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On the patterns and processes of wood in northern California streams

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ABSTRACT

Forest management and stream habitat can be improved by clarifying the primary riparian and geomorphic controls on streams. To this end, we evaluated the recruitment, storage, transport, and the function of wood in 95 km of streams (most drainage areas < 30 km^2) in northern California, crossing four coastal to inland regions with different histories of forest management (managed, less-managed, unmanaged). The dominant source of variability in stream wood storage and recruitment is driven by local variation in rates of bank erosion, forest mortality, and mass wasting. These processes are controlled by changes in watershed structure, including the location of canyons, floodplains and tributary confluences; types of geology and topography; and forest types and management history. Average wood storage volumes in coastal streams are 5 to 20 times greater than inland sites primarily from higher riparian forest biomass and growth rates (productivity), with some influence by longer residence time of wood in streams and more wood from landsliding and logging sources. Wood recruitment by mortality (windthrow, disease, senescence) was substantial across all sites (mean 50%) followed by bank erosion (43%) and more locally by mass wasting (7%). The distances to sources of stream wood are controlled by recruitment process and tree height. Ninety percent of wood recruitment occurs within 10 to 35 m of channels in managed and less-managed forests and upward of 50 m in unmanaged Sequoia and coast redwood forests. Local landsliding extends the source distance. The recruitment of large wood pieces that create jams (mean diameter 0.7 m) is primarily by bank erosion in managed forests and by mortality in unmanaged forests. Formation of pools by wood is more frequent in streams with low stream power, indicating the further relevance of environmental context and watershed structure. Forest management influences stream wood dynamics, where smaller trees in managed forests often generate shorter distances to sources of stream wood, lower stream wood storage, and smaller diameter stream wood. These findings can be used to improve riparian protection and inform spatially explicit riparian management.

1. Introduction

Protecting riparian sources of wood to streams has become a major component of forestry policy in western states (FEMAT, 1993; U.S. Forest Service and BLM, 1994). Examples include establishing riparian protection zones for wood recruitment (Young, 2000), mandating or promoting stream wood abundance standards or targets (NMFS, 1996; Fox and Bolton, 2007), monitoring abundance of wood in streams (Schuett-Hames et al., 1999), and implementing stream wood restoration programs (Cederholm et al., 1997). The processes of forest mortality, bank erosion, streamside landsliding, debris flows, and wildfires govern the supply of wood to streams (e.g., Murphy and Koski, 1989; Benda and Sias, 2003). The spatial distribution of different wood recruitment processes within a watershed or across landscapes varies substantially because of the diversity in forest composition and age, topography, stream size, climate, and the history of natural and human disturbances (e.g., floods, fires, logging).

Spatial and temporal variability in wood recruitment processes can complicate the management and regulation of stream wood in both headwater channels (nonfish-bearing) and larger fish-bearing streams. For example, site-specific riparian buffers could be designed based on whether forest mortality, bank erosion, or mass wasting is the dominant recruitment agent. If wood recruitment from channel migration or landsliding is important, local buffers could conceivably extend outward beyond streamside forests to protect such sources of wood (Reeves et al., 2003). Riparian forests could be managed for specific ecological objectives such as thinning dense young stands to increase the density of large trees (Beechie et al., 2000) or altering conifer–hardwood composition, strategies that require information on tree species and forest growth and mortality (Liquori, 2006). Thus, an understanding of riparian processes that govern wood recruitment to streams can enhance protection strategies for riparian forests across physically and ecologically diverse watersheds (Martin and Benda, 2001).

In California, the management of riparian areas is a major emphasis in forest management (Ligon et al., 1999; Berbach, 2001). California's

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forest practice rules require a standard riparian buffer width along all fish-bearing streams (46 m, 150 ft) and smaller buffers a subset of nonfish-bearing streams, although some select timber harvest is allowed within them. These buffer widths are based primarily on the presence or absence of fish or nonfish aquatic species, hillslope gradient, and yarding system with no consideration of watershed to regional scale variability in riparian processes. In 2010, California adopted new forest practice rules that allow for a more site-specific, spatially explicit approach to riparian management (CAL FIRE, 2010).

Previous studies in California do not adequately characterize watershed to regional variability of wood recruitment to streams. For example, Harmon et al. (1986) and Lisle (2002) compiled stream wood volumes across several regions in California limited to data available at the time, where much of the data was from the humid north coastal areas and where the various surveys often used disparate measures of stream wood. In coast areas, Keller et al. (1995) documented the abundance and effects of old-growth redwood logs on channel morphology, while Wooster and Hilton (2004) measured stream wood volumes and accumulation rates, and Benda et al. (2002) estimated the relative contribution of forest mortality, bank erosion, and landsliding recruitment to streams in managed and old-growth redwood forests. Studies in the Sierra Nevada have focused on wood function and transport (Berg et al., 1998), effects of wildfire on stream wood (Berg et al., 2002), and stream wood abundance and function in managed and old-growth forests (Ruediger and Ward, 1996).

Despite these studies, little information exists on the spatial variability in wood recruitment and its effects on channel morphology, across different forest types, and in the more inland regions of California. To improve understanding and management of wood in streams across northern California, our primary study objective was to summarize general patterns, processes, and controls on stream wood recruitment, storage, transport, and the effects of wood on channel morphology. Specific questions that underpin our study include:

- How do wood volumes and recruitment processes vary at reach scales and what controls the variation?
- What are the similarities and differences in wood dynamics between regions?
- What are the distances to sources of stream wood and how do they vary?
- What are the dynamics of key wood pieces that form jams?
- What are the controls on wood-formed pools?
- What are the patterns of wood transport in streams?
- What are the influences of forest management on stream wood?

This study uses a synoptic approach that compiles a large set of previous wood surveys to quantify wood recruitment, storage, transport, and other characteristics along ~95 km of streams primarily in small forested mountain basins (<30 km^2) with managed and unmanaged forests. Such robust wood surveys are rare and revealed some unique findings, including the controls on spatial variation of wood in streams and wood-formed pools. All the surveys used the same wood budget methodology (similar to sediment budgets, e.g., Keller and Swanson, 1979; Benda and Sias, 2003) and field crew. Few quantitative wood budgets have been published (e.g., Martin and Benda, 2001; Benda et al., 2002) and this study provides most comprehensive budget to date. The findings are useful to geomorphologists and forest managers concerned with wood in streams.

2. Study areas

The study summarizes previously unpublished wood surveys we conducted along 65 km of channels surveyed in four California geomorphic provinces (California Geological Survey, 2002), including the Coast Ranges, Klamath Mountains, Cascade Range, and Sierra Nevada (west slope) (Fig. 1). Physical processes and attributes that may fundamentally influence the supply of wood to streams vary across these four regions, including erosion rates, precipitation, peak-flow timing, and riparian conifer species and biomass density (Table 1). Study reaches were limited to basins <30 km^2 to minimize the effects of fluvial redistribution of wood (e.g., Seo and Nakamura, 2009) and thereby to ensure that adequate amounts of wood were available for identifying the processes of recruitment (mortality, bank erosion, landsliding). To expand the analysis, we included field data from a previous published study we conducted using the same methods in the northern Coast Range, encompassing 9 km of streams in basins <30 km^2 (Benda et al., 2002). All the surveys combined cover a length of 76 km. To evaluate wood transport, an additional 19 km of stream reaches in basins draining areas from 30 to 70 km^2 were included to capture potentially longer transport distances in larger streams. In total, data on wood recruitment, storage, and transport from 95 km of streams from 73 reaches are evaluated in this paper.

The study not only focused on fish-bearing streams but also included smaller headwater (nonfish-bearing) channels. The study sites encompassed a range of channel gradients, widths, drainage areas, and forest biomass density (volume of trees per area, minimum tree size for site-specific surveys was 10 cm in diameter and 1.5 m in height) (Table 2). To evaluate the various wood metrics for potential influences from regional and management controls, the surveyed reaches were stratified into nine groups based on four geomorphic provinces and three forest management groups (managed, less managed, unmanaged) (Table 2).

Managed forests include private forests with individual trees <100 years old that were often entirely or nearly clear-cut in the early 1900s to 1930s with no native forest remaining except for residual old-growth trees in gorges that cannot be accessed. Some old abandoned logging roads were in riparian areas of managed forests, particularly in the Coast Ranges, a result of legacy logging in the 1950s and 1960s prior to forest practice rules. Less-managed forests include public and private forests that were selectively cut with some upslope clearcutting; forests had longer harvest rotations than managed forests and contain individual trees up to 200 or more years old, with some remnant small stands of native forest. Riparian buffer zones were along streams in managed and less-managed forests depending on the stream type, including buffer widths of 7.6 m (25 ft, ephemeral streams), 23 m (75 ft, streams with nonfish aquatic life), and 46 m (150 ft, fish-bearing streams). Selective cutting occurred within the buffers. Unmanaged forests include old-growth public parklands. A description of the forest metrics and harvest history available for private managed and less managed forests is included in Appendix A. The majority of channels surveyed were in managed forests (51 km), followed by less-managed (15 km), and unmanaged forests (11 km) (Table 2).

2.1. Coast Ranges

Surveys took place in the Ten Mile and Noyo River watersheds near Fort Bragg, CA (Fig. 1). Sites from the Benda et al. (2002) study included tributaries of Redwood Creek (Redwood National and State Parks) and tributaries of the Van Duzen River. The Mediterranean climate of the northern Coast Ranges is characterized by high annual precipitation (150–200 cm) that supports the coastal dominant species of coast redwood (*Sequoia sempervirens*), followed by Douglas-fir (*Pseudotsuga menziesii*) inland. Tan oak (*Lithocarpus densiflorus*), Pacific madrone (*Arbutus menziesii*), and Live oak (*Ouercus wislizenii*) are mixed with conifers inland; while red alder (*Alnus rubra*), willow (*Salix lasiandra*), and big leaf maple (*Acer macrophyllum*) are the dominant deciduous tree species in riparian areas. Geology is mostly Franciscan mélange (Complex), a mixture of highly deformed and weakly metamorphosed sedimentary rocks, with some interbedded marine volcaniclastic sediments (Cashman et al., 1995). The mechanically weak rock in combination with heavy rainfall and tectonic uplift has created a steep landscape highly prone to mass wasting that produces some of the highest erosion rates in the continental United States (Nolan and Janda, 1995). Erosion

