape varied considerably. Median basin volume below the spillway elevation (sediment storage capacity) was approximately 0.9 m^3. Five basins had capacities less than 0.5 m^3.

After each winter, field crews measured the total volume of sediment in each basin. Differences in moisture content of sediment were disregarded. The sediment in the basins was removed, and subsamples of sediment were preserved for particle size analysis. To estimate the magnitude of sediment yield including sizes not deposited, we used a technique that compares the probable size distribution of the source material to the size distribution of the deposit (Reid and Dunne 1996, p. 49).

Results

Thirty sedimentation basins were installed prior to runoff producing rainstorms in autumn of 2001. Two sediment basins were directly affected by mass wasting and were subsequently excluded. Two other sites were damaged by runoff and were decommissioned immediately to avoid potential erosion. Two additional sites added to represent recent harvest on lands not subject to HCP requirements were excluded from analysis because of unique bedrock geology. The final data set contained 24 sites with an unbalanced distribution among experimental blocks *(table 1)*. The data were collected at the same sites over a two-year period and analyzed with respect to unit-area sedimentation (L/ha) *(table 2).*

Table 1—*Distribution of sample sites among treatment types.*

	Bedrock geology		
Management	**Franciscan**	**Wildcat**	**Yager**
Control	3	2	3
Pre-HCP	1	1	4
HCP	3	3	4

We used a split-plot treatment of repeated measures (MathSoft 1999) to structure our analysis of variance. Exploratory data analysis revealed that the data were extremely skewed with an overabundance of small sediment yields *(fig. 1)*. We used the Box-Cox function to determine the ideal transformation (Crawley 2002). Box-Cox fits positive and negative exponents, so a non-significant number (0.01) was added to each observation. Given the average magnitude of trapped sediment volume, this small addition should not influence the final result. It also made sense from a geomorphic perspective. We did not expect any observations of absolutely no sediment yield over the course of an entire water year, but we did anticipate sites with yields small enough to be undetectable. The best transformation was the fifth root of unit-area sedimentation, and the transformed data more closely approximated a normal distribution *(fig. 2).*

Table 2—*Summary of collected sediment basin data.*

Site	Mgmt	Geology	Drainage area	Channel length	Sediment volume		Sediment size[1]	
					2002	2003	d_{50}	d_{84}
			ha	*m*	*L*	*L*	*mm*	*mm*
699B	Control	Franciscan	2.5	101	595	889	3.2	10.9
713A	Control	Franciscan	0.8	147	0	575	--	--
717A	Control	Franciscan	0.8	114	0	0	--	--
600A	Control	Wildcat	4.8	56	11	114	2.0	8.0
702D	Control	Wildcat	0.4	37	0	11	--	--
463A	Control	Yager	1.9	170	0	8	--	--
470A	Control	Yager	1.0	78	22	208	3.7	11.5
721A	Control	Yager	1.0	15	175	238	4.0	13.0
699	HCP	Franciscan	1.9	116	114	131	--	--
713	HCP	Franciscan	1.3	52	0	168	--	--
717	HCP	Franciscan	3.6	324	42	132	0.2	0.6
571	HCP	Wildcat	0.8	61	0	0	--	--
600	HCP	Wildcat	3.6	472	224	265	0.2	0.9
702	HCP	Wildcat	4.8	300	55	163	1.5	13.0
463	HCP	Yager	7.5	392	7	17	4.7	11.5
470	HCP	Yager	10.9	140	65	45	3.0	15.0
721	HCP	Yager	2.1	71	0	61	--	--
734	HCP	Yager	1.9	154	36	178	0.1	0.5
460	Pre-HCP	Franciscan	1.3	129	735	265	0.1	0.9
798	Pre-HCP	Wildcat	2.5	196	8	112	1.6	5.2
781	Pre-HCP	Yager	2.9	165	962	2,120	0.2	0.9
795	Pre-HCP	Yager	0.8	41	4	30	0.4	1.5
821	Pre-HCP	Yager	1.5	152	256	606	5.0	13.0
823	Pre-HCP	Yager	1.5	129	21	360	0.1	0.2

[1]Particle size analysis of trapped sediment was completed only for the 2002 water year.

