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Large Woody Debris Volumes and Accumulation Rates in Cleaned Streams in Redwood Forests in Southern Humboldt County, California

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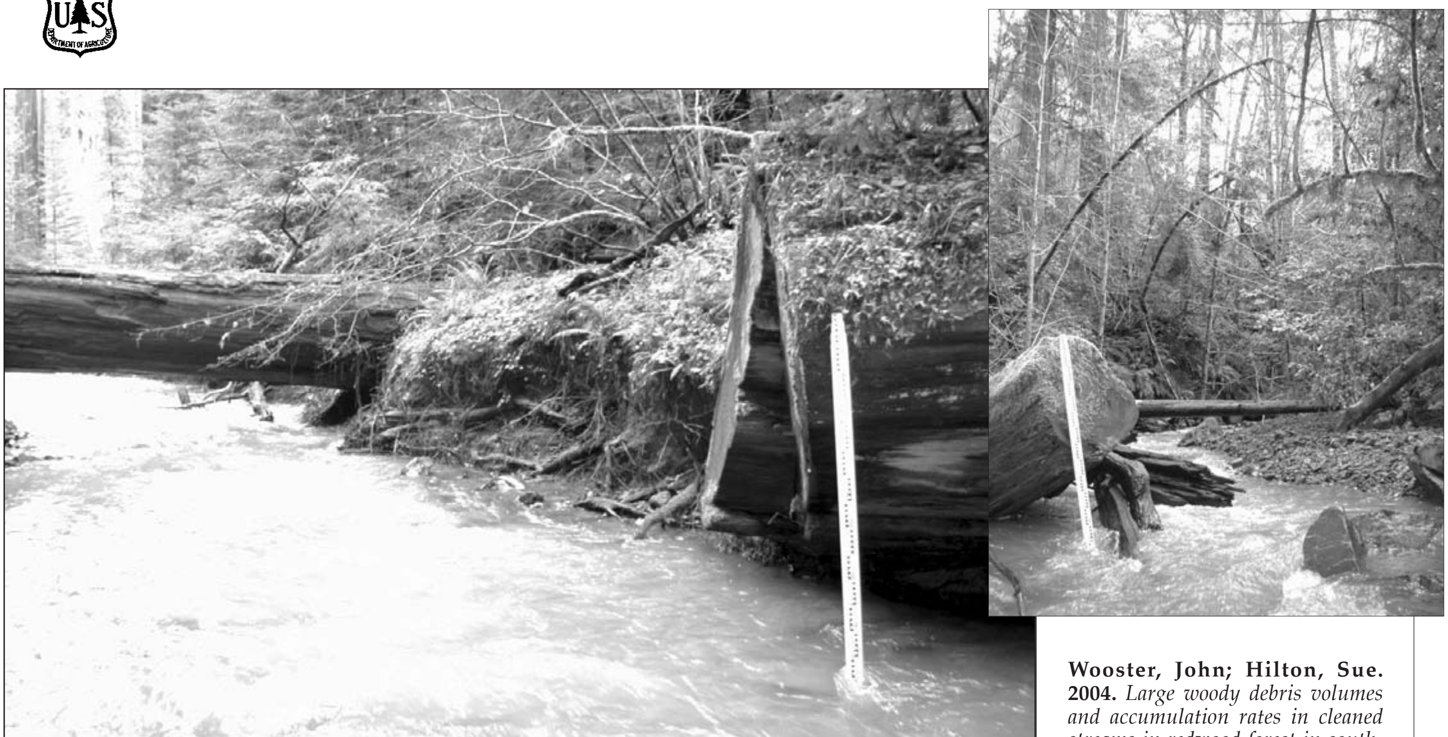

Old growth (L) and second growth (R) redwood streams with "cleaned" LWD in foreground and recently recruited LWD spanning the channel in the background. (1.5 m stadia rod for scale).

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Large woody debris (LWD) was inventoried in 1999 in five streams where LWD was removed in the early 1980s, and no LWD has been artificially introduced since. All study sites are second order channels near the confluence of the South Fork and main-stem Eel River, California. Watershed contributing areas range from 4.7 to 17.4 km^2, and mean active channel widths within study reaches range from 5.6 to 8.4 m. Vegetation is dominated by redwood (*Sequoia sempervirens* (D. Don) Endl.); three streams have old- and second-growth study reaches and two streams are entirely second growth. LWD volumes in old-growth reaches averaged 589 m^3/ha compared to 251 m^3/ha for second-growth

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Introduction

Large woody debris (LWD) is a fundamental component of streams in forested watersheds. LWD can provide stability to the streambed and banks, influences the routing of sediment, promotes pool formation, provides nutrients for aquatic invertebrates, and is an essential element of quality anadromous fish habitat (Bilby and Likens 1980, Harmon and others 1986, Bisson and others 1987). The complex input and output relationships that determine a stream's LWD "standing crop" are often affected by land use practices. Murphy and Koski (1989), using a model developed for undisturbed old-growth streams in southwest Alaska, predict that in the 90-year period following clear-cut logging without a streamside buffer strip, LWD would be reduced by 70 percent and recovery to pre-logging levels would take more than 250 years. Andrus and others (1988) report that in a small coastal Oregon watershed riparian trees must grow longer than 50 years to supply an adequate volume of LWD. Documenting accumulation rates of LWD in streams with different forest management practices is important for understanding how land management affects stream ecosystems.

Before the positive aspects of wood in streams were widely understood, LWD was considered deleterious to anadromous fish because it formed

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reaches. The mean volumes in cleaned old-growth streams were significantly less (90 percent confidence level) than in undisturbed old-growth redwood streams in Prairie Creek, California (Keller and others 1985), with our reaches averaging less than a third of the mean volume in undisturbed reaches. LWD accumulation rates since cleaning were estimated using field evidence to exclude any pieces left during cleaning. Input rates averaged 13.7 m^3/ha/yr for old growth and 4.2 m^3/ha/yr for second growth. The discrepancy between old- and second-growth accumulation rates is primarily in the rate of input from the hillslope to the potential zone (defined as >0.5 m above the water surface and extending 1 m laterally from the active channel). Of new LWD in the active channel, 41 percent (by volume) was associated with pools and 65 percent (by volume) was trapped in debris jams.