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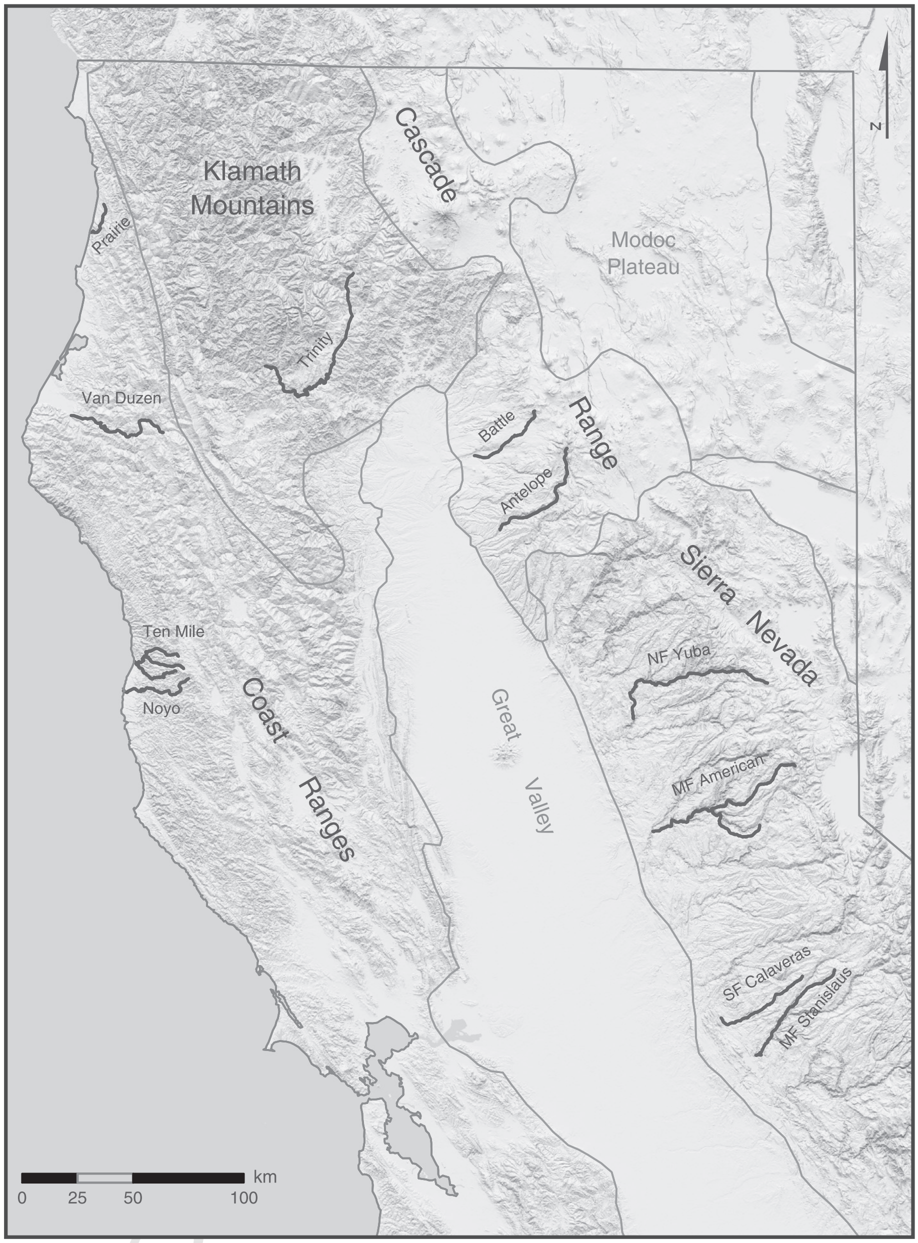

Fig. 1. Location of the major drainages of the study sites and the geomorphic provinces of northern California (California Geological Survey, 2002). Refer to Tables 1 and 2 for regional characteristics.

rates in the Coast Ranges average 667 t km^{-2} y^{-1} based on reservoir sedimentation rates (Minear and Kondolf, 2009). Most of the erosion occurs during a few episodic winter storms, where a few large floods over the past century can dominate decadal sediment supply (e.g., Brown and Ritter, 1971; Kelsey, 1980) (Table 1).

2.2. Klamath Mountains

Study sites in the Klamath Province included tributaries of the Trinity River (Fig. 1). The climate of the Klamaths has an annual average precipitation of ~130 cm y^{-1}, falling as a mixture of rain and snow at higher elevation. The riparian forest community is comprised of mixed conifers dominated by Douglas-fir, and also includes ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), incense cedar (*Calocedrus decurrens*), and white fir (*Abies concolor*). Riparian deciduous species include white alder (*Alnus rhombifolia*), Pacific dogwood (*Cornus nutallii*), big leaf maple, and black oak (*Quercus kelloggii*). The geology consists primarily of metavolcanic, metasedimentary, and granitic rocks, with some glacial deposits at higher elevations (Harden, 1997). Like the Coast Ranges, this steep terrain is also highly erosive (average erosion rate of 849 t km^{-2} y^{-1}; Minear and Kondolf, 2009), generated during intense winter storms, where post-fire erosion may dominate sediment supply (e.g., Colombaroli and Gavin, 2010) (Table 1).

2.3. Cascade Range

Cascade study locations focused on tributaries to Antelope and Battle Creeks that drain to the Sacramento River (Fig. 1). The Mediterranean climate of the Cascades is characterized by moderate annual

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Table 1
Physical processes and attributes that influence wood supply to streams by geomorphic province.

Province	Mean sediment yield (t km^{-2} y^{-1})	Mean annual precipitation (cm y^{-1})	Peak flow/erosion timing	Role of post-fire erosion	Dominant riparian conifer	Riparian biomass density[a] (m^3 ha^{-1})
Coast Ranges	667[b]	150–200	Episodic winter storms	Moderate to low	Redwood	490–3941
Klamath Mountains	849[b]	130	Episodic winter storms	High	Douglas fir	348
Cascade Range	255[c]	110–120	Winter storms, spring snowmelt	Likely high	Mixed	196–902
Sierra Nevada	350[b]	103–128	Spring snowmelt, rain on snow	Likely high	Mixed	106–258

[a] See Table 2 for details.
[b] Minear and Kondolf (2009), volumes converted to mass using bulk density conversion factor of 1.6.
[c] Benda et al. (2004).

precipitation that averages 110 to 120 cm y^{-1}. The riparian forest community is comprised of mixed conifers dominated by ponderosa pine and includes sugar pine, Douglas-fir, incense cedar, and white fir. Riparian deciduous species include white alder, Pacific dogwood, big leaf maple, and black oak. Cascade Range geology in the vicinity of the study areas includes gently sloping volcanic tablelands interspersed with volcanoes and their remnants, including Lassen Peak and Brokeoff Mountain (Harden, 1997). The harder rocks, gentler terrain, and flows moderated by snow melt and low runoff spring-fed systems appear to produce lower erosion rates in comparison to the Klamaths and Coast Ranges. In a previous study, we estimated an erosion rate of 255 t km^{-2} y^{-1} for Judd Creek, one of the two Cascade sites in this study, where most of erosion is predicted to occur following fires (Benda et al., 2004) (Table 1).

2.4. Sierra Nevada

Study locations in the Sierra Nevada Province included tributaries to the Yuba, American, Calaveras, and Stanislaus Rivers (Fig. 1). The Sierra's climate is characterized by cold winters and moderate annual precipitation that occurs as both rain and snow, primarily between late fall and early spring, and averages from 103 to 128 cm y^{-1}. Unlike the other geomorphic provinces in this study, Sierran annual peak flows generally occur during the spring snowmelt, while mid-winter rain on snow events have produced all the largest floods in major Sierra Nevada rivers (Kattelmann, 1996). The riparian forest community in the study areas is comprised of mixed conifers, including ponderosa pine, sugar pine, Douglas-fir, incense cedar, white fir, Lodgepole pine (*Pinus contorta*), and jeffrey pine (*Pinus jeffryi*). Noble fir (*Abies procera*) and red fir (*Abies magnifica*) are also present at higher elevations of some areas, while giant sequoia (*Sequoiadendron giganteum*) is dominant in the old-growth (unmanaged) site. Riparian deciduous species include varying proportions of willows, alders, maples, Pacific dogwood, and occasional black cottonwood (*Populus trichocarpa*). The Sierra Nevada is a tilted fault block composed of granitic, metamorphic, and volcanic rocks. The snowmelt-moderated peak flows and harder rocks of the Sierra Nevada appear to produce lower erosion rates (350 t km^{-2} y^{-1}; Minear and Kondolf, 2009) in comparison to the Klamaths and Coast Ranges (Table 1). Post-fire erosion likely plays a major role in sediment supply (e.g., Ahlgren and Ahlgren, 1960).

3. Methods

3.1. Wood recruitment

We evaluated wood recruitment to streams using a wood budget (Benda and Sias, 2003), where the mass balance of wood is governed by input, output, and decay, a relationship expressed as

$$\Delta S = [I\Delta x - L\Delta x + (Q_i - Q_o) - D]\Delta t \quad (1)$$

where ΔS is a change in storage volume within a reach of length Δx, over time interval Δt. Change in wood storage is a consequence of wood recruitment (I); loss of wood from overbank deposition in flood events and abandonment of jams (L); fluvial transport of wood into (Q_i) and out of (Q_o) the segment; and in situ decay (D) (Benda and Sias, 2003).

Total wood input (I) can be summarized as

$$I = I_m + I_f + I_b + I_l + I_e \quad (2)$$

including tree mortality by suppression, disease, senescence, or sporadic blowdown (I_m); toppling of trees following stand-replacing fires and windstorms (I_f); inputs from bank erosion (I_b); wood delivered by landslides, debris flows, and snow avalanches (I_l); and exhumation of wood buried in the bed or bank or the recapture of wood previously deposited on the banks (I_e).

Table 2
Physical characteristics of streams and forests for the nine region-forest groups; these characteristics cover the 76-km of streams that were used to evaluate wood storage and recruitment in basins <30 km^2.

Geomorphic province and forest management	No. of reaches (sites)	Total survey length (km)	Drainage area (km^2)		Stream gradient (%)		Stream channel width (m)		Riparian biomass density (m^3 ha^{-1})		Annual forest growth (m^3 ha^{-1} yr^{-1})
			Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean
Coast—unmanaged	5	4.5	16.8	8.2	2.6	2.3	15.8	1.6	3941	1627	-
Coast—managed	34	20.7	6.4	6.9	6.7	8.1	4.9	3.5	490	409	1.52[a]
Klamaths—less managed	7	8.5	11.0	9.2	10.1	5.0	6.0	2.2	671	348	0.75[b]
Cascades—unmanaged	3	4.2	19.6	9.4	7.4	3.7	7.3	2.6	902	363	-
Cascades—less managed	2	0.9	23.5	3.2	9.3	9.8	5.7	1.5	196	42	0.75[b]
Cascades—managed	6	5.5	6.0	5.9	8.8	5.9	3.5	1.2	596	129	0.79[b]
Sierras—unmanaged	1	2.0	5.8	–[c]	3.8	–	4.4	–	-[d]	-	-
Sierras—less managed	2	5.2	16.3	5.6	2.7	0.4	4.0	1.1	258[e]	72	0.93[e]
Sierras—managed	17	24.3	10.0	10.4	5.2	3.1	4.4	3.0	106[e]	95	0.71[e]

[a] Estimate not based on site-specific data, as a proxy we used data from Waddell and Bassett (1996).
[b] Estimate not based on site-specific data, as a proxy we used data from Waddell and Bassett (1997a) that combines the Klamaths and the Cascades into one region, including areas east into the Modoc Plateau.
[c] Only one reach sampled.
[d] No data.
[e] Estimate not based on site-specific data, as a proxy we used data from Waddell and Bassett (1997b) that combines the Sierras with areas west of Sacramento.