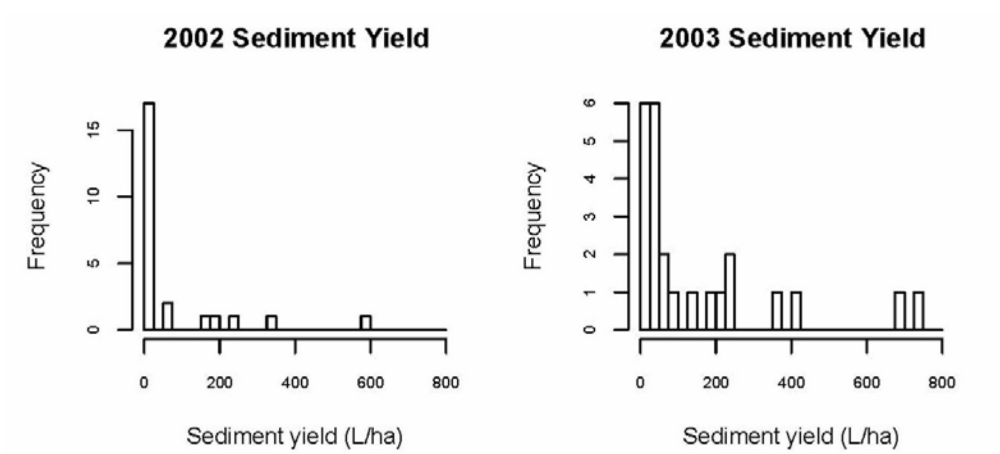

Figure 1—Observed sediment yield (basin sedimentation) was highly skewed. There were more zeroes observed in the dry water year of 2002.

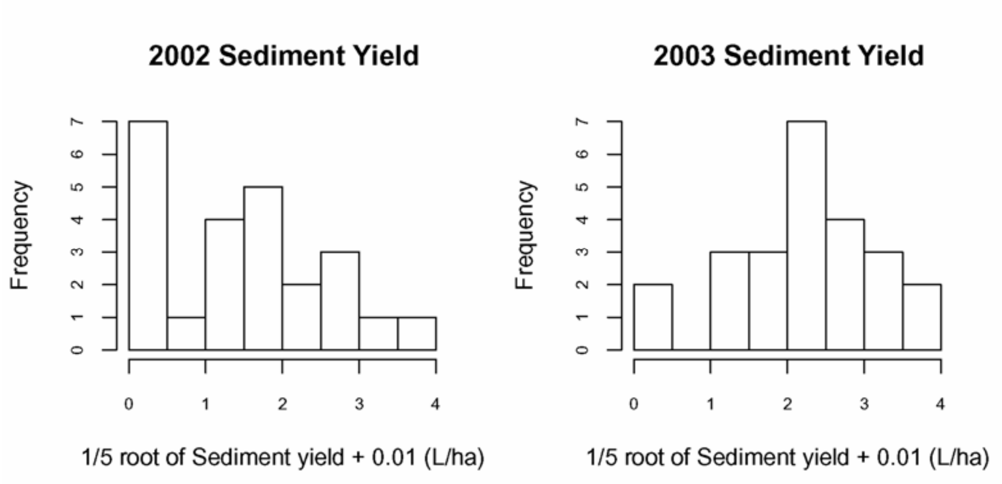

Figure 2—A 1/5-root transformation created a nearly normal distribution of sediment yield (basin sedimentation). A small, non-significant number (0.01) was added to every observation to facilitate the transformation.

Graphical assessment of the central tendency and dispersion of the data suggested there was tremendous variation in sediment yields in Class III streams *(figs. 3, 4* and *5).*

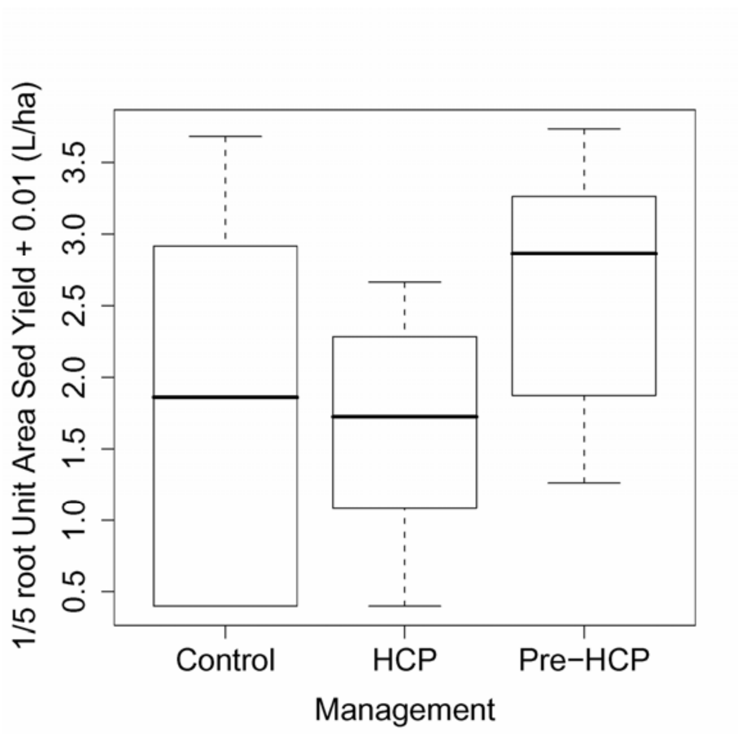

Figure 3—Box plot of the management predictor.

