

Effects of Forest Management on Streamflow, Sediment Yield, and Erosion, Caspar Creek Experimental Watersheds

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Abstract

Caspar Creek Experimental Watersheds were established in 1962 to research the effects of forest management on streamflow, sedimentation, and erosion in the rainfall-dominated, forested watersheds of north coastal California. Currently, 21 stream sites are gaged in the North Fork (473 ha) and South Fork (424 ha) of Caspar Creek. From 1971 to 1973, 65% of the timber volume in the South Fork was selectively cut and tractor yarded, and from 1985 to 1991, 50% of the North Fork basin was harvested, mostly as cable-yarded clearcuts. Three unlogged tributaries serve as controls.

Annual suspended sediment loads changed 331% after logging the South Fork compared to 89% for the North Fork and -40% to 269% for North Fork subwatersheds. In clearcut units, storm peaks increased as much as 300%, but as basin wetness increased, percentage peak flow increases declined. Flow increases are explained by reduced transpiration and interception. Ongoing measurements show a return to pre-treatment flow conditions approximately 12 years post-harvest, but sediment yields have yet to recover.

Landslides are predominantly associated with roads, landings, and tractor skid trails in the South Fork watershed and windthrow in the North Fork watershed.

Keywords: peak flow, sediment, erosion, landslides, timber harvest

Introduction

For more than four decades, researchers have investigated the effects of forest management on streamflow, sedimentation, and erosion in the Caspar Creek Experimental Watersheds of north coastal California. The California Department of Forestry and Fire Protection and the USDA Forest Service, Pacific Southwest Research Station, began a simple paired watershed study in 1962 with the construction of weirs on the two major Caspar Creek tributaries, the North Fork and the South Fork. Initially, this partnership was born out of necessity. The research station was charged with evaluating harvest impacts in major timber production regions, but the National Forest system lacked significant ownership within the coast redwood Douglas-fir forest type. The Jackson Demonstration State Forest, comprised of nearly 20,000 ha of second-growth forest, met this need, and a successful, long-standing partnership was begun. As management practices have evolved, so, too, have the research questions and technologies. Today, researchers operate 21 gaging stations within the experimental watersheds and utilize state-of-the-art data loggers programmed with sophisticated sampling algorithms, instream turbidimeters, and automated pumping samplers to measure discharge and sediment transport. Additional investigations of the processes important to hydrologic and ecosystem function are emphasized. The Caspar Creek Experimental Watersheds have produced a wealth of data and an extensive library of scientific publications used to guide natural resource management policy.

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Methods

Site

The Caspar Creek Experimental Watersheds are located about 7 km from the Pacific Ocean and about 10 km south of Fort Bragg in northwestern California at 39°21'N 123°44'W (Figure 1). Uplifted marine terraces incised by antecedent drainages define the youthful and highly erodible topography. Hillslopes are steepest near the stream channel and become gentler near the broad, rounded ridgetops. About 35% of the basins' slopes are less than 17 degrees, and 7% are steeper than 35 degrees. Elevation ranges from 37 to 320 m.

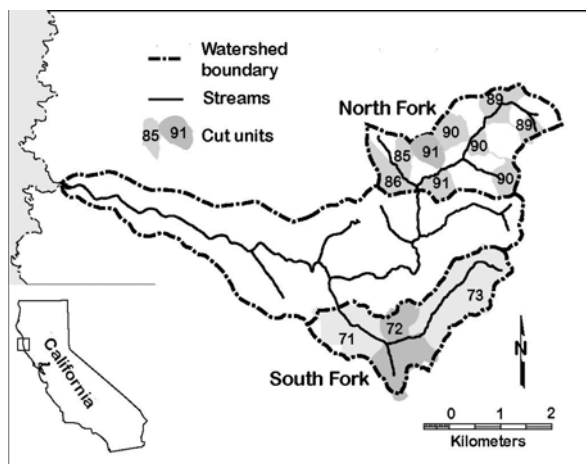


Figure 1. Caspar Creek Experimental Watersheds.