We focused solely on wood recruitment (I). Thus, we ignored over bank deposition of wood and jam abandonment (L) and did not analyze wood flux by fluvial transport (Q). Loss of wood from overbank deposition and fluvial transport likely was small because we limited our analysis of wood storage and recruitment to smaller basins with drainage areas <30 km^2 (76 km of channels; Table 2). We did assess certain aspects of fluvial transport of wood (such as spacing between log jams) and used an additional 19 km of surveys from larger basins (95 km of channels combined) and a transport model (Benda and Sias, 2003) to predict mean transport distance over the lifetime of the pieces (see next section). Although we observed (but did not measure) exhumation of buried wood in debris flow and alluvial deposits in coastal streams, we set I_e to zero because we could not date the partially buried wood (necessary for estimating recruitment rates). Because decay of wood mass occurs primarily through loss of density rather than volume (Hartley, 1958), we omit loss of volume from decay in Eq. (1) as such loss would be insignificant during our budget periods of up to four decades, where maximum decay classes are 20 to 42 years for deciduous and conifer trees, respectively (see later). Moreover, in the 95 km of streams surveyed in this study, we only observed loss of wood volume in highly decayed rotten wood; most rotten wood could not be identified to a recruitment source and therefore is not included in the recruitment rate calculation (see later). Our study sites did not include areas of recent fires and thus post-fire toppling of trees (e.g., Harmon et al., 1986; Bendix and Cowell, 2010). We also did not encounter concentrated toppling from intense windstorms (e.g., Reid and Hilton, 1998). Given these constraints, Eq. (1) reduces to

$$\Delta S/\Delta t\Delta x = (I_m + I_b + I_l). \quad (3)$$

Although wood recruitment can be calculated using channel length or area, we use channel area to normalize wood volumes for channels of different sizes. As the stream width increases, a larger portion of tree and volume will intersect the stream. Consequently wood volumes per channel area account for increasing wood volume with increasing channel width, where as wood volumes per channel length do not. Using wood volumes per area (where wood volume is only measured within the bankfull channel boundaries) allows for a comparative analysis across channels of different sizes across the four physiographic regions. We also report wood storage per unit channel length.

3.2. Fluvial transport of wood

Fluvial transport and redistribution of wood in streams are important when considering the role of headwater streams (nonfish-bearing) on the wood supply to larger, fish-bearing channels. We applied a wood transport model (Benda and Sias, 2003) in order to examine how a few landscape factors (channel size, tree size, jam spacing, and jam longevity) impose constraints on wood transport.

In that model, the transport distance (ξ) over the lifetime of wood is predicted by:

$$\xi(x,t) = L_j * \left(T_p/T_j\right) * \beta^{-1}(x,t) \quad for\ T_p \geq T_j, \quad (4)$$

where ξ is the mean transport distance [m] over the lifetime of a piece of wood; L_j is the average distance between transport-impeding jams; T_p is the lifetime in years of wood in fluvial environments; T_j is jam longevity in years; and β is the proportion of channel spanned by a jam (Benda and Sias, 2003). In this derivation, transport is limited to interjam spacing, and it can become a multiple of jam spacing (L_j) when the lifetime of mobile wood exceeds jam longevity (T_j). We estimate jam longevity (T_j) from the average age of key pieces forming jams in a reach (see wood age estimates later). In the absence of measurements on how wood transport is affected by the proportion of a channel spanned by a jam, transport of wood is assumed to be inversely and linearly proportional to the ratio of piece length (L_p, pieces creating jams) to channel width (w) ($\beta = L_p / w$) (for additional details see Benda and Sias, 2003).

3.3. Field data collection and analysis

We surveyed all pieces of wood within the bankfull channel that were ≥10 cm in diameter (as measured in the middle of the log) and 1.5 m in length (after Sedell and Triska, 1977). Wood storage is reported in volume rather than number of pieces. Wood volume was calculated as a cylinder, using the piece length within the bankfull channel and the diameter at the midpoint of the piece. Volumes of root wads were not included, and consequently wood volumes of such pieces are underestimated. For each recruited wood piece, the perpendicular slope distance from the bankfull channel edge to its source (e.g., bank erosion scarp, base of tree for mortality, top of landslide scarp) was measured using a laser rangefinder. To estimate recruitment rates of wood, the process by which each piece of wood entered the channel

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was identified (recruitment wood) for a subpopulation of all pieces (those where the source could be identified). Wood pieces were assigned one of four source categories: bank erosion (rootwad attached and bank erosion scarp evident), mass wasting (streamside landslide, earth flow, debris flow), mortality (senescence, disease, or blow down), or logging (saw marks). Pieces of wood that formed wood jams (the accumulation of at least two pieces that blocked at least a third of the channel) were noted as 'key' pieces (e.g., Bisson et al., 1987).

Where possible, the age of recruited wood (time since it was recruited to the stream) was dated directly from dependent saplings by counting their growth rings using an increment borer, or the bole or primary stem of the dependent sapling was cut with a saw and rings were counted. A count of branch nodes was also used to age woody vegetation growing near or on trees and overturned stumps. In total, we aged 489 pieces of wood that were also used to develop relationships between wood decay class and age (see results later). The age of most recruited wood surveyed could not be determined directly and was assigned a decay class using a modified version of a snag classification system developed by Hennon et al. (2002). Ages were later assigned to these pieces based on the age–decay class relationships. Decay class categories included: (i) wood with leaves or needles still intact, (ii) wood with twigs intact (no needles), (iii) wood with full branches, (iv) wood with primary branches, (v) wood with partial primary branches (nub), (vi) hard (solid) wood with no branches, and (vii) rotten wood with no branches. When calculating the age–decay class relationships, we distinguished between humid coastal forests and the other three drier inland regions because of climate differences that may affect decay rates; we also differentiated between conifer and deciduous trees. We did not differentiate decay classes by tree species because it was often difficult to identify the species of older wood and because the sample size of some species was limited.

To estimate Δt in Eq. (3), the arithmetic mean age of recruited wood in the study reach was used. The proportion of wood in each decay class was based on number of trees, rather than on volume, to reduce the variability in Δt that can arise from variations in the temporal sequence of smaller or larger tree recruitment. Preferentially weighting the oldest wood in the calculation of Δt (e.g., Murphy and Koski, 1989) may yield an overestimate in the mean age of recruited wood. By using an arithmetic mean, this error is countervailed by the loss of wood with increasing age, a process that would tend to underestimate the mean age. While this error is not quantified, it is likely similar or smaller than errors typically encountered in mass transfer budgets in watersheds, such as in sediment budgets (e.g., Dietrich and Dunne, 1978).

In this study, residence time refers to the length of time wood remains within a given reach. We estimated the residence time (turnover time) of wood in streams by dividing the total volume of wood (excluding logging-related wood) by the recruitment rate (e.g., Lienkaemper and Swanson, 1987). This calculation assumes equivalence between the input and output of fluvially transported wood. Because estimates of wood recruitment are minimums considering that some transport of wood occurs (and input may not always equal output over short time periods), residence times likely represent minimum values (e.g., Wooster and Hilton, 2004).

The relative proportion of wood by volume that entered streams from varying distances away from channel banks is estimated. The resulting cumulative distributions are referred to as 'source distance curves' (McDade et al., 1990; Robison and Beschta, 1990). Distances to each source of wood were used to construct curves for each study segment and aggregated for each region-forest management group.

Channel morphology was characterized every 100 to 200 m within the study segment reaches, including stream gradient using a laser rangefinder or clinometer. Bankfull width was estimated using a tape or laser range finder. The effect of stream wood on formation of pools

Table 3
Summary of stream wood characteristics for the nine region-forest groups; these characteristics cover the 76-km of streams that were used to evaluate wood storage and recruitment in basins <30 km^2.

Geomorphic province and forest management	% of recruit wood volume		Mean recruit wood diameter (m)	% of total wood storage volume by process			Total wood storage volume per stream area (m^3 ha^{-1})			Total wood recruitment rate (m^3 ha^{-1} y^{-1})		Residence time of wood in streams (years)
	Conifer	Deciduous		Unknown process	Known process (recruit)	Logging (cut)	Mean	σ	CV (%)	Mean	σ	
Coast–unmanaged	77	23	0.85	79	21	0	845	923	109	5.0	4.1	168
Coast–managed	74	26	0.43	57	20	22	1059	1545	146	11.4	15.1	71
Klamaths–less managed	90	10	0.43	42	54	4	190	160	84	9.7	11.7	19
Cascades–unmanaged	94	6	0.41	39	60	1	13	10	77	6.5	3.5	2
Cascades–less managed	17	83	0.18	45	55	0	54	45	83	8.7	9.3	6
Cascades–managed	90	10	0.33	32	53	15	107	136	127	8.6	14.6	13
Sierras–unmanaged	89	21	0.40	40	59	1	166	114	69	7.6	–[a]	–
Sierras–less managed	98	2	0.40	39	52	9	65	84	129	1.2	0.4	48
Sierras–managed	91	9	0.34	49	37	14	226	289	128	9.2	19.4	20

[a] Only one reach sampled.

(with a residual depth over 0.5 m) was inventoried as well as other pool-forming elements including bedrock, boulder, or hydraulic scour or forcing (associated with outside meander bends or side channels and tributary confluences).

4. Results and discussion

4.1. General patterns of wood in streams

A principle study objective was to evaluate the patterns in wood storage and recruitment to improve understanding and management of wood in northern California streams. Only a portion of all wood pieces across all regions could be directly linked to a recruitment process (range 20–60%, average 46%; Table 3) and thus wood recruitment rates and recruited wood storage volumes are based on a subsample of pieces. Volumes of total wood storage (conifer and deciduous combined) comprise all sources, including recruited, unknown, and logging-related wood. Overall, conifers dominated recruited total wood storage (mean 88%) with the exception of the Cascades, less-managed forest site where deciduous trees accounted for 83% of the in-stream wood volume (Table 3). Average diameters of recruited trees in the coastal sites ranged from 0.5 to 1.7 m. Average diameters of recruited trees were similar across the Klamaths, Cascades, and Sierras (range 0.33–0.9 m; Table 3), with the exception of the Cascades, less-managed forest group with an average diameter of 0.18 m, reflecting the dominance of deciduous trees at this site. Logging-related wood averaged 7% across all sites, with 22% occurring in coastal managed forests. Most of the logging-related wood in coastal channels appeared to be a legacy of tractor logging that occurred prior to 1970s forest practice regulations. We also observed extensive incision of low