Retrieval Terms: stream cleaning, large woody debris (LWD), accumulation rate, redwood forests, riparian, channel, debris jams, salmonid habitat, northern California (CA)

potential migration barriers and contributed to increased bank erosion attributed to deflected flow. Early salmonid restoration efforts focused on removing LWD from streams, a practice known as "stream cleaning." Floods in the north coast region of California in 1955 and 1964, combined with intensive logging, delivered large volumes of LWD to streams. The Energy Resources Fund of 1980 and the 1981 Bosco-Keene Assembly Bill 951 allocated one million dollars per year for salmon restoration. As part of the salmonid restoration plan, streams were to be cleaned at the rate of at least 100 miles per year (California Resources Agency 1982). Early stream cleaning efforts often removed all LWD below a stream's high water mark. By 1986-87 the stream restoration paradigm began to shift towards selectively removing debris jams while strategically replacing LWD as instream structures.

This study investigates cleaned streams in order to measure current LWD loads and to quantify LWD accumulation rates since cleaning. Study sites with no instream structures were selected to minimize artificial contributions to accumulation rates. Stream cleaning provides a reference point to measure rates of LWD deposition. Accumulation rates were estimated based on accrued LWD volumes and time elapsed since cleaning. Accumulation rates and volumes were compared between channels adjacent to unharvested old-growth (OG) redwood stands and channels in managed second-growth stands. The results provide information on how quickly cleaned reaches are recovering, and how much additional LWD is required to compensate for diminishing potential recruitment volumes following conversion from old-growth to second-growth forests.

Study Sites

Five streams in or bordering Humboldt Redwoods States Park (HRSP) in southern Humboldt County, California were selected as study sites (*fig. 1*). The two primary selection criteria were: 1) extensive stream cleaning pre-1986 and 2) no installation of instream structures. Vegetation in all study sites is dominated by redwood. Bridge, Elk, and Fish Creeks are tributaries to the lower South Fork (SF) Eel River and are partially in HRSP. The reaches within HRSP boundaries are unharvested old-growth (OG) redwood. Old-growth reaches begin at the confluence with the SF Eel River and extend upstream 500 to 800 meters. All stream channels within old-growth boundaries were cleaned. Above park boundaries, cleaned reaches

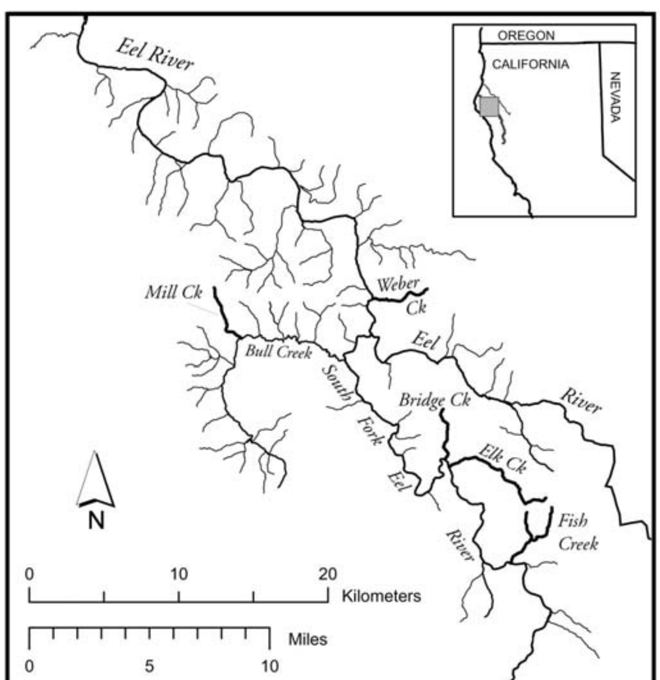

Figure 1—Location of five study sites in southern Humboldt County, California

extend into privately owned second-growth redwood stands. Mill Creek is a tributary to Bull Creek; Bull Creek drains into the SF Eel. HRSP acquired Mill Creek in 1965, and the riparian zone is second-growth redwood that was last harvested in the early 1950s. Weber Creek is a tributary to the main stem Eel River directly below the confluence of the main stem and SF Eel. Weber Creek watershed is a managed redwood forest owned by Pacific Lumber Company. For all study sites, stream cleaning began at stream mouths and proceeded upstream.

The climate of the SF Eel River is one of the wettest in California; average annual precipitation ranges from 140 to 280 cm/yr (period of record 1900-1980, Rantz 1968, Goodridge 1981). Most rainfall in the region occurs in large, frontal storms between November and April that produce the bulk of stream runoff. Snowmelt and rain on snow are minor contributors to runoff (Brown and Ritter 1971). Prior to stream cleaning, the study region experienced approximately 100-year flood events in 1955 and 1964. Based on data from Scotia (on the main stem Eel downstream of study sites), there were three 20- to 25-year flood events between cleaning and data collection: February 1986, January 1995, and January 1997 (USGS 2002; Syvitski and Morehead 1998). The lower SF Eel is underlain by Franciscan greywacke sandstone deposited in deep marine environments during the Cretaceous (Page 1966). Slopes are steep and mantled with highly erodible soils in which large rotational slides are common. All study reaches are in lower depositional reaches of second order streams (based on USGS quad maps) where the gradient is ≤4 percent and elevations are ≤200 m above sea level (*table 1*).