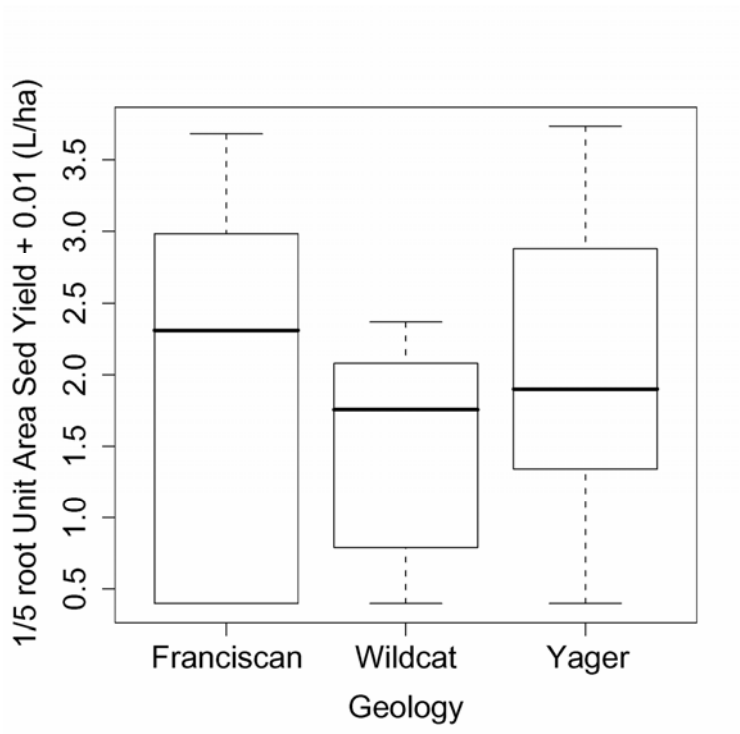

Figure 4—Box plot of the geology predictor.

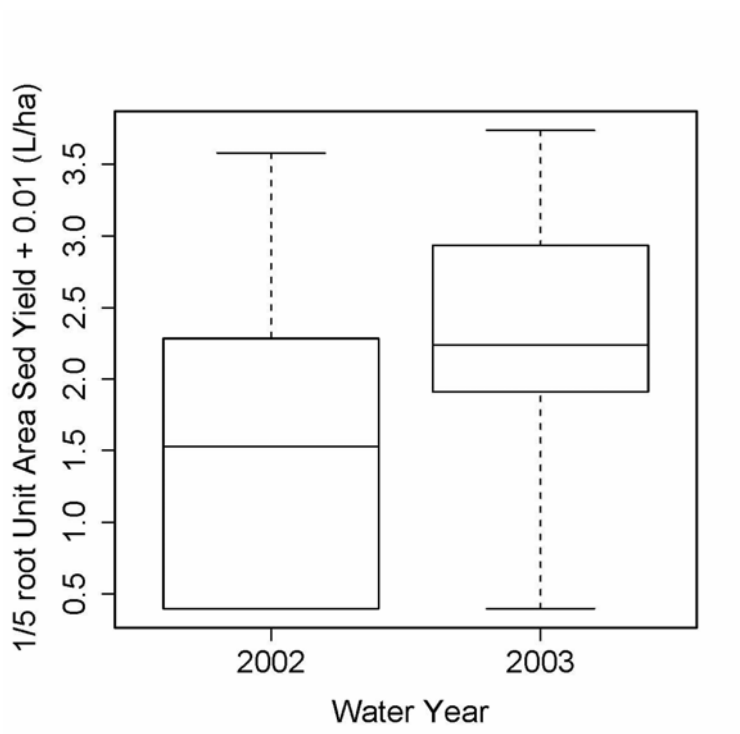

Figure 5—Box plot of the predictor water year.

An analysis of variance model was fit to test the effects of management, geology, and water year on unit-area sediment yield:

```
model <-     aov((Sed.yield+0.01)^0.2
             ~ Mgmt*Geology*Year + Error(Site))
```

The `Error(Site)` term accounted for the temporal psuedoreplication in our observations (MathSoft 1999). Time was the only significant predictor in this model *(table 3)*. Diagnostic plots of the model suggested that sites in Franciscan (`co2`) geology were the most likely to be outliers. Removing this geology from the analysis did not alter the result.