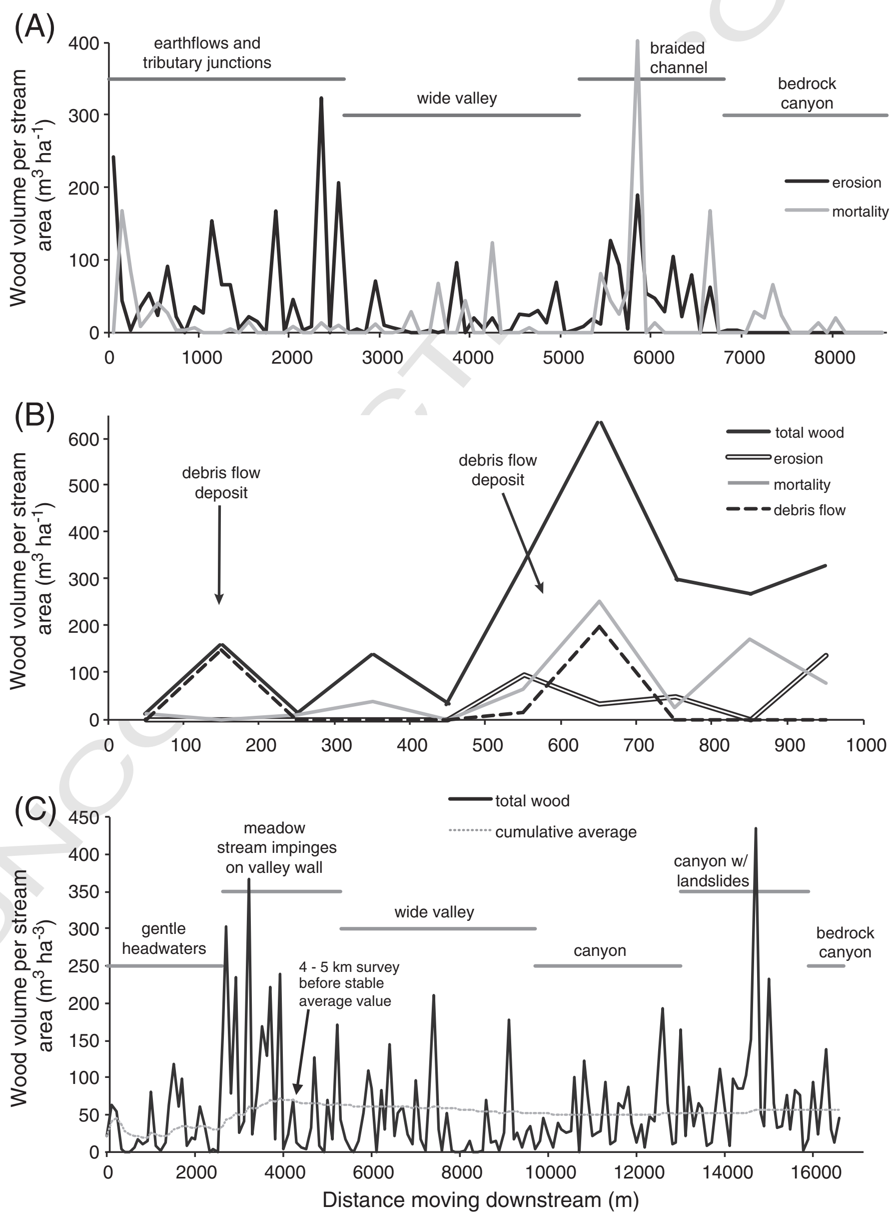

Fig. 2. Longitudinal plots of stream wood volumes by process and the local influences on recruitment processes, including earthflows, debris flows, tributary junctions, wide valleys, bedrock canyons, and braided channels. Three example stream segments from the (A) Sierras, (B) Klamath Mountains, and (C) Sierras are shown. Total wood volume included in stream wood that was not linked to a recruitment process.

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order coastal streams, another result of legacy tractor logging where small streams were filled with slash and sediment for use as skid trails, landings, and roads (Burns, 1972). While gullying of low order coastal channels is also associated with nineteenth century logging, when stream wood was removed from channels to allow oxen and steam donkeys to drag cut logs down the channel (Reid et al., 2010), the incision we observed was primarily in response to filling of streams during tractor era logging.

4.2. Spatial variation in stream wood storage and recruitment

Processes and volumes of recruited wood were highly variable across all study sites (wood volumes coefficient of variation range 69–146%; Table 3) caused by variations in geology, topography, valley width, and channel morphology along a study reach. For example, along a continuous 8000-m segment of Pilot Creek (Sierra Nevada), high wood recruitment resulted from localized bank erosion along streams bounded by earthflows and from elevated tree mortality from floodplain aggradation in braided channel sections (Fig. 2A). In contrast, zones of low wood recruitment occur where bank erosion is lower in more stable valley and canyon sections with more competent banks, including bedrock banks. Spatially variable wood storage is also driven by wood recruitment from debris flows originating in steep headwater channels. Along a 1000-m reach in the Klamath Mountains, wood from two debris flow deposits accounted for 27% of the recruited wood volume concentrated along 100–200 m channel reaches (Fig. 2B). The strong influence of local geology and valley width controls on the spatial distribution of wood recruitment processes and volumes often becomes more apparent with longer continuous surveys. This is best illustrated along a 16-km survey of Haypress Creek in the Sierras, where stream wood volumes decrease in wide valleys and peak near earthflows (Fig. 2C). Here, wood storage can vary by three orders of magnitude, a finding consistent with other long continuous wood surveys (e.g., Marcus et al., 2011; Wohl and Cadol, 2011). These observations add to the growing recognition of strong local geomorphic process controls on the spatial variation of wood in streams, including valley width (geometry), mass wasting, and tributary confluences (e.g., Benda and Sias, 2003; Comiti et al., 2006; Bigelow et al., 2007; Wohl and Cadol, 2011; Rigon et al., 2012). Forest management history may also influence the spatial distribution of wood in streams (e.g., Czarnomski et al., 2008); however, detailed harvest histories were not available for our sites to make such evaluations.

We did not detect a clear relationship between wood volumes and channel size (width and drainage area) or channel gradient. While early wood studies with short surveys found a relationship between channel size and wood volumes (e.g., Bilby and Ward, 1989), our findings are more consistent with longer continuous surveys that found no such correlation (e.g., Wohl et al., 2004; Marcus et al., 2011). One exception occurs in managed coastal forests, where wood recruitment from bank erosion was greater in small basins (<4.5 km^2) compared to larger watersheds (4.5–30 km^2) ($p < 0.13$, Mann–Whitney test). This may be caused by historical tractor logging in which headwater coastal streams were often filled with slash and soil to create skid trails, roads, and landings (Burns, 1972). As a result, many of these low order coastal streams are now highly incised (gullied) and disconnected from their floodplains, with actively eroding banks that undercut and recruit trees to the channel.

Wood recruitment processes do not appear to vary by channel size (basins < 30 km^2) in our study because spatial variation in wood recruitment processes is driven primarily by local variation in watershed attributes such as earthflows, debris flows, streamside landslides, valley width, channel morphology (e.g., braided channels), tributary junctions, and canyons (Fig. 2). Many of these upland and riverine controls on wood recruitment are distributed in watersheds based on geology, topography, and river network characteristics of individual watersheds. As one consequence of the high spatial variation in wood volumes and their local controls, setting targets for and monitoring stream wood volumes (e.g., Fox and Bolton, 2007) may be dubious or require very long continuous surveys. For example, variable wood volumes in Haypress Creek (83% coefficient of variation) do not converge on a stable mean value until 4–5 km (Fig. 2C). Temporal variation in pulses of wood õrecruitment from wind, floods, and following wildfire (e.g., Mondry, 2004; Kaczka, 2009; Marcus et al., 2011) further complicates using 'reference conditions' for stream wood. Alternatively, targets and monitoring may be more appropriate and feasible for riparian forest stands (e.g., Pollock et al., 2012), the source of stream wood.

4.3. Regional wood patterns

4.3.1. Regional patterns in wood storage volumes

Wood volumes in streams were fairly similar across regions of northern California with the exception of the Coast Ranges (Fig. 3A). There is significantly more wood storage per unit area in the coast-forest groups compared to inland groups ($p < 0.01$, Mann–Whitney test). Total stream wood storage averaged 850 to 1100 m^3 ha^{-1} in both unmanaged and managed coastal forests compared to 200 m^3 ha^{-1} or less in the Klamaths, Cascades, and Sierras (Fig. 3A). On average, the coastal groups have 5 to 20 times higher (up to 3 orders of magnitude) stream wood storage compared to inland areas (Table 3; Fig. 4). The high wood storage in unmanaged coastal forests is driven in part by the massive size of coast redwood trees (biomass density up to 10,000 m^3 ha^{-1}; Westman and Whittaker, 1975) and slow decay, resulting in long stream residence time (168 years; Table 3). Forest biomass is lower in coastal managed forests (490 m^3 ha^{-1}), but the high wood storage there (compared to inland areas) may be related to higher growth rates (Table 2), longer residence times of stream wood (71 years; Table 3), and the considerable contributions of historical logging slash and mass wasting to the total wood volume (22% and 25%, respectively; Table 3, Fig. 5). In summary, the substantially higher stream wood volumes in the Coast Ranges create a decreasing trend in volumes from the coast eastward to Klamaths, Cascades, and Sierra regions in concert with decreasing riparian forest biomass density, wood residence times (Fig. 4), forest growth (productivity) rates (Table 2), erosion rates (Table 1) and associated wood contributions from landslides (Fig. 5), and amounts of logging slash (Table 3). Of all these factors, higher forest biomass and growth rates (productivity) of redwood forests (Table 2) are likely the primary driver of higher wood volumes in coastal streams compared to inland areas.

4.3.2. Regional patterns in wood recruitment rates and processes

Wood was recruited to streams by a variety of processes (mortality, bank erosion, landsliding) across all regions, with landslide recruitment more common in the coastal and Klamath regions (Fig. 5). Wood recruitment rates represent the rate of supply of wood to streams over time and require an estimate of the wood age. For coastal sites, we combined age data from the northern redwood region contained in Benda et al. (2002) with data from the southern coastal sites that yielded 140 aged pieces for conifers and 40 pieces for deciduous trees. The mean ages for seven decay classes of conifer and deciduous trees individually ranged from 1 to 48 years (unpooled data; Table 4). As a result of variable decay rates, several age–decay classes overlapped. These classes were pooled to create four decay classes with different mean ages ($p < 0.25$, Tukey HSD) (pooled data; Table 4). Mean ages for recruited wood in the Klamath, Cascade, and Sierra geomorphic provinces (combined: 225 conifer and 84 deciduous pieces) ranged from 1 to 40 years. The 7 decay classes were also pooled into 4 classes (Table 5), similar to the coastal sites. Note that older rotten stream wood was not included in the

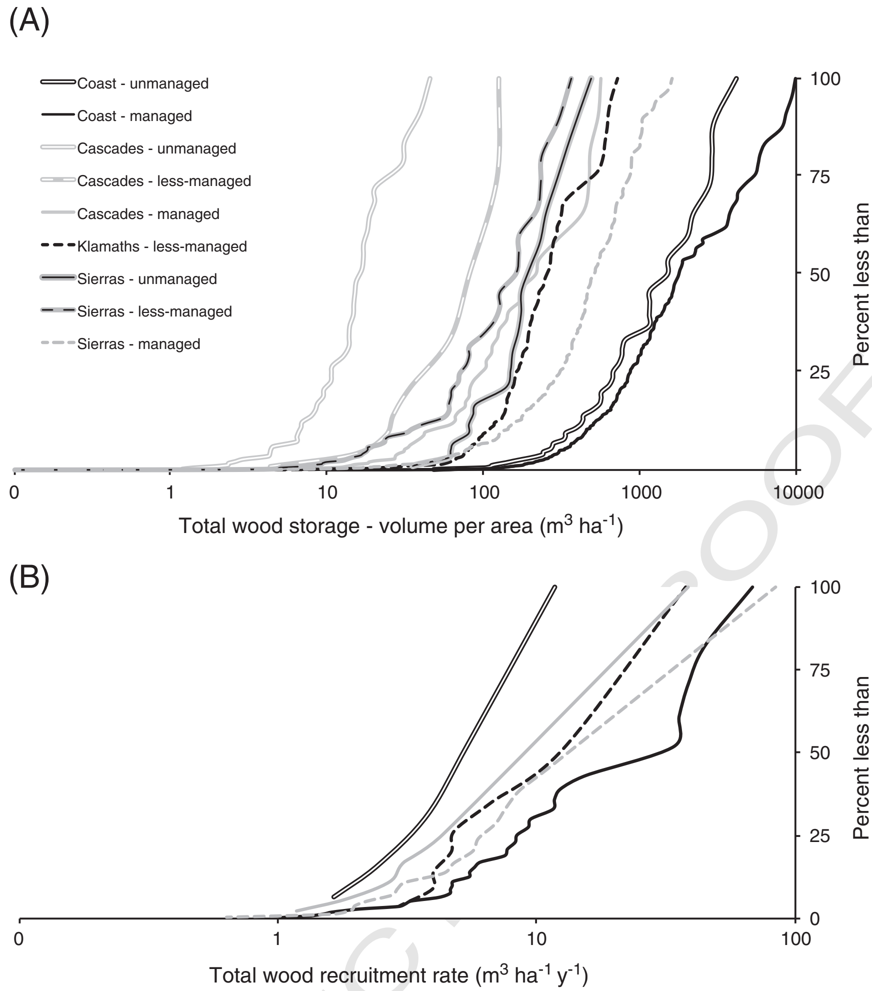


Fig. 3. Cumulative distributions of (A) total wood storage (per unit channel area) and (B) total wood recruitment rate are plotted according to region-forest management groups. At least five reaches were required for calculating distributions of recruitment rates, a number only available in five region-forest groups.

rate calculation because it could not be identified to a recruitment source, hence the rates reflect more recent recruitment of wood to streams.