Methods

Calculation of Cleaned Reach and Sample Plot Selection

The California Conservation Corps (CCC) provided labor crews that cleaned the study sites in the 1980s. A CCC database provided dates of stream cleaning, length of cleaned reach, and a history of fish habitat improvement structures (*table 2*). The California Department of Fish and Game (CA DFG) surveyed all study streams before CCC cleaning. The CA DFG stream surveys outlined sizes and locations of debris jams and recommended reaches suitable for cleaning. The CCC database and CA DFG stream surveys were used to identify potential lengths of cleaned reaches for each study site. In Bridge, Fish, and Weber Creeks, potential lengths of cleaned reaches were shortened based on field observations of a tapering off or termination of cleaning efforts. The total length of cleaned reach at each site was broken into 100-m-long sub-reaches, and a random sample of these was selected for inventory. The first 100-m sub-reaches above mainstem confluences were excluded from sampling due to backwater influences during high flows in the trunk stream. The lower 400 m of Mill Creek function as a side channel to Bull Creek at high flows and were also eliminated from sampling. Active channel widths were measured at the beginning, middle, and end of each sub-reach. Sub-reach area was calculated by multiplying the mean active channel width plus 2 m of potential zone by the 100-m sub-reach length.

Table 1—*Characteristics of five study streams, southern Humboldt County, California.*

Study site	Legal description at confluence	Stream order	Elevation range	Watershed area	Stream gradient in study reach	Mean active channel width in study reaches		Last period of logging in second-growth reaches
	(T, R, S)		*m*	*km²*	*pct.*	*m*		
						OG	*2nd*	
Bridge	2S 3E 20	2	50-670	6.5	3	6.7	5.8	late 1950s
Elk	2S 3E 21	2	50-610	17.4	2	9.6	5.8	late 1950s
Fish	3S 3E 11	2	60-550	11.4	2-3	8.8	8.1	late 1950s
Mill	1S 1E 25	2	80-590	6.5	2-3	-	7.9	early 1950s
Weber	1S 2E 14	2	40-730	4.7	4	-	5.6	1960s

Table 2— *Summary of stream cleaning history and sample size.*

Study site	Time between last cleaning and survey	Length of cleaned reach	Sample size	Total number of pieces measured
	yr	*m*	*no. of 100 m sub-reaches*	
Bridge - OG	13.7	490	3	93
Elk - OG	15.6	700	3	80
Fish - OG	19.3	600	3	60
Total Old Growth	**-**	**-**	**9**	**233**
Bridge - 2nd	13.7	500	4	85
Elk - 2nd	15.6	2900	5	115
Fish - 2nd	19.3	600	5	160
Mill	13.6	900	6	102
Weber	16.6	500	4	293
Total Second Growth	**-**	**-**	**24**	**755**

Volume of Woody Debris

LWD volumes were inventoried during the summer of 1999. In each sub-reach, volumes were calculated for all pieces greater than 20 cm in diameter and 1.5 m in length. LWD was inventoried in the effective zone, defined as within the active channel and up to 0.5 m above the water surface (summer low flow) or channel bed, and in the potential zone, suspended 0.5 m or more above the channel and extending laterally 1 m beyond the active channel bank on both sides of the stream. The definitions of effective and potential zones are identical to ones used for LWD studies in the Caspar Creek Experimental Watershed (O'Connor and Ziemer 1989). The original definitions were adapted from Swanson and others (1984). Studies used for comparing results presented in this paper (O'Connor and Ziemer 1989, Keller and others 1985, Lienkaemper and Swanson 1987) define LWD as ≥10 cm diameter. We used a 20-cm-diameter threshold because field observations and anecdotal information were inconclusive as to whether the 10- to 20-cm-diameter range would have been targeted by stream cleaning crews. Where conditions permitted, diameters at both ends were recorded for pieces greater than 5 m in length and for shorter pieces that clearly tapered in diameter. Lengths were broken into effective and potential segments for logs occupying both zones. Lengths extending past the potential zone were not included. Volumes of each piece were calculated using Smalian's formula for the frustum of a paraboloid:

$$\text{Volume} = \frac{\pi(D_1^2+D_2^2)L}{8} \qquad (1)$$

where D_1 and D_2 are the diameters at each end and L is piece length. D_1 was measured above root swell for pieces with root wads and at the largest measurable diameter for pieces without. When only one diameter was measured this value was used for D_1 and D_2. Volumes were calculated separately for irregular root wads without trunks. These volumes were calculated as a product of length, width, and height, and a percent pore space was estimated and deducted from root portions with an open framework.

Accumulation Rates

Decay classes were assigned for each piece according to a classification system adapted from Maser and Trappe (1984) (*table 3*). All measured pieces were assigned a pre- or post- stream-cleaning age class according to guidelines in *table 4*.

Accumulation rates were derived for each sub-reach by combining "new" and "probably new" wood and dividing by the number of years between final stream cleaning and the 1999 LWD inventory.

$$\text{Accumulation Rate} = \frac{(\text{new + prob new wood}(m^3))}{(\text{sub-reach area (ha)})\,(\text{yrs post cleaning})} = m^3/\text{ha}/\text{yr} \qquad (2)$$

Table 3— *A five-class system of evaluating decay of coniferous woody debris (Maser and Trappe 1984).*

Decay Class	Bark	Twigs	Texture	Shape	Wood color
I	Intact	Present	Intact	Round	Original color
II	Intact	Absent	Intact	Round	Original color
III	Trace	Absent	Smooth, some surface abrasion	Round	Original color, darkening
IV	Absent	Absent	Abrasion, some holes and openings	Round to oval	Dark
V	Absent	Absent	Vesicular, many holes and openings	Irregular	Dark