Soils are well-drained clay-loams, 1 to 2 meters in depth, derived from Franciscan greywacke sandstone and weathered, coarse-grained shale of Cretaceous age. Hydraulic conductivities are high and subsurface stormflow is rapid, producing saturated areas of only limited extent and duration (Wosika 1981).

The climate is typical of low-elevation coastal watersheds of the Pacific Northwest. Winters are mild and wet, characterized by periods of low-intensity rainfall delivered by the westerly flow of the Pacific jet stream. Snow is rare. Average annual precipitation is 1170 mm. Typically, 95% falls during the months of October through April. Summers are moderately warm and dry with maximum temperatures moderated by frequent coastal fog. Mean annual runoff is 650 mm.

Like most of California's north coast, the watersheds were clearcut and broadcast burned largely prior to 1900. By 1960, the watersheds supported an 80-year old second-growth forest composed of coast redwood (*Sequoia sempervirens* (D. Don) Endl.), Douglas-fir

(*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.). Forest basal area was about 700 m³ ha⁻¹.

Anadromous fish, including both coho salmon (*Oncorhynchus kisutch*) and steelhead (*Oncorhynchus mykiss*) inhabit the North Fork and the South Fork of Caspar Creek and are protected by state and federal endangered species regulations.

Study design

The Caspar Creek study is a classic paired watershed design where one or more gaged catchments are designated as controls and others are treated with road building, logging, and other timber management practices. After a calibration period wherein a statistical relationship between the catchments is defined, any subsequent change is inferred to be a treatment effect.

The 473-ha North Fork of Caspar Creek and the 424-ha South Fork of Caspar Creek have been gaged continuously since 1962 using 120° V-notch weirs widening to concrete rectangular sections for high discharges. During the early 1980s, three rated sections were constructed upstream of the North Fork weir and 10 Parshall flumes were installed on North Fork subwatersheds with drainage areas of 10 to 77 ha.

Stream discharge was initially recorded using mechanical chart recorders. These were replaced in the mid-1980s with electronic data loggers equipped with pressure transducers. Subsequent upgrades have been implemented as technology has progressed. Early suspended sediment estimates were derived from sediment rating curves, manual depth-integrated sampling, and fixed stage samplers (Rice, et al. 1979). Statistically based sampling algorithms that trigger automated samplers were utilized beginning in the 1980s (Lewis, et al. 2001). In addition, an annual survey of sediment accumulation in the settling basin upstream of each weir has been made since 1963.

Erosion measurements include periodic field surveys to document the location, size, and disposition of landslides. Erosion features greater than 7.6 m³ (10 y³) have been recorded annually since 1986. Erosion has on occasion been sampled at a finer scale using erosion plots (Rice et al. 1979, Rice 1996).

Treatment phase I: selection harvest with tractor yarding

After establishing a calibration relationship between

the North Fork and the South Fork (1963 to 1967), a main-haul logging road and main spurs were built in the South Fork. The road right-of-way occupied 19 ha, from which 993 m³ ha⁻¹ of timber was harvested. The entire south Fork watershed was logged and tractor yarded between 1971 and 1973 using single-tree and small group selection to harvest 65% of the stand volume. Roads, landings, and skid trails covered approximately 15% of the South Fork watershed area (Ziemer 1981).

Treatment phase II: clearcutting with skyline-cable yarding

A study of cumulative effects began in 1985 in the North Fork watershed. Three gaged tributary watersheds within the North Fork were designated as controls while seven were designated for harvest in compliance with the California Forest Practice Rules in effect in the late 1980s. Two units (13% of the North Fork watershed) were clearcut in 1985-86 and excluded from the cumulative effects study. However, this harvest affects all subsequent analyses of North Fork weir data. After a calibration period between 1985 and 1989, clearcut logging began elsewhere in the North Fork in May 1989 and was completed in January 1992. Clearcuts occupied 30-99% of treated watersheds and totaled 162 ha. Between 1985 and 1992, 46% of the North Fork watershed was clearcut, 1.5% was thinned, and 2% was cleared for road right-of-way (Henry 1998).