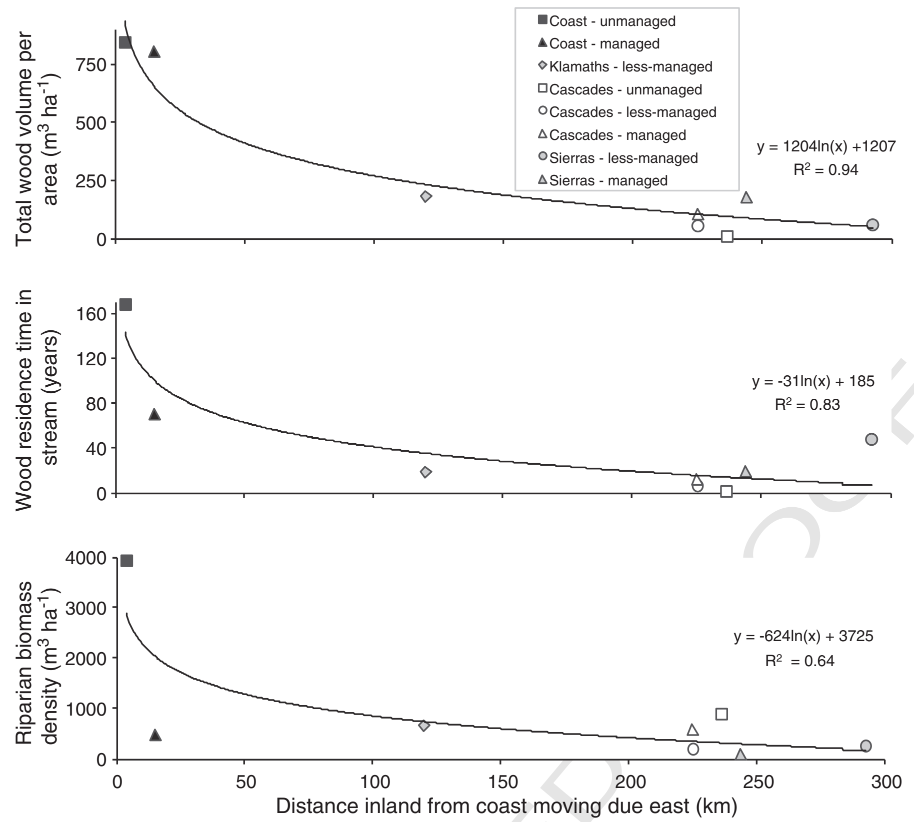
Because recruitment rates are calculated for each forest management group (involving multiple reaches), the sample size for recruitment rates is smaller than wood storage volumes (calculated at individual 100-m reach intervals). Consequently, for statistical comparisons, region-forest groups needed at least five sites, leaving Coast unmanaged and managed forests, Klamath less-managed forests, Cascades managed forests, and Sierras managed forests (Table 2).

Wood recruitment by bank erosion is important across all regions, ranging from 22 to 63% of the total recruitment rate (Fig. 5A). Because conifer trees dominate in riparian forests, forest mortality was typically higher for conifers compared to deciduous, with the exception of the Sierras (Table 6). Wood recruitment rates from mortality were also substantial across all regions, comprising 37–78% of the total wood recruitment rate (Fig. 5A). Wood recruitment by landsliding occurred in the coastal, Klamath and Cascade regions, ranging from 11 to 22% of total recruitment (Fig. 5A). Wood recruitment by landsliding contributes to the high overall wood recruitment rates in the coastal unmanaged and managed forests, as well as in the Klamath and Cascade less-managed forests (Fig. 5). We observed wood recruitment by landsliding in Sierra streams, but only in drainage areas beyond the 30-km^2 study limitation for analysis of wood volumes and recruitment (Fig. 2C). These larger basins were not analyzed for wood recruitment and storage to minimize the effects of fluvial redistribution; however, they were analyzed for wood transport (see later).

Similar to the differences in wood storage volume between coastal forests and inland sites, wood recruitment rates between the two areas also varied (Fig. 3). The coastal managed forests had the highest recruitment rates reflecting relatively large inputs from mass wasting (Fig. 5A). Coastal unmanaged forests had the lowest recruitment rates reflecting low forest mortality rates (e.g., Benda et al., 2002), despite very high biomass densities (Table 2). The remaining inland groups (Cascade managed, Klamath less-managed, and Sierra less-managed) had similar rates, although Sierra managed had the highest rates (Fig. 3B).

4.4. Distances to sources of wood

Source distance curves quantify the proportion of riparian wood delivered according to distance away from the channel edge by bank erosion, forest mortality and landsliding (McDade et al., 1990; Van Sickle and Gregory, 1990). Shapes of source distance curves are strongly influenced by the processes of wood recruitment, particularly at the reach scale (Benda et al., 2002). For example, a majority of wood volume is recruited close to the channel edge where bank erosion dominates



Q2 **Fig. 4.** Coastal to inland (west to east) plots of (A) total wood storage, (B) stream wood residence time, and (C) riparian forest biomass in northern California. Total wood volumes shown here exclude unnatural sources from logging (cut wood). The Sierras unmanaged site is omitted because of the absence of forest biomass information.

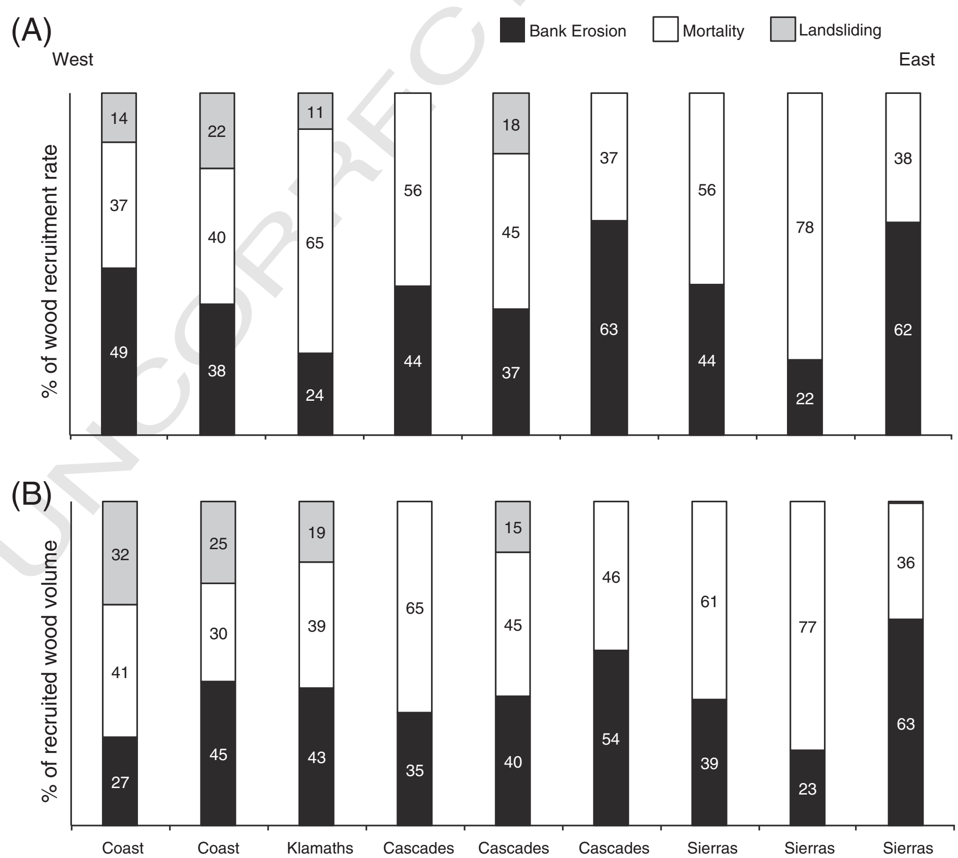


Fig. 5. The proportion of (A) wood recruitment rates by process and (B) recruited wood volume across the nine region-forest management groups in northern California.

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Table 4
Age statistics for stream wood decay classes in the Coast Range; age of decay classes was determined from dependent saplings and other indicators and used to assign ages to recruited wood, mean age values in years.

Unpooled				Pooled			
Decay class	Mean	σ	n	Class	Mean	σ	n
Conifers							
Needle[a]	1.0	–	–	Needle[a]	1.0	–	–
Twig	4.1	1.5	12	Twig, branch	5.0	2.4	25
Branches	5.9	2.7	13	Primary, nub	17.9	15.1	30
Primary branches	10.0	10.5	15	Hard, rotten	42.4	27.6	85
Nub	25.7	15.0	15				
Hard	41.2	27.6	70				
Rotten	47.9	27.8	15				
Deciduous							
Leaf[a]	1.0	–	–	Leaf[a]	1.0	–	–
Twig[b]	4.1	1.5	12	Twig[b], branch	4.4	1.8	19
Branch	5.1	2.1	7	Primary, nub, hard	11.2	6.4	13
Primary branches	10.0	0.0	2	Rotten	20.5	14.3	8
Nub	9.0	0.0	1				
Hard	11.6	7.3	10				
Rotten	20.5	14.3	8				

[a] Age of needle and leaf decay classes are assumed to be 1 year.
[b] Twig decay class data was not available for deciduous trees, so conifer data was used as a surrogate.

(Fig. 6A and B). Mortality recruitment extends the source distance curves away from the channel edge. Landslides extend the curves even farther from the channel up the hillslopes. Forest management histories and thus tree age and height influence the source distance; managed forests with smaller trees have shorter source distances compared to less-managed and unmanaged forests with taller trees (Fig. 6B). In managed forests of the Sierras and Cascades where no landslides were encountered, 90% of the wood originates from within 10 m of the channel; the remaining 10% is supplied from a distance equivalent to one tree height. We did not observe increased blowdown of trees from narrow buffers that may influence source distance curves. Rather, short source distances are related to bank erosion that dominates wood recruitment in managed forests of the Sierras and Cascades (62% and 63%, respectively; Fig. 5A). Shorter source distances are also found in deciduous forests. For example, 77% of wood recruited in the Cascades, less-managed forests is from deciduous trees (Table 3), where recruitment from mortality is limited by small deciduous trees that skew the source distance curves closer to the channel (Fig. 6C). In contrast, 90% of the wood originates from within 30 m of the channel in managed coastal forests (Fig. 6D), where landslides comprise 22% of the recruitment rate (Fig. 5A). In less-managed forests with taller trees and smaller contributions from landslides (0–18% of recruitment rate; Fig. 5A), 90% of the wood is derived from within 15 to 35 m of the channel (Fig. 6C). In unmanaged and taller coastal redwood and Sierran sequoia forests, the source distance for 90% of wood recruitment is between 35 and 50 m (Fig. 6C).