Table 4— *Chronological classification criteria.*

Classification	Criteria
Old	• Bucked ends and keyed into banks perpendicular to flow, usually bucked at active channel margin • Trapped in jams under bucked pieces or in a position deposited prior to bucked logs • Jam pieces with burn scars resulting from fires set by crews to remove jams • Pieces identified in Department of Fish and Game stream surveys prior to stream cleaning • Deeply embedded and deformed due to constant fluvial erosion: usually very large amorphous redwood pieces with minimal surface area exposed and fluvially incised grooves on surface, not in danger of causing a jam, and nearly impossible to remove
Probably Old	• Decayed logs (≥IV decay class) that added bank stability, were oriented parallel to flow, were deeply keyed into banks, caused minimal threat of jam formation and would have been difficult to remove • Trapped in jams with old pieces in a manner suggesting similar depositional time, usually in the internal structure of a debris jam showing evidence of cleaning • Hillslope delivered logs that were ≥IV decay class, posed no threat of forming a jam, and were out of the active channel • Pieces with sprouts, alders, or other vegetative indicators that were established post LWD deposition and were >20 years old • Decayed logs (≥IV decay class) that would have been inaccessible to hand crews
New	• Pieces with recent mechanism for input such as fresh slides or bank collapse • Minimally decayed logs oriented perpendicular to flow that had potential for trapping other debris and would have been easily removed by hand crews • Logs with needles or leaves still intact (decay class I) and decay class II unless contradictory evidence was present • Fluvially deposited pieces trapped on upstream side of pieces meeting "new" criteria defined above
Probably New	• Logs trapped in debris jams with new pieces and oriented in a position that suggests deposition after that of "new" pieces • Logs deposited near logs showing evidence of cleaning in an orientation/location that would have merited removal which were easily accessible by hand crews • Debris jams without distinct old or new evidence that are not identified by Department of Fish and Game stream surveys, are in reaches with other cleaned pieces, and would have been easily removed • Hillslope delivered pieces with minimal weathering or revegetation of root throw pits

Debris Delivery

A delivery mechanism was assigned for individual LWD pieces in order to assess predominant debris sources. Debris sources were broken into "hillslope" or "fluvial."

Direct hillslope inputs included bank erosion, landslides, and windthrow. Additional hillslope evidence included pieces with rootwads upslope and broken segments that could be linked with related pieces on the hillside. Fluvial pieces have been mobilized from their original channel deposition site and have no evident hillslope link. Although wind fragmented pieces may be in their original location, their upslope origin is difficult to identify. Such pieces were likely labeled as fluvial.

Additional Data

We noted whether pieces were associated with debris jams. A debris jam was defined as an aggregation of three or more pieces satisfying the LWD criteria. Each piece within a debris jam was measured. Tree species were also recorded. Redwood and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) were the only species found in substantial quantity. Other species identified were bigleaf maple (*Acer macrophyllum* Pursh), tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.), madrone (*Arbutus menziesii* Pursh), and red alder (*Alnus rubra* Bong.). LWD that could not be identified was classified as coniferous, hardwood, or unknown. LWD that was associated with pools was also noted. Pool association was defined by presence of LWD in the effective zone in or adjacent to a pool. Pools were defined and classified as main, backwater, scour, or plunge according to a scheme adapted from Bisson and others (1987).

Analysis

We looked for differences in wood volumes, inputs, and accumulation rates between old-growth and second-growth reaches. Mean and total values of each variable for each stand condition (old- or second-growth) were calculated using stratified sampling estimators (Cochran 1977). For example, the total LWD volume/ha in old-growth reaches was estimated as:

$$\text{Volume}_{OG} = \frac{\sum_c N_c \bar{V}_c}{N} \qquad (3)$$

where c is an old-growth creek reach, $\bar{V}_c$ is the mean total volume/ha for all sub-reaches in that reach, N_c is the number of 100-meter sub-reaches in the reach (sampled and unsampled), and N is the total number of sub-reaches in all old-growth reaches. Satterthwaite's (1946) procedure for estimating variances and degrees of freedom was used to calculate confidence intervals and perform t-tests.

Results

LWD Characteristics

The frequency distributions of LWD tree species remained relatively consistent between old- and second-growth reaches (*fig. 2*). The decrease of redwood LWD in second growth may be partially attributed to the increase in pieces classified as unknown and conifer spp. but could also reflect differences in stand composition. *Figure 2* also shows similar percent frequency distributions for chronological classifications of LWD for old- and second-growth reaches. The high frequency of old LWD in both reach types appears to indicate that stream cleaning was not thorough. However, a significant percentage of the old LWD category are remnants of modified jams or are logs cut during stream cleaning at or near channel margins that now extend into the present potential zone. The higher frequency of "old" than "new" pieces indicates that fewer pieces have accumulated since cleaning

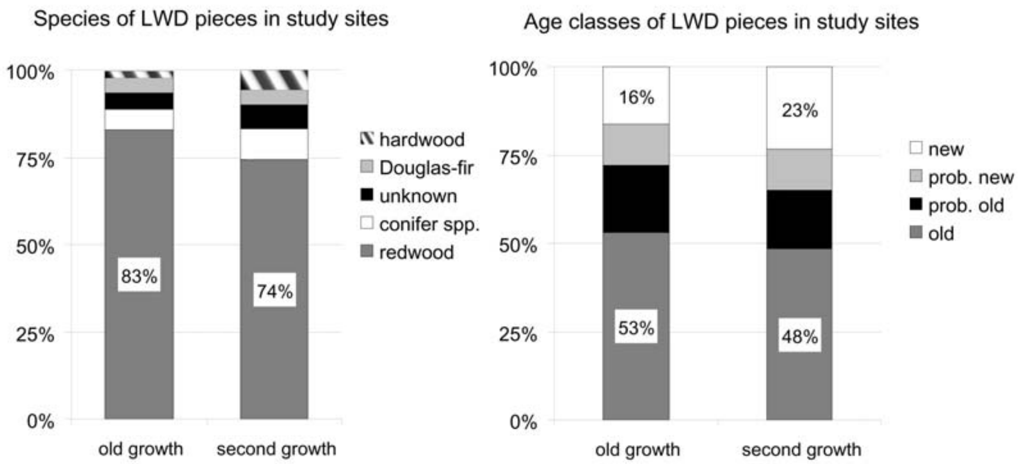

Figure 2—*Percent frequency distribution of LWD (Large Woody Debris) tree species and frequency distribution of LWD chronological classifications for three old-growth and five second-growth study sites.*

than were present before cleaning. Since our "old" counts do not include pieces that were completely removed, the actual ratio of pre-cleaning to recently-added pieces is probably much higher.