Table 3—*Analysis of variance (including repeated measures) for sediment yield in Class III streams.*

Error: Site	**df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Mgmt	2	7.6654	3.8327	2.6618	0.1025
Geology	2	2.2431	1.1215	0.7789	0.4766
Mgmt:Geology	4	2.1362	0.5340	0.3709	0.8257
Residuals	15	21.5988	1.4399		

Error: Within	**df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Time	1	5.8530	5.8530	14.2147	0.0018
Mgmt:Time	2	0.5163	0.2582	0.6269	0.5476
Geology:Time	2	0.0458	0.0229	0.0556	0.9461
Mgmt:Geology:Time	4	1.4453	0.3613	0.8775	0.5004
Residuals	15	6.1763	0.4118		

Attempts to analyze our data with generalized linear models were hampered by the small sample size and the unbalanced design. We could not fit a complete model of management, geology, and time with all of the interaction terms. Tests of management and geology alone affirmed that they were non-significant predictors ($p = 0.3846$ and $p = 0.8577$, respectively). We fit a simple additive model without any interactions by assuming that the non-significant management:geology interaction would not become significant with the inclusion of time in the model. Testing this model by deletion (Crawley 2002) also suggested that time was the only significant predictor ($p = 0.0425$) of unit-area sediment yield in these Class III streams.

Sediment trapping efficiency likely varied among sediment basins of different size and geometry, as well as at different levels of sedimentation at individual sites. In the first year, 12.5 percent of sites had sedimentation greater than one-third of estimated capacity. In the second year, this was true for 33 percent of the sites. Sedimentation equaled or exceeded estimated storage capacity at three sites in the first year and at two sites in the second year. Consequently, our observations were right-censored, and the measured unit-area sedimentation in some cases is only a lower limit. Therefore, it may be more appropriate to analyze these data using nonparametric statistical tests that would be less sensitive to the structure of our data.

The observed variances in unit-area sediment yield were not constant between the different management categories or geologic formations, so we performed the Kruskal-Wallis One-Way Analysis of Variance on Ranks on each of the two years of data separately. We tested the geology and management classes in separate analyses *(tables 4* and *5).* These nonparametric analyses were consistent with the parametric analyses; no significant differences were found among management or geologic groups.

Table 4—*Kruskal-Wallis One-Way Analysis of Variance on Ranks on transformed data for 2002 observations.*

Group	N	Missing	Median	25 percent	75 percent
Control	8	0	0.789	0.398	2.309
HCP	10	0	1.529	0.398	1.809
pre-HCP	6	0	2.258	1.364	3.190

H = 3.876 with 2 degrees of freedom (p = 0.144).

Group	N	Missing	Median	25 percent	75 percent
Franciscan	7	0	1.638	0.398	2.808
Wildcat	6	0	1.221	0.398	1.628
Yager	11	0	1.705	1.082	2.545

H = 1.233 with 2 degrees of freedom (p = 0.540).

Table 5—*Kruskal-Wallis One-Way Analysis of Variance on Ranks on transformed data for 2003 observations.*

Group	N	Missing	Median	25 percent	75 percent
Control	8	0	2.407	1.611	3.096
HCP	10	0	2.041	1.329	2.368
pre-HCP	6	0	2.964	2.138	3.341

H = 5.067 with 2 degrees of freedom (p = 0.079).

Group	N	Missing	Median	25 percent	75 percent
Franciscan	7	0	2.663	2.130	3.156
Wildcat	6	0	1.979	1.883	2.138
Yager	11	0	2.490	1.495	2.997

H = 3.064 with 2 degrees of freedom (p = 0.216).

Discussion

Our data suggested that among the potential factors controlling sediment yield in the Class III watersheds that we studied—management, geology, and water year—only water year served as a significant predictor. Specifically, there was significantly greater sediment yield during Water Year 2003 than during Water Year 2002.

These two water years had differences in measured precipitation. Using data from the California Data Exchange Cooperative (http://cdec.water.ca.gov) and precipitation stations from Scotia and Eureka Woodley Island, WY 2002 was near-normal. Scotia, located within about 10 miles of the study area, reported about 90 percent of average and Eureka 105 percent of average. Abundant rainfall occurred in November and December 2001 at both stations; at Scotia, rainfall in each month was about 150 percent of average. WY 2003 was wetter than average, with Scotia reporting 137 percent of average and Eureka 142 percent of average. December 2002 was exceptionally wet. Eureka and Scotia were far above average for the month, 364 percent and 316 percent respectively. Scotia had nearly 700 mm of rain (over 27 inches) in that month. Rainfall would correlate with streamflow, sediment transport capacity, and channel erosion potential, as well as potential surface erosion processes.