Overall, regional variability in source distance curves is driven primarily by tree height, where the taller trees of the coastal redwood area have the greatest source distance (Fig. 6), with site potential tree (old growth) heights of 80 m (270 ft) or taller (Viers, 1975). Reach to watershed scale variation can be influenced by forest age, where managed (younger) forests have shorter source distances (Fig. 6C and D). Otherwise, reach-scale variation in wood recruitment processes (bank erosion, landsliding and mortality) governs variation in source distances (Fig. 6A and B). The occurrence of deciduous forests can dramatically shorten the source distances, driven by the concentration of deciduous trees located near channels.

4.5. Recruitment of key pieces forming wood jams

The majority of key pieces in managed forests are recruited by bank erosion (60–70%), while mortality supplies just over half of key pieces to streams in unmanaged forests (51–52%) and the remaining portion coming primarily from bank erosion (Fig. 7). Streamside landsliding is locally important in recruiting key pieces of wood in the coastal, Cascades, and Klamath Mountains (up to 25%). Data are not available on key pieces in unmanaged coastal forests.

The diameter of key pieces of wood that form log jams ranged from about 0.3 m to > 1.5 m and averaged 0.72 m (Fig. 8). The majority of key pieces with diameters > 0.8 m are located in the coastal unmanaged and coastal managed regions, indicating the importance of large trees and the legacy of large older logs left in streams following mid-twentieth century logging (Table 3).

4.6. Wood formation of pools

Pools in all study reaches (except in the Klamaths, no data) were associated with one of four pool-forming processes: hydraulic scour (outside meander bends, tributary, and side channel confluences), bedrock, boulder, and wood. Wood-formed pools averaged 35% and ranged from 9 to 78% across all region-forest management groups (Fig. 9). Two of the three highest values (> 50%) occurred in the coastal groups where channel gradients averaged 2 to 7% (Table 2). Boulder-formed pools dominated in the Cascades and boulder and bedrock pools dominated in the Sierras. Hydraulic scour pools occurred mostly in low gradient (average 2.5%) channels that meander through meadows of the Sierras, less-managed forests.

Combining the data from all regions, we found the highest proportion of wood-formed pools in association with the lowest stream power (Fig. 10A), while boulder- or bedrock-formed pools were more common in reaches with high stream power (Fig. 10B). These same relationships were also found in Oregon coastal streams (Stack, 1988). The proportion of wood- or boulder-formed pools showed no correlation with gradient or drainage area alone. While the morphology and physical processes in large channels with low slopes (pool–riffle) are fundamentally different than small channels with high slopes (step-pool) (Montgomery and Buffington, 1997), they both have low stream power where wood is more likely to deposit and potentially form

Table 5
Age statistics for stream wood decay classes in the Klamaths, Cascades, and Sierras (all combined); age of decay classes was determined from dependent saplings and other indicators and used to assign ages to recruited wood, mean age values in years.

Unpooled				Pooled			
Class	Mean	σ	n	Class	Mean	σ	n
Conifers							
Needle[a]	1.0	0.1	27	Needle	1.0	0.1	27
Twig	4.3	2.5	51	Twig, branch	5.0	3.9	85
Branch	6.2	5.3	34	Primary, nub	11.8	7.6	65
Primary branches	11.8	7.6	54	Hard, rotten	29.8	17.1	48
Nub	11.5	7.8	11				
Hard	28.0	17.3	41				
Rotten	40.3	12.3	7				
Deciduous							
Leaf[a]	1.0	0.1	25	Leaf, twig, branch	2.0	1.7	53
Twig	2.9	2.2	18	Primary, nub	6.8	4.9	22
Branch	2.8	1.8	10	Hard, rotten	12.9	11.0	9
Primary branches	7.0	3.6	13				
Nub	6.4	6.5	9				
Hard	12.8	4.7	6				
Rotten	13.2	20.6	3				

[a] Age of needle and leaf decay classes is assumed to be 1 year.

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Table 6
Wood recruitment rates from bank erosion and landsliding are shown for region-forest groups with at least 5 study segments; wood recruitment rates from mortality are shown for all groups for more detailed comparisons of mortality rates.

Geomorphic province and forest management	Conifer mortality		Deciduous mortality		Total mortality		Bank erosion		Landsliding	
	(all values in $m^3\ ha^{-1}\ y^{-1}$)									
	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Coast—unmanaged	1.3	1.3	0.5	0.8	1.9	1.6	2.5	1.7	0.7	1.6
Coast—managed	2.9	5.8	1.7	4.0	4.6	8.5	4.4	4.4	2.5	7.9
Klamaths—less managed	5.5	10.6	0.8	1.2	6.3	10.6	2.3	1.2	1.0	0.9
Cascades—unmanaged	3.2	1.7	0.4	0.5	3.7	2.1				
Cascades—less managed	0.42	0.5	3.5	3.4	3.9	3.8				
Cascades—managed	2.6	3.3	0.6	0.8	3.2	3.7	5.4	11.0	–[a]	–
Sierras—unmanaged	3.0	-[b]	1.2	-	4.2	-				
Sierras—less managed	0.9	1.0	0.004	0.03	0.94	1.1				
Sierras—managed	1.6	1.4	3.1	11.8	4.7	11.5	4.5	8.0	–	–

[a] No landsliding observed.
[b] Only a single segment surveyed.

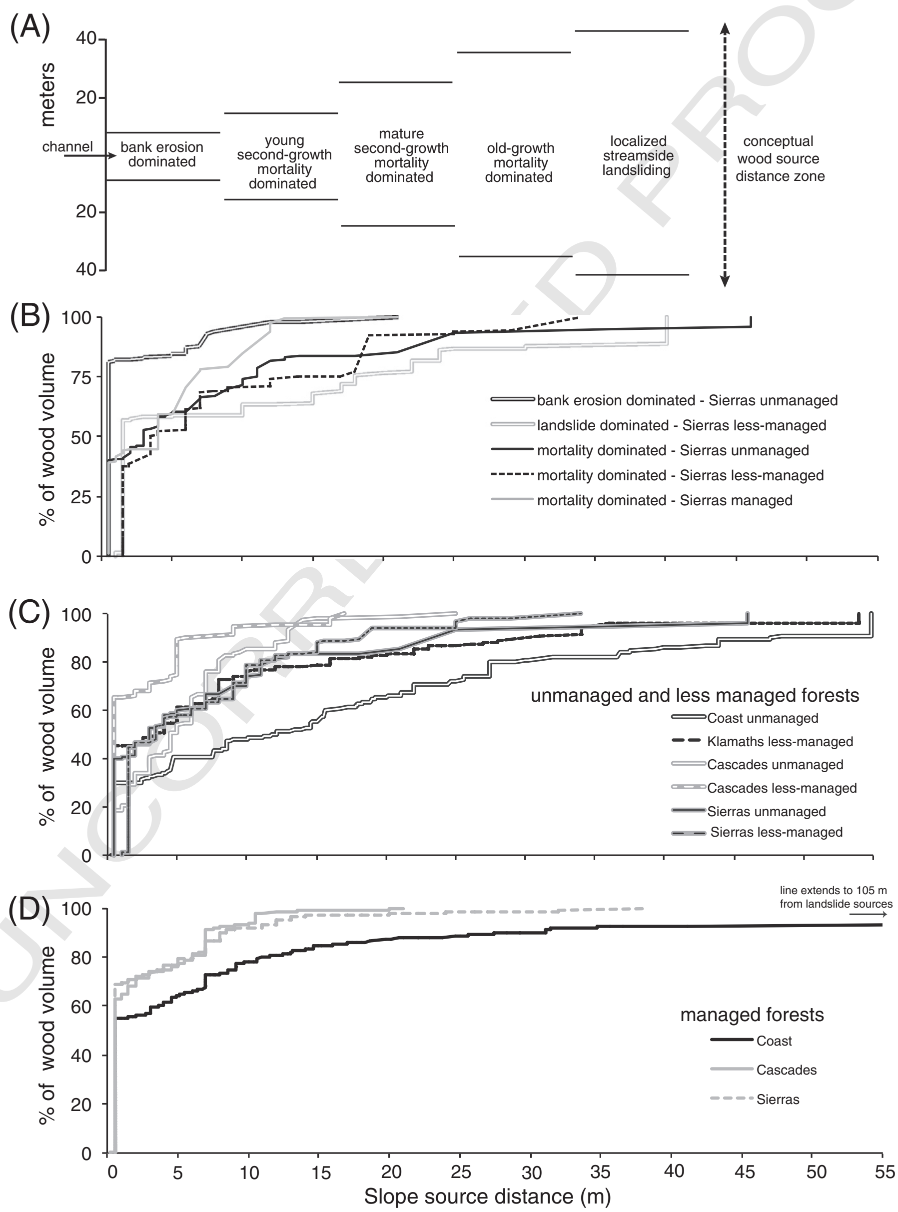

Fig. 6. (A) Conceptual planform of wood recruitment zones based on source distances for reaches dominated by various recruitment processes. The varying source distances have implications for the design on streamside protection areas. (B) Distances to sources of stream wood in Sierra reaches with different dominant recruitment processes (bank erosion, mortality, landsliding, and forest management). (C) Distances to sources of stream wood in less-managed and unmanaged forests. (D) Source distance in managed forests of the coast, Cascade, and Sierra regions. Data includes all recruitment processes including mortality, bank erosion and landsliding; landsliding occurs in coast unmanaged, coast less-managed, Klamath less-managed, and coast and Sierra managed groups.

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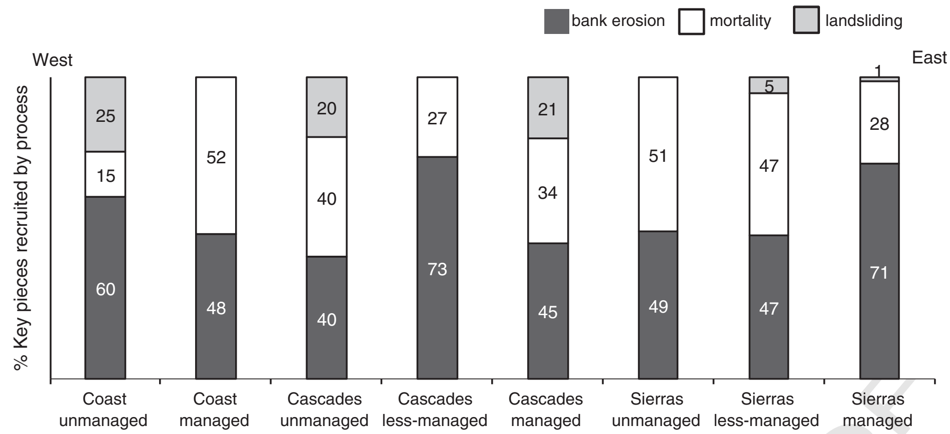

Fig. 7. Histogram showing the percentage of key pieces forming wood jams by recruitment process for each of the 9 region-forest management groups, from west to east.

pools. Other factors we did not measure may also influence the location of wood-formed pools, such as flow depth.