Roughly two-thirds (68 percent) of newly recruited LWD was found in debris jams (*table 5*). Fifty percent of old LWD was found in jams, which is a higher frequency than expected if cleaning crews targeted debris jams. However, most old LWD found in jams were remains of large debris structures in the potential zone where in-channel segments had been removed. Approximately 50-60 percent of LWD pieces in all categories appeared to be hillslope delivered; hillslope inputs accounted for the majority of the volume in all categories (85 percent of new and 70 percent of old volume.) About a quarter of all pieces in the effective zone were pool associated, and approximately 40 percent of the effective zone volume was associated with pools.

Table 5 also summarizes sizes and volumes of new and old LWD. Lengths and volumes for old LWD are likely to be smaller than before stream cleaning because many old pieces were partially removed, although diameters may reflect original values. Average large-end diameter is greater in old-growth reaches, and new pieces have smaller diameters than old pieces in both second-growth and old-growth reaches. The smaller diameter for new pieces in both reach types may reflect conversion from old- to second-growth stands and a slower decay rate for large pieces of old LWD. Old-growth fluvial inputs may reflect upstream, non-old-growth watershed conditions due to the short length (<800 m) of old-growth

Table 5— *Comparison of new and old LWD (Large Woody Debris) pieces in old-growth and second-growth reaches.*

Pre/post stream cleaning		New LWD			Old LWD		
Reach type		*Old G*	*2nd*	*Combined*	*Old G*	*2nd*	*Combined*
Number of pieces measured		64	263	327	169	492	661
Pct. trapped by jams	(pct. of pieces)	48	73	68	42	53	50
	(pct. of vol.)	**57**	**74**	**65**	**54**	**61**	**58**
Pct. hillslope delivered	(pct. of pieces)	52	59	57	50	55	53
	(pct. of vol.)	**93**	**76**	**85**	**71**	**70**	**70**
Pct. in effective zone that is pool associated	(pct. of pieces)	20	28	26	25	20	21
	(pct. of vol.)	**34**	**44**	**41**	**49**	**31**	**39**
Average large end diameter	**m**	0.51	0.35	0.38	0.60	0.48	0.51
Average length	**m**	6.8	6.0	6.2	4.5	3.5	3.8
Average volume	**m^3**	3.4	0.7	1.3	1.9	0.9	1.2

Table 6— *Volumes by zone, accumulation rates, and residence times for three old-growth and five second-growth study sites. Values are means ± the standard error of the mean (group means are weighted). Residence times are based on mean accumulation rates.*

Study Site	Total LWD volume	Potential zone volume	Effective zone volume	Volume of new wood	Accumulation Rate	Residence Time
	m^3 / ha	*m^3 / ha*	*m^3 / ha*	*m^3 / ha*	*m^3 / ha / yr*	*yr*
Bridge - OG	562 ± 99	392 ± 204	220 ± 40	96 ± 46	7.0 ± 3.4	80
Elk - OG	723 ± 204	615 ± 214	130 ± 23	236 ± 178	15.1 ± 11.4	47
Fish - OG[1]	455 ± 190	424 ± 183	40 ± 18	339 ± 170	17.6 ± 8.8	26
Mean Old Growth	**589 ± 82**	**490 ± 84**	**125 ± 11**	**232 ± 67**	**13.7 ± 4**	**43**
Bridge - 2^{nd}	216 ± 64	148 ± 52	95 ± 31	38 ± 24	2.7 ± 1.8	80
Elk - 2^{nd}	183 ± 56	108 ± 39	102 ± 26	37 ± 14	2.3 ± 0.9	80
Fish - 2^{nd}	355 ± 139	314 ± 126	51 ± 20	112 ± 59	5.8 ± 3.0	61
Mill	139 ± 56	104 ± 44	45 ± 20	50 ± 17	3.7 ± 1.2	38
Weber	758 ± 225	607 ± 181	205 ± 63	253 ± 96	15.2 ± 5.8	50
Mean Second Growth	**251 ± 30**	**180 ± 22**	**96 ± 13**	**67 ± 8**	**4.2 ± 0.5**	**60**

[1]In sub-reach 3 of Fish OG there was an unmeasurable jam not included in calculated volumes. The jam formed a 5-m-tall vertical step in the channel profile, and sediment was completely aggraded to the top of the jam. Only one side of the jam was exposed, and piece lengths were undeterminable. The jam was entirely old wood; there were buck and burn marks throughout, and the jam was clearly outlined in California Department of Fish and Game surveys. The jam had no exposed upstream side to trap new wood. The total space occupied by the jam was estimated at 340 m^3; percent wood was not available.

reaches in this study. New pieces tended to be longer than old pieces in both reach types. The shortness of old pieces is likely a result of stream cleaning and increasing fragmentation and splintering with time. New LWD in old-growth reaches has the highest average piece volume, largely as a result of three hillslope-derived pieces averaging 36.6 m^3. Excluding these pieces drops the mean new piece volume in old-growth reaches from 3.4 to 1.7 m^3.