The sediment yield data did not reveal significant differences among either management or geologic substrate, suggesting that for purposes of estimating minimum sediment yield from these Class III streams, a grand mean of the data set provides the best summary statistic. The statistical power of our analysis was low ($\beta < 0.2$) compared to the typical desired power ($\beta > 0.8$). Given the relatively small sample size and high variance of the data, this in not a surprising outcome. Sample size calculations suggest that between about 25 and 125 samples would be required in each group to attain $\beta > 0.8$ when $\alpha < 0.05$.

The degree to which sediment yields may be larger than observed sedimentation depends on the size distribution of eroded sediment and the trapping efficiency of the basins. Considering the fact that several basins contained a high proportion of fine sand (0.25 to 0.125 mm) *(table 2),* there is cause to believe that the basins were relatively efficient sediment traps.

Size distribution of soils derived from Wildcat and Franciscan parent material in the region were obtained from other studies (PALCO 2003) to estimate annual sediment yield at each of the sediment basins. In the Franciscan, about 23 percent of soil material was coarser than two mm, whereas in the Wildcat, only eight percent of material was coarser than two mm. We assumed that the sedimentation basins captured all material coarser than two mm; the average median grain size in deposits was 1.9 mm. Using the mean volume of sediment deposited in 2002 (0.139 m^3), the mean volume of eroded soil would be 0.139 m^3 / 0.23 = 0.60 m^3 for Franciscan and 0.139 m^3 / 0.08 = 1.70 m^3 for Wildcat. Using an estimate of the original soil density of 830 kg/m^3 (PALCO 2003), and the mean watershed area of 3.3 ha, estimated annual sediment yield for these sites in 2002 would be range from 150 to 440 kg/ha. Alternatively, we estimated sediment yield using the same technique for each site individually. We assumed that each basin captured all sizes coarser than the median size and that the Yager soil size distribution to be the mean of the Franciscan and Wildcat size distributions. Using this approach, we found the mean yield to be about 320 kg/ha. Either approach is likely to overestimate yield because the sedimentation basins are probably more efficient sediment traps than assumed for the calculation, and the estimate of sediment yield would decrease with increasing trap efficiency. Although this technique is imprecise, it produces an estimate of maximum likely sediment yield. The upper range of sediment yield could be constrained considerably by conducting additional studies on basin trapping efficiency.

The estimated range of mean sediment yield of 150 to 440 kg/ha for the Class III watersheds in this study can be compared to sediment yields measured in larger Class II watersheds at Caspar Creek (Lewis 1998). The clearcut drainages studied at Caspar Creek (BAN, CAR, EAG, GIB, and KJE) had mean drainage area of 20 ha, and the mean annual sediment yield post-harvest was 440 kg/ha. This comparison suggests that the Class III channels observed in this study produced sediment at rates not greater than observed for Class II channels in clearcut watersheds at Caspar Creek. The comparison also suggests that the use of sedimentation basins for studies of sediment yield produces results consistent with prior studies, even considering uncertainty in trapping efficiency.

Conclusions

This study was motivated by concerns that erosion processes in Class III channels (low-order headwater stream channels) could be sensitive to forest management activities, and it evaluated the efficacy of conservation practices to minimize disturbance to such channels that could affect downstream water quality. This study confirmed that studies in rugged, previously disturbed and heavily vegetated terrain is challenging. We were not successful in developing the desired distribution of sample sites, and this hampered quantitative evaluation of the data.

We did not find statistically significant differences in sedimentation between sites with differing geologic substrates and management histories. Although HCP sites did tend to have lower sedimentation than pre-HCP sites, high variance in the data and low statistical power (β) prevented us from concluding whether HCP management practices are more effective at preventing erosion and sedimentation. We also found that there was no correlation between measures of channel conditions and ground disturbance near streams and observed sedimentation. This suggested that the erosion processes responsible for observed sedimentation were of a dispersed nature and/or operated at a relatively small scale.

We estimated likely sediment yields based on sedimentation data for these types of channels, and we found that they were of similar magnitude to measured sediment yields for substantially larger clear cut drainages in Caspar Creek. Our estimation technique was likely to overestimate sediment yield, and it is likely that sediment yield from these small Class III watersheds was in fact lower than that in the larger Class II watersheds. These quantitative comparisons suggested that erosion and sedimentation processes in Class III watersheds were not strongly differentiated in magnitude or process from somewhat larger Class II watersheds.

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