4.7. Fluvial wood transport patterns

We did not observe regional or management influences on patterns in wood transport, rather drainage area appeared to be the primary controlling factor on wood transport (Figs. 11 and 12). Across the four study regions in northern California, field measurements of stream wood in basins <70 km^2 indicate the distance between wood jams (<10 m in the smallest streams to several hundred meters in larger channels) increased with drainage area (Fig. 11A). Similarly, the proportion of the channel spanned or blocked by jams (100 to 30%) decreased with drainage area (Fig. 11B), and jam age (45 years to <10 years) decreased with drainage area (Fig. 11C). All of these spatial trends are anticipated in fluvial wood transport (Benda and Sias, 2003). The statistical regressions for these parameters, along with an assumed lifetime of wood in fluvial environments (T_p) of 100 years (using a $3\%\ y^{-1}$ wood decay rate; Benda and Sias, 2003), are used in Eq. (4) to predict wood transport distance. Predicted wood transport distance (over the lifetime of wood in streams) varied from <100 m to several thousand meters in channels with drainage areas of 1 to 75 km^2, with transport distance increasing with drainage area ($r^2 = 0.52$; Fig. 12A).

If fluvially mobile pieces are defined as log length less than channel width (e.g., Lienkaemper and Swanson, 1987), then the percent of mobile pieces (out of the total inventoried pieces of wood) ranged from about 30% to almost 100%, providing a weak positive correlation ($r^2 = 0.54$) between mobile pieces and drainage area (Fig. 12B).

The transport of wood by stream flow is an important consideration in the mass balance of stream wood. For example, knowing the proportion of wood in fish-bearing streams that originates from headwater channels (nonfish-bearing) could inform riparian protection strategies of such small streams. In addition, wood transport may also affect the redistribution of pieces and the formation of wood accumulations (jams), including their size and spacing. This may have implications for the formation and spatial distribution of aquatic habitats throughout channel networks.

Relative to estimating wood recruitment rates in streams, estimating fluvial wood transport distance remains a more imprecise science. In this study we applied a simple model (Benda and Sias, 2003), parameterized by field data (Eq. (4): jam spacing, proportion of the channel blocked by the jam, jam age, and wood decay), to make estimates of average wood transport distance in streams (over the lifetime of wood in streams). The results indicate that in small headwater streams (<2 km^2), average wood transport distances may range from 50 to 250 m, which is likely an overestimate considering that most headwater channels have low stream power and flow depths to move wood. Excluding potential transfer of wood by debris flows, this suggests that only the lower portion of headwater channels may transport

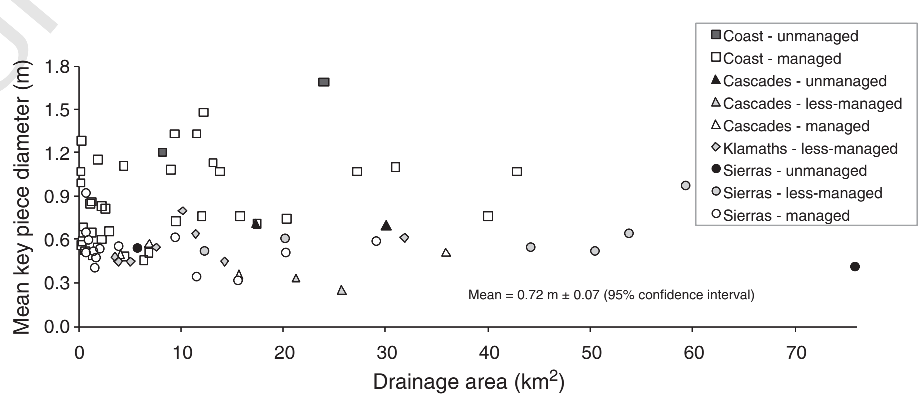

Fig. 8. Plot of the mean diameter of key pieces that create wood jams by drainage area.

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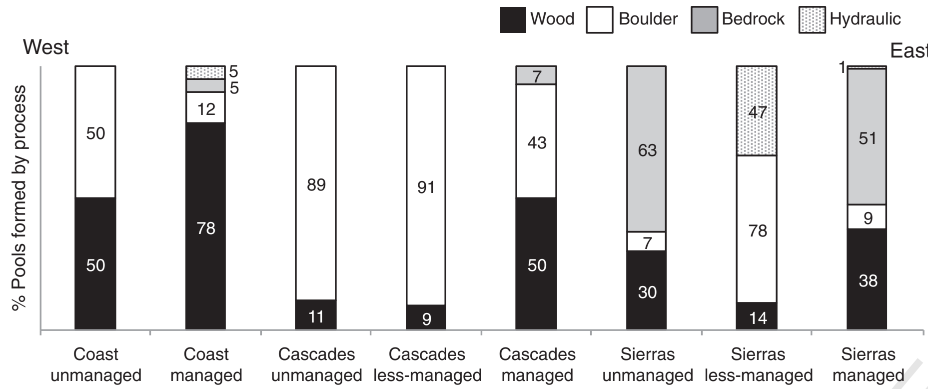

Fig. 9. Histogram showing the percentage of pools formed by process for each of the 9 region-forest management groups, from west to east.

woody debris to larger fish-bearing streams. While the relationship between transport distance and channel size is moderate ($r^2 = 0.52$; Fig. 12A), it could be used to create watershed-scale maps of wood transport to help guide field studies or riparian protection strategies. Such strategies might also consider identifying and protecting the sources of wood to headwater streams that transfer wood to larger streams by debris flows, for example using combined wood recruitment and debris flow modeling (e.g., Burnett and Miller, 2007).

In contrast to our findings on wood transport, Lassettre and Kondolf (2003) observed and modeled wood transport in a coastal stream where 90% of the wood transport distances exceeded jam spacing during flood events (≥15 years), suggesting second-order channels (drainage area 6.5 km^2) may be a more important source of wood to larger fish-bearing streams. The different findings suggest that further field measures and more sophisticated models are needed to clarify the magnitude of wood supplied from low to high order streams by fluvial transport. For example, Lassettre and Kondolf (2003) showed that jams are destroyed during certain magnitude floods or that flows overtop jams allowing wood transport past wood obstructions. Thus the parameter of jam longevity in Benda and Sias (2003) could be reduced based on flood magnitude or that effectiveness of wood capture by jams could be reduced during large floods. Further research on fluvial transport of wood at all scales is also merited because the majority of wood in streams is fluvially transported and cannot be identified by recruitment source (39 to 79% of the wood in our study; Table 3).

4.8. Forest management influences on stream wood

How does forest management affect the patterns of wood in streams? While the whole size distribution of wood pieces contributes to complex habitat, larger wood is typically more geomorphically effective and beneficial for aquatic habitat (e.g., large wood creates large pools; Rosenfeld and Huato, 2003). While smaller pieces of wood may cause some sediment storage and the creation of small steps that reduce

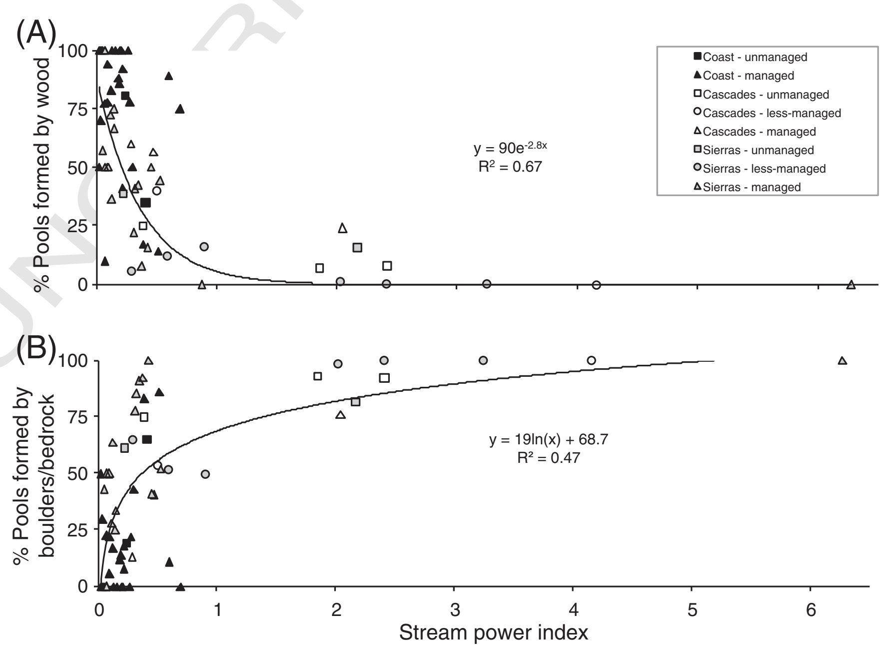

Fig. 10. (A) Relation between the percentage of wood formed by wood and stream power. (B) Relation between the percentage pools formed by boulders/bedrock and stream power. The stream power index is the product of slope and drainage area.

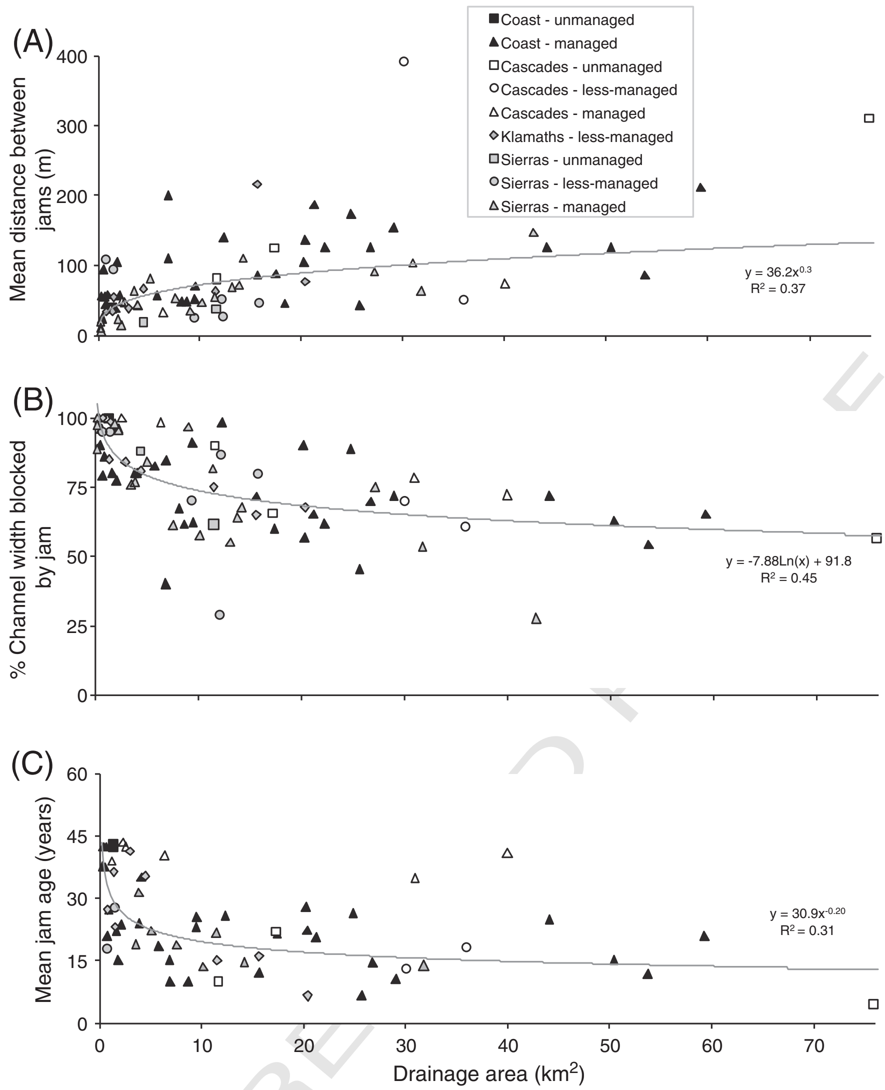

Fig. 11. Relation between drainage area and (A) the distance between log jams, (B) percent of channel blocked by jams, and (C) jam age. These relationships are used in Eq. (4) to predict average transport distances of wood in Fig. 12.

stream energy in small headwater streams (nonfish-bearing) (Jackson and Sturm, 2002), larger logs are more effective in trapping sediment in steep headwater streams that are prone to debris flows (May and Gresswell, 2003). Previous studies have documented clear differences in the size and influence of stream wood in younger (managed) and older (unmanaged) forests (e.g., Bilby and Ward, 1991; Ralph et al., 1994; Benda et al., 2002). We detected similar trends that were driven simply by the diameter and height of trees in younger and older forests. Owing smaller tree heights, managed (younger) forests in all regions have shorter distances to sources of wood compared to less-managed and unmanaged (older) forests (Fig. 8). Similarly, managed forests in all regions had the smallest diameter of recruited wood pieces (Table 3), also reflecting the smaller trees in managed forests. The recruitment of large wood pieces that create jams (mean diameter 0.7 m) is primarily by bank erosion in managed forests and by mortality in unmanaged forests (Fig. 9A). This dynamic also likely reflects the smaller riparian tree size in managed forests, where small tree tops recruited farther from the channel by mortality often do not have the girth to be an effective key piece, while trees recruited by bank erosion include rootwads and thicker trunks with more geomorphic influence on streams to create jams. In unmanaged forests, larger trees recruited by mortality do have sufficient size to be geomorphically effective key pieces that create jams.