LWD Volume and Accumulation Rates

Weighted mean volumes and accumulation rates in old-growth reaches were over twice those in second-growth reaches (135 percent and 245 percent greater, respectively). Total volumes of woody debris in old-growth channels averaged 589 m^3/ha and ranged from 100 to 1063 m^3/ha for nine sub-reaches in three creeks, while second-growth channels averaged 251 m^3/ha and ranged from 30 to 1044 m^3/ha for 24 sub-reaches in five channels (*table 6*). A t-hypothesis test showed old-growth volumes were significantly greater than second-growth at a 90 percent confidence level, with a confidence interval on the mean difference of 168-509 m^3/ha. Accumulation rates in old-growth reaches averaged 13.7 m^3/ha/yr and ranged from 0.1 to 37.5 m^3/ha/yr. Second-growth channels averaged 4.2 m^3/ha/yr and ranged from 0 to 24.4 m^3/ha/yr. The confidence interval on the mean difference (0.01-19.1 m^3/ha/yr) indicates that old-growth accumulation rates were significantly higher than those in second-growth reaches.

Although we believe that we did identify most pieces not removed by crews, there was an element of subjectivity in determining whether LWD was deposited post-cleaning ("new") or pre-cleaning ("old"). Assigning "new" or "old" status to LWD is essential for estimating accumulation rates. The "probably old" and "probably new" categories have the highest potential for error; only LWD with definitive evidence were included in the "new" and "old" categories. All accumulation rates presented in this study are calculated based on "new" and "probably new" categories. A reasonable approximation for maximum potential error would be to either include "probably old" or exclude "probably new" from accumulation rates. By including all "probably old" LWD, accumulation rates were 21.1 m^3/ha/yr and 6.4 m^3/ha/yr for old and second growth, respectively. By excluding all "probably new" LWD, accumulation rates were 7.0 m^3/ha/yr and 3.3 m^3/ha/yr

Table 7— *Hillslope and fluvial accumulation rates in three old-growth and five second-growth study sites. Values are means ± the standard error of the mean (group means are weighted).*

Study Site	Hillslope accumulation rate	Fluvial Accumulation rate
	m^3 / ha / yr	*m^3 / ha / yr*
Bridge - OG	6.8 ± 3.4	0.2 ± 0.1
Elk - OG	13.2 ± 12.1	1.9 ± 1.8
Fish - OG	16.8 ± 8.7	0.8 ± 0.2
Mean Old Growth	**12.7 ± 4.2**	**1.1 ± 0.6**
Bridge - 2nd	1.5 ± 0.7	1.2 ± 1.1
Elk - 2nd	1.4 ± 0.6	1.0 ± 0.5
Fish - 2nd	5.1 ± 2.6	0.7 ± 0.4
Mill	2.1 ± 1.0	1.6 ± 1.0
Weber	12.2 ± 5.0	3.0 ± 1.4
Mean Second Growth	**2.9 ± 0.4**	**1.3 ± 0.3**

for old and second growth, respectively. In all cases, accumulation rates are higher in old- than in second growth, indicating that the general pattern we observed is not affected by misclassification of individual pieces.

The mean residence times of LWD in both reach types were similar to old-growth Douglas-fir forests in Oregon (Lienkaemper and Swanson, 1987). The residence or turnover time of woody debris can be calculated by dividing the total volume of wood by the accumulation rate. A residence time assumes the inputs and outputs have reached equilibrium, an unlikely premise considering the impacts of stream cleaning and the high spatial and temporal variability in LWD inputs. Assuming that wood volumes are below equilibrium due to cleaning, and that accumulation rates are reasonable, the residence times calculated would represent minimum estimates. The mean residence time was 43 years in old growth and 60 years in second growth, ranging from 26 to 80 years for all study reaches. These estimates may contain unknown errors propagated in the accumulation rates due to a small number of samples, small observation periods relative to redwood decay rates, and potential mislabeling of LWD age. Lienkaemper and Swanson (1987) reported an average turnover time of 50 years, ranging from 12 to 83, for five streams in old-growth Douglas-fir forests in H. J. Andrews Experimental Forest, Oregon. Their accumulation rates were similar to our old-growth rates, averaging 11.8 m^3/ha/yr and ranging from 5 to 20 m^3/ha/yr.

Data from this study indicate that these old-growth reaches accumulate LWD volume faster than second-growth reaches due to a higher hillslope delivery rate

Table 8— *Effective and potential zone accumulation rates and percent hillslope contribution for three old-growth and five second-growth study sites. Site values are means ± one standard deviation. Values are means ± the standard error of the mean (group means are weighted).*

Study site	Potential zone accumulation rate	Proportion of new potential from hillslope	Effective zone accumulation rate	Proportion of new effective from hillslope
	m^3 / ha / yr	*pct. by volume*	*m^3 / ha / yr*	*pct. by volume*
Bridge - OG	5.9 ± 3.1	98	1.4 ± 1.4	96
Elk - OG	14.7 ± 11.5	90	0.6 ± 0.5	7
Fish - OG	17.2 ± 8.7	97	0.4 ± 0.2	29
Mean Old Growth	**13.1 ± 4.0**	**94**	**0.8 ± 0.3**	**48**
Bridge - 2nd	2.6 ± 1.6	57	0.3 ± 0.2	20
Elk - 2nd	1.4 ± 0.5	70	1.3 ± 0.8	43
Fish - 2nd	5.6 ± 2.9	91	0.3 ± 0.2	47
Mill	2.8 ± 0.8	64	1.2 ± 0.7	33
Weber	14.2 ± 5.5	83	1.4 ± 0.5	48
Mean Second Growth	**3.4 ± 0.4**	**78**	**1.1 ± 0.4**	**41**