In contrast to the harvest treatment of the South Fork in the 1970s, stream-buffer rules mandated equipment exclusion and 50% canopy retention within 15 to 46 m of watercourses providing aquatic habitat or having fish present. Most of the yarding (81% of the clearcut area) was accomplished using skyline-cable systems. Yarders were situated on upslope landings constructed well away from the stream network. New road construction and tractor skidding was restricted to ridgetop locations with slopes generally less than 20%. Four harvest blocks, 92 ha total, were broadcast burned and later treated with herbicide to control competition (Lewis, et al. 2001). Pre-commercial thinning in 1995, 1998, and 2001 eliminated much of the dense revegetation and reduced basal area in treated units by about 75%.

Results

Storm peaks

Ziemer (1981) analyzed peak discharges from 174 storm peaks occurring between 1963 and 1975 and later (1998) expanded upon this analysis with data collected through 1985. This analysis detected no significant increases in storm peaks following selection harvest of 65% of the South Fork watershed stand volume *except* within the smallest flow classes (recurrence interval less than 0.125 year). Early fall peaks increased by about 300%, but these were small storm events.

Lewis et al. (2001) analyzed the peak flow response to clearcutting in the North Fork using 526 observations representing 59 storms on 10 treated watersheds. After logging, eight of the 10 tributary watersheds experienced increased storm peaks ($p < .005$). In clearcut units, storm peaks increased as much as 300%, but most increases were less than 100%. The largest increases occurred during early season storms. As basin wetness increased, percentage peak flow increases declined. In the larger, partially clearcut North Fork watersheds, smaller peak flow increases were observed. Under the wettest antecedent moisture conditions of the study, increases averaged 23% in clearcut watersheds and 3% in partially clearcut watersheds. The average storm peak with a 2-year return period increased 27% in the clearcut watersheds (Ziemer 1998) and 15% in the partially clearcut watersheds. Ongoing measurements show a return to pre-treatment flow conditions approximately 12 years post-harvest and minimal response to the pre-commercial thinning (Figure 2).

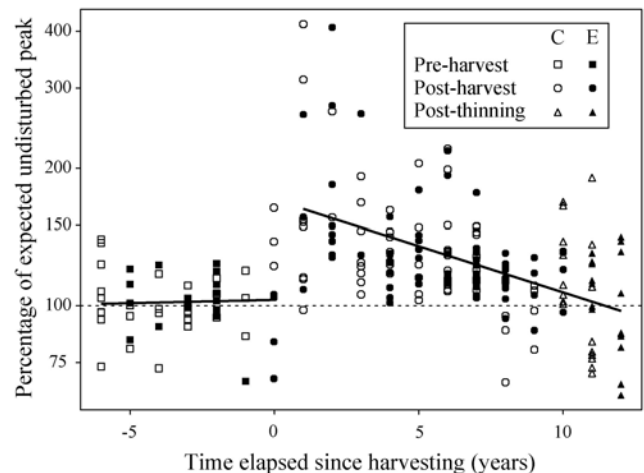


Figure 2. Peak flows observed in North Fork clearcut units C and E from 1986 through April 2003. Reduced transpiration resulting in wetter soils in logged units explains some of the observed increases in streamflow. In addition, recent research at Caspar Creek has documented significant increases in net precipitation within clearcut areas due to reduced canopy interception. Under forested conditions, canopy interception is significant even during the wettest mid-season storms. Preliminary results show that, annually, about 20% more precipitation is delivered to the forest floor after logging.

Sediment loads

Sediment load estimates for the North Fork and South Fork are the sum of the sediment deposited in the weir pond and the suspended load measured at the weir. Comparison of sediment loads produced following the 1971-73 harvest of South Fork and the 1989-92 harvest of North Fork must be made cautiously. Improved and more intensive sampling methods greatly enhance the accuracy of load estimates for the latter study. And large landslides in the North Fork in 1974 and 1995 strongly influence the comparison.

On the South Fork, the suspended sediment loads increased 335% after road building and averaged 331% greater during the 6-year period after tractor yarding. Annual sediment load (including suspended and pond accumulations) increased 184% for the 6-year post-harvest period 1972-1978, returning to pretreatment levels in 1979 (Lewis 1998).

Using the South Fork as the control basin for logging the North Fork, no significant change in annual sediment load was detected after clearcutting 48% of the watershed area. However, analyses using tributary controls were more illuminating. Suspended sediment loads changed 89% at the North Fork weir, primarily due to one landslide in 1995, and -40% to 269% at other gaged locations. The mean annual sediment load increased 212% ($262 \text{ kg ha}^{-1}\text{yr}^{-1}$) in clearcuts and 73% ($263 \text{ kg ha}^{-1}\text{yr}^{-1}$) in partially clearcut watersheds. Recent data analysis suggests that sediment loads in North Fork tributaries remain elevated through water year 2002, more than a decade after harvest (Figure 3).

Erosion

Increased sediment loads in the South Fork following road building and tractor harvest are explained by increased sediment delivery to stream channels (Rice 80

1979). Road building and bridge construction within the riparian zone directly impacted much of the perennial stream. The following winter, 36 discrete landslides were documented along the newly constructed road—17 delivered an estimated 822 m^3 to the stream and 19 deposited 382 m^3 along the road

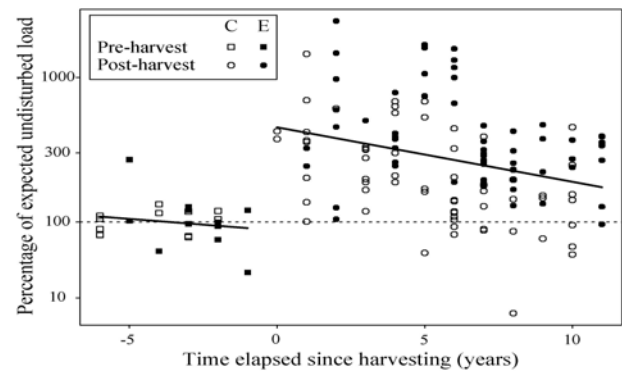


Figure 3. Sediment loads observed in North Fork clearcut units C and E from hydrologic year 1986 through 2002.

surface (Krammes and Burns 1973). Aerial photos of South Fork Caspar taken in 1975 portray 66 recently active landslides. Of these, all but three are associated with roads, landings, or skid trails (Cafferata and Spittler 1998). A field survey of landslides conducted in 1976, three years after tractor harvest was completed on the South Fork, recorded 99 discrete erosion features as small as 4.2 m^3 (150 ft^2). Landslides displaced approximately $189 \text{ m}^3 \text{ ha}^{-1}$ of material (Tilley and Rice 1977). Of these, 85% were associated with roads, landings, or skid trails. In 1994, this survey was repeated documenting 10 additional or re-activated landslides displacing 1515 m^3 of material. Only two of these were not road-related. Another episode of road-related landsliding was observed in the mid-1990s as stream crossing failures became more common. Of the 38 South Fork landslides documented between 1994 and 2003, 89% are road, landing, or skid trail related. These more recent landslides displaced 5804 m^3 and delivered 3503 m^3 to the stream channel. An aging system of logging roads and skid trails continues to deliver sediment to the stream channel.

North Fork sediment load increases were correlated to flow increases and, to a lesser degree, the length of intermittent channels logged or burned (Lewis et al. 2001). Increased erosion is attributed to increased gullyng of headwater channels. Field investigations documented gullyng and bank erosion in unbuffered channels subjected to intense broadcast burns and logging disturbance.