to the potential zone. Accumulation rates from hillslope sources averaged 9.7 m^3/ha/yr (333 percent) higher in old-growth reaches than in second-growth reaches, with a 90 percent confidence interval of -0.1 to 19.6 m^3/ha/yr *(table 7)*. This difference was not evenly distributed between the effective and potential zones. Hillslope inputs to the potential zone averaged 12.3 m^3/ha/yr and 2.6 m^3/ha/yr in old- and second- growth reaches, respectively, but hillslope inputs to the effective zone averaged 0.4 m^3/ha/yr in both old- and second-growth stands. Hillslope inputs have a greater impact in the potential zone in part because a large percentage of hillslope recruits span the channel (>0.5 m above active channel) and do not come into contact with the effective zone. The old-growth hillslope accumulation estimates seem consistent with reported mean forest floor input rates in old-growth Douglas-fir forests in Oregon and Washington that ranged from 11.2 to 17.5 m^3/ha/yr (Grier and Logan 1977, Sollins 1982). Grier and Logan (1977) and Sollins (1982) defined LWD as pieces greater than 10 cm in diameter, and a 400 kg/m^3 conversion was used to compare results.

Mean accumulation rates for fluvially transported LWD in old- and second-growth reaches show no significant difference (confidence interval -1.7 to 1.3 m^3/ha/yr). The old-growth riparian zones examined here extend a short distance from the bottom of their respective watersheds. Thus the majority of contributing watershed upstream of old-growth reaches was second growth, which may explain a lack of statistical difference between reach types for fluvial inputs. Fluvial input rates for old-growth sub-reaches did not increase as length of upstream old-growth riparian zone increased. The maximum extent of old-growth riparian forest upstream of any of the study reaches was 400 meters, for sub-reach 1 in Elk Creek. The fluvial accumulation rate in sub-reach 1, Elk Creek, was 0.1 m^3/ha/yr, which was the lowest for any of the old-growth reaches sampled in this study. It appears that the relatively short length (≤400 m) of old-growth riparian zones upstream of our study sub-reaches was not enough to produce fluvial accumulation rates indicative of old-growth watersheds at our study sites. Additionally, the fluvial accumulation rate of old-growth watersheds may be small due to low mobility of large pieces from old-growth hillslopes. Longer time spans than those covered in this study, encompassing large, infrequent storms, may be required to properly evaluate old-growth fluvial inputs and piece mobility.

For all study reaches the potential zone accumulates LWD at a faster rate than the effective zone *(table 8)*. The potential zones in old-growth reaches accumulate LWD faster than those in second growth; however, effective zones in old growth and second growth accumulate at similar rates. The potential zone accumulates an average of 13.1 m^3/ha/yr in old growth and 3.4 m^3/ha/yr in second growth *(table 8)*. Our estimated confidence interval on this mean difference (9.5 m^3/ha/yr) is 0.2-19.2 m^3/ha/yr. In the potential zone, most of the accumulated wood (95 percent by volume in old growth and 78 percent in second growth) came from hillslopes. The effective zone accumulated wood at an average of 0.8 m^3/ha/yr in old-growth reaches and 1.1 m^3/ha/yr in second-growth reaches. These rates were not significantly different. Hillslope inputs were less important in the effective zone, contributing 48 percent of the new wood in this zone in old-growth reaches and 41 percent in second-growth reaches. The observed difference between old- and second-growth reach types in the potential but not the effective zone can be attributed partly to the large volume of hillslope inputs spanning the channel within the potential zone that do not reach the effective zone in old-growth reaches.

Discussion

Harmon and others (1986) refer to LWD as a regularly neglected ecosystem component due to sampling difficulties attributed to its inherent wide variations in space and time. The high standard deviations in LWD volumes and accumulation rates in this study attest to the dynamic nature of LWD. A "feast or famine" pattern was often evident among contiguous reaches; three adjacent old-growth reaches in Fish

Creek had respective volumes of 519, 100, and 747 m^3/ha and accumulation rates of 22.6, 0.4, and 29.7 m^3/ha/yr. Lienkaemper and Swanson (1987) reported that one or two trees dominated the volume of debris delivered in a 7 to 9 year observation period, and in one watershed (#9) a single tree accounted for 75 percent of all wood delivered over 8 years.

Geomorphic and hydrologic variations between study sites were minor due to similar locations within watersheds and within the region. Watershed area ranged from 4.7 to 17.4 km^2. Typically, a larger watershed produces a wider active channel, and wider channels tend to retain fewer LWD pieces due to increased piece mobility (Bilby and Ward 1989; Lienkaemper and Swanson 1987). However, larger channels tend to retain pieces with greater volumes and have a higher percentage of LWD associated with the effective zone (Bilby and Ward 1989; Robison and Beschta 1990). All of our study sites are second order channels, and gradient and active channel widths are relatively similar between streams, which may explain the lack of an obvious effect of watershed area in LWD volumes and accumulation rates.

The efficacy of the CCC stream cleaning crews is an important component of the accumulation rates presented in this study. Based on conversations with CA DFG and CCC personnel, we concluded that stream cleaning before 1986 was thorough. Evidence of stream cleaning was prevalent throughout study reaches, suggesting cleaning crews indeed treated the entire study reach. However, the level of wood removal may have varied somewhat between crews and crew leaders. Our classification of unremoved pieces as "old" or "probably old" should have prevented differences between crews from affecting our accumulation rates, if our classifications were accurate. Since large wood and debris jams were more likely removed because of greater potential for forming barriers, older LWD that were mislabeled as "new" or "probably new" are presumed low in number and likely to have relatively small volumes. Our analysis of the effects of misclassifying LWD depositional age class on accumulation rates further indicates that any likely errors would not affect our conclusion that accumulation rates are higher in old than in second growth.

An objective of the study was to quantify and assess the current woody debris loads in cleaned streams with no installed instream structures. The mean old-growth volume of 589 m^3/ha for cleaned reaches is significantly less (p-value = 0.04) than the mean value of 1950 m^3/ha reported by Keller and others (1985) for seven reaches in second-order undisturbed redwood-dominated streams in Prairie Creek, California. Keller and others (1985) included the 10 to 20 cm diameter range in their volumes, which was not included in this study. Although frequency may be high, the proportion of total volume in the 10- to 20-cm diameter range is assumed to be small. LWD in the 10- to 20-cm diameter range in a 1998 woody debris inventory in Redwood Creek, California, accounted for <1 percent of the total wood volume for a 7,215-m study reach in which 2,818 pieces were measured (Kramer and Klein 1999). Control populations for uncleaned but logged second order redwood streams have not been identified. The mean second-growth volume of 251 m^3/ha for cleaned reaches was slightly lower than the mean value of 339 m^3/ha reported for the North Fork Caspar Creek (NFC) (O'Connor and Ziemer 1989). The NFC is a managed second-growth forest that was effectively

Table 9— *Estimated LWD accumulation rates (m^3/ha/yr) for potential and effective zones in the North (NFC) and South (SFC) Forks Caspar Creek, Jackson Demonstration State Forest, California (Keppeler 1996)*

Stream	Data Source	Accumulation period	Last Logging	Accumulation rate m^3/ha/yr
NFC	O'Connor and Ziemer 1989	1926-1986	about 1900	5.3
NFC	Keppeler, 1996	1926-1996	1989-1991	6.3
NFC	Surfleet and Ziemer 1996	1986-1994	1989-1991	7.5
NFC	Keppeler, 1996	1994-1996	1989-1991	32.6
SFC	Keppeler, 1996	1994-1996	1971-1973	13.6

cleaned during logging 90 to 100 years before O'Connor and Ziemer's LWD inventory. Although the NFC is predominantly second-growth redwood, LWD were primarily Douglas-fir and grand fir *(Abies grandis)* due to their shorter life cycles (O'Connor and Ziemer 1989). LWD species distributions in second-growth reaches noted in this study do not follow patterns observed in NFC, possibly because Douglas-firs that were established after logging have yet to reach maturity in the shorter time period following harvest.

Table 9 lists LWD accumulation rates for Caspar Creek calculated by Keppeler (1996), including data from Surfleet and Ziemer (1996), and O'Connor and Ziemer (1989). The revised long-term accumulation rate of 6.3 m^3/ha/yr for the NFC site is less than the old-growth and slightly greater than the second-growth mean accumulation rates presented in this study. The NFC site was an approximately 100-year-old second-growth redwood forest before logging, with selectively logged buffers, in 1989. Therefore, one would expect the NFC accumulation rate to lie between the rates for old-growth and second-growth reaches logged in the 1950s and 1960s presented in this study. The NFC accumulation rate may be closer to our second-growth rates partly because the Douglas-fir and grand fir that made up most of that volume were not as large as the old-growth redwoods that contributed wood to our old-growth study sites. As previously outlined, old-growth accumulation rates in this study probably reflect old-growth hillslope inputs and second-growth fluvial inputs. The effect of second-growth fluvial inputs on old-growth accumulation rates is unclear because pieces derived from second-growth forests have lower volumes but higher mobility.

Weber Creek has a considerably larger LWD accumulation rate and volume than the other second-growth reaches in our study. The riparian zone in Weber Creek was last logged in the 1960s, and this site has the highest mean total volume of LWD and the second highest accumulation rate. Large flow events in 1995 and 1997 appear to have caused massive bank erosion and failures on both sides of the channel above sub-reach 1 (200 m above mouth). Hillslope failures extended 6 to 20 m upslope and delivered as many as 37 redwoods to the channel in sub-reach 3. Assuming trees derived from the hillslope with decay class I or II were delivered during the 1995 event, the average input rate for LWD in the three sub-reaches above sub-reach 1 was 60.6 ± 41.1 m^3/ha/yr from 1995 to 1999. Keppeler (1996) also notes a high input rate of 32.6 m^3/ha/yr for the NFC following post-logging windstorms *(table 9)*. Though the effects of large inputs are attenuated over time, they create extreme spatial and temporal variability in LWD accumulation, and their effects must be evaluated over long time periods. Bisson and others (1987) suggest that periods <25 years are subject to episodic swings in LWD trends.

Conclusion

Approximately 14 to 19 years following stream cleaning, the volumes of woody debris in cleaned old-growth redwood reaches were significantly less than those in uncleaned reaches. Old-growth reaches were found to accumulate LWD at a faster rate than second-growth reaches; however, the difference in input rates appears in the potential but not the effective zone. The old-growth accumulation rate, 13.7 m^3/ha/yr, is derived from old-growth hillslope inputs and primarily second-growth fluvial inputs since the majority of upstream riparian zones are second growth. Hillslope-derived LWD accumulates more quickly in old-growth reaches, 12.7 m^3/ha/yr compared to 2.9 m^3/ha/yr for second growth. Hillslope-derived LWD contributes >75 percent of the new volume in old- and second-growth potential zones. The mean accumulation rate in the effective zone was <2 m^3/ha/yr in both old-growth and second-growth reaches, and more than half of that wood was fluvially-derived in both reach types. The significance of upstream LWD inputs is emphasized by the substantial fluvial contribution to the effective zone. Rates observed in this study suggest that streams with a 40- to 50-year-old second-growth riparian zone accumulate LWD at about 50 percent of the rates characteristic of stream reaches bordered by old-growth redwood forest. The higher accumulation rates in old growth versus developed second growth are consistent with Murphy and Koski's (1989) modeling results that predict LWD in previously undisturbed streams will decline over time after logging due to the decreased supply of debris provided by second-growth forests. If instream LWD loading is to be maintained at pre-logging levels, forest management practices will need to ensure that sufficient steps are taken to compensate for decreased LWD accumulation rates following harvest. Due to the high spatial and temporal variability in LWD noted in this study and others, additional long-term studies would be useful to better understand and quantify the dynamic aspects of LWD.

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