The annual inventory of failures exceeding 7.6 m³ suggests that post-harvest erosion and sediment delivery mechanisms are quite different in the North Fork than were documented in the South Fork (Table 1). North Fork windthrow plays a far greater role in soil displacement, but delivers less displaced sediment to stream channels. Of 145 erosion features documented post-harvest (1990-2003), 84 were windthrow-related and only 10 were road-related. Uncut areas of the North Fork are included in this tally because these areas were impacted by edge-effect windthrow and new road construction. Windthrow displaced 2240 m³ but delivered only 27% of this sediment. Clearcutting left adjacent timber stands and riparian buffers vulnerable to windthrow, but relatively little of the sediment displaced by uprooted trees was delivered to the stream. In contrast, road-related landslides on the North Fork delivered about half of the 3264 m³ volume displaced. Most of these, including the largest (2012 m³), are associated with the pre-existing mid-slope road that spans the north side of the watershed. This road was constructed circa 1950 to the standards of the time.

Table 1. Comparison of post-harvest Erosion features inventoried on the North Fork and South Fork.

Erosion Features	South Fork	North Fork
6-year post-harvest¹		
Total number	99	81
Volume (m ³)	80046 ²	7285
Delivered Volume (%)	na	39%
Road-related number	85	6
Volume (m ³)	na	533
Delivered Volume (%)	na	8%
Windthrow-related number	na	45
Volume (m ³)	na	1204
Delivered Volume (%)	na	25%
1990-2003		
Total number	38	145
Volume (m ³)	5804	11878
Delivered Volume (%)	61%	45%
Road-related number	34	10
Volume (m ³)	5556	3264
Delivered Volume (%)	63%	52%
Windthrow-related number	5	84
Volume (m ³)	316	2240
Delivered Volume (%)	20%	27%

¹1971-1976 on South Fork, 1990-1995 on North Fork. ²Reported as 100 yd³ acre⁻¹ (Tilley and Rice 1977).

Most of the erosion features discussed above are smaller than 76 m³. Of greater concern to land managers is how timber harvest alters the frequency of large landslides. Debris slides account for a major amount of mass wasting within the Franciscan geology of the Caspar Creek region. Such landslides occur infrequently in response to critical rainfall intensities. Clearly, mass wasting increased following tractor harvest of the South Fork, but attempts to discern a post-harvest change in landslide frequency in the North Fork have been inconclusive (Cafferata and Spittler 1998). Twelve large landslides have occurred post-harvest in the North Fork watershed. The two largest occurred in clearcut units more than 10 years after harvest and account for 60% (5617 m³) of the volume of all post-harvest erosion features. Of the remaining 10, five occurred in harvest units and five in control watersheds. While serving as a control watershed, the North Fork experienced two other large landslides (in 1974 and 1985) that displaced 4568 m³.

Bawcom (2003) evaluated 50 clearcut units on Jackson Demonstration State Forest including the 10 North Fork Caspar clearcuts. Of 32 recent debris slides larger than 76 m³, 28 (two of six in North Fork Caspar) were road-related. Most were associated with decades-old roads low on the slope near watercourses. No increase in the rate of landsliding within JDSF clearcuts was detected.

Conclusions

Timber harvest and road building affect runoff processes, sediment yields, and erosion. Caspar Creek studies document increases in peak flows, suspended sediment loads, and erosion after two very different harvest treatments. Response was highly variable between treatments and among individual treated tributaries. California's modern forest practices rules appear to mitigate, but do not eliminate these impacts.

Changes in basin wetness and canopy interception explain post-harvest flow increases. Sediment loads following partial clearcutting were correlated to flow increases. With forest regrowth, flow increases diminish returning to pre-harvest flow conditions after about 10 years. Sediment yields do not appear to recover as quickly and persist at double the pretreatment levels 12 years after harvest.

Erosion and sedimentation from ground extensively disturbed by road building and tractor yarding remain elevated decades after harvest. The present condition of the South Fork watershed is typical of much of the tractor-yarded lands in the redwood region that are entering yet another harvest cycle. It is becoming crucial for landowners, regulatory agencies, and the public to understand the interactions between proposed future activities and prior disturbances. A third phase of Caspar Creek research is being initiated in the South Fork to examine the effects of re-entry on runoff and sediment production from previously tractor-logged redwood forests. Much remains to be learned regarding restoring impacted ecosystems and mitigating impacts from future harvests. The Caspar Creek Experimental Watersheds provide a long-term research resource for furthering this scientific endeavor.

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