We also evaluated how forest mortality and thus wood recruitment from mortality vary between managed and unmanaged forests. Three of the study regions have wood recruitment data spanning managed to unmanaged forests. We omit the coastal data based on the absence of a 'less-managed forest' category and because unmanaged redwood forests have very low mortality rates (e.g., 0.025% y^{-1} compared to 0.5% y^{-1} for other coastal conifer forests, e.g., Franklin, 1979). In the Cascades and Sierras, the managed forests had moderately high mortality recruitment rates that were higher than the less-managed forests (Cascades: 2.6 versus 0.42 $m^3\ ha^{-1}\ y^{-1}$; Sierras: 1.6 versus 0.9 $m^3\ ha^{-1}\ y^{-1}$), but lower than the unmanaged forests (3.2 and 3.0 $m^3\ ha^{-1}\ y^{-1}$) for the Cascades and Sierras (Table 6). This pattern may reflect the forest mortality changes that accompany forest growth in general, where managed forests have high mortality during the stem exclusion stage, while less-managed forests with vigorous growth have the lowest mortality, and unmanaged (older) forests with increasing senescence have the highest mortality rates (Spies and Franklin, 1988). Because these rates are back-calculated (e.g., Benda and Sias, 2003) and therefore preliminary, more direct measurements of mortality rates in forests would advance our understanding about how forest age influences wood recruitment rates.

The temporal pattern of mortality rates indicates that although mortality may be higher in managed forests, the wood recruited to the

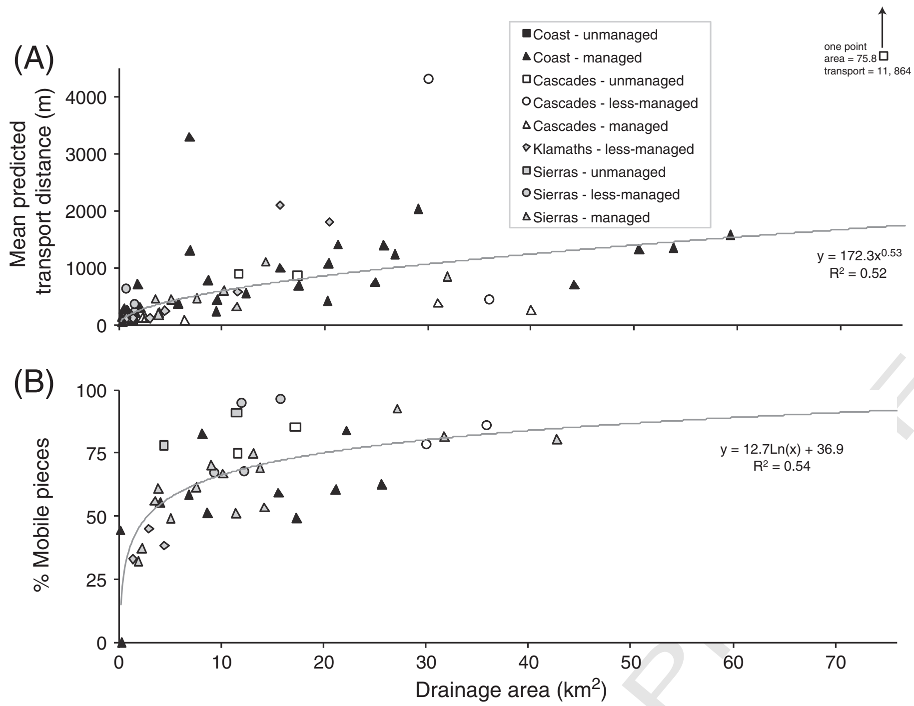

Fig. 12. (A) Predictions of wood transport distance using Eq. (4) and the regressions in Fig. 11 (for distances between jams, proportion of channel blocked by jams, and jam age), and assuming a lifetime of wood in streams of 100 years (using a 3% y^{-1} wood decay rate). (B) Relation between drainage area and the percent of mobile pieces increases downstream. Fluvially mobile pieces are defined (assumed) to be any pieces shorter than the channel width.

streams is of smaller diameter (Table 3). The lower mortality recruitment when trees are vigorously growing following stem exclusion may depress wood storage in streams. Wood storage may increase in the unmanaged (older) forests when forest mortality increases (Table 6).

5. Implications for riparian management

From this study, we outline several implications for riparian management in California, with specific reference to wood supply and function in streams. Other factors such as thermal loading, erosion and sediment delivery, nutrient input, and terrestrial wildlife habitat requirements may dictate other riparian management considerations.

- *Spatially variable protection.* Significant variability in recruitment, storage, and source distances of stream wood results from varying upland and riverine watershed attributes. The dimensions of riparian protection zones (width, location) could be spatially variable depending on the dominant wood recruitment process such as bank erosion, forest mortality, and landsliding associated with various geologic, topographic, and river network controls. Implementing a spatially explicit approach to riparian protection could include some field work in combination with GIS-based terrain mapping to predict wood recruitment.
- *Targets and monitoring.* Reference wood storage targets in restoration or monitoring have no clear basis because of the large spatial and temporal variability in stream wood recruitment processes and storage volumes. Consequently, targets for and monitoring of riparian forest stands (the source of stream wood) may be more appropriate (e.g., Pollock et al., 2012).
- *Source distances.* Most wood recruitment comes from within ~40 m of streams in less-managed forests, and upwards of 50 m or more in old-growth forests. These patterns could be used to design site-specific stream protection measures to ensure adequate wood recruitment to streams.
- *Near stream protection.* Bank erosion is often an important process of wood recruitment to streams. Trees recruited by bank erosion include rootwads that typically have more geomorphic influence in streams. Consequently, streamside trees potentially recruited by bank erosion could be one focus of protection (e.g., no selective cutting within 5 m of the stream).
- *Protection of mass wasting source areas.* Sources of wood from landslides and debris flows can be locally important in all regions, but particularly in the coastal and Klamath landscapes (e.g., Mondry, 2004). Protection of such sources could be delineated through modeling (e.g., Burnett and Miller, 2007).
- *Wood transport.* Fluvial transport of wood may range from a couple of hundred meters in headwater streams (or less) to several thousand meters in larger streams. This information provides a first-order approximation of the connectivity between fish- and nonfish-bearing streams with respect to wood flux.
- *Additional research.* Riparian forest policy in California would greatly benefit from larger studies of unmanaged riparian forests and areas with varying lag times since natural disturbance (e.g., fire and flooding). Episodic wood supply following wildfire in drier regions of California may be a substantial component of long-term wood recruitment to streams (e.g., Bendix and Cowell, 2010), similar to other regions (e.g., Arseneault et al., 2007; King et al., 2013).

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Appendix A. Harvest history for selected forest types

t7.1	Geomorphic province	Forest type	Watershed	Harvest years	Age range (yrs)	Diameter range (m)	Height range (m)	Species composition (%)	Descriptive harvest history
t7.2	Coast	Managed	LNF Noyo	1900, 1960s, 1980s	20–100	1.8–18	9–51	Rwd[a]-65, DF[b]-10, WW[c]-10, Hwds[d]-15	Originally logged around 1900 (essentially a clearcut scattered non-merch/cull trees left; areas burned). Road building adjacent to the creek conducted in 1965 and partial cuts conducted by tractor throughout watershed in the mid-late 1960s; partial cut of riparian areas/shelterwoods, clearcuts conducted upslope in 1980s; cable yarding near streams with tractors upslope. Riparian areas have been partially harvested.
t7.3	Coast	Managed	Redwood	1930s, 1980s–present	20–70	1.8–11	7–43	Rwd-65 DF-20, Hwds-15	Entire watershed logged between late 1920s and mid-1930s, all by railroad spurs along the mainstream portions of the watershed (essentially a clearcut scattered non-merch/cull tees left; areas burned). Yarding conducted principally by skyline upslope to ridges rail inclines used to transport logs back down to mainline railroad. Road construction into watershed commenced in late 1970s, with harvest re-entries in the 1980s on. Only small portion of the old railroad grades have been utilized. Roads constructed to facilitate cable yarding along major streams and tractor yarding upslope. Silviculture is a mixture of clearcut and selection. Riparian areas partially harvested in the 1980s utilizing thinning from below.
t7.4	Coast	Managed	Bear Haven	1940s 1960s–70s 1990s on	30–60	1.8–11	8–43	Rwd-55, DF-30, WW-10, Hwds-5	Logging commenced in this watershed in the early 1940s. Railroad was constructed up the bottom of the main branch and South Fork. Railroad later converted to a truck road. Most of area after about 1950 was yarded by tractors. The next significant harvest occurred in the late 1960s. Earliest logging was an economic clearcut that removed the largest trees to remove the lands from the tax roles. Subsequent entries cut residual trees down to smaller diameters. Substantially all residual old growth trees were harvested by the early 1980s. Harvesting commenced in the young growth in the early 1990s. Silviculture applied has included a mixture of selection, commercial thinning and clearcut. Riparian areas have been partially harvested.
t7.5	Cascades	Managed	Judd	1870s–1900s 1960s–present	30–100	0.6–11	9–38	PP[e]-35, SP-10, WF-35, DF-6, IC[f]-13, Hwds-1	Originally logged around 1900–1930s: oxen logging, a near complete clear cut. Road building to access in modern times,1950s built off of old railroad grades, selection cut and thinnings from the 1950s through the 1990s, tractor based clearcutting with riparian buffers begin in 1995. Partial Cutting in the riparian areas from 1950s on. Entire drainage is rolling gentle slopes that do not require cable yarding.
t7.6	Klamaths	Less managed	SF Indian	1950s–present	30–200+	0.6–11	9–43	PP-09, SP[g]-03, WF[h]-06, DF-35, IC-2, Hwds-45	Original logging started in 1950s, never clearcut, always light selection, road building to access in modern times 1950s, light selection/ high risk salvage continued through the 1970s, selection logging in the 1980s through 1990s. Tractor based clearcutting with buffers begin in 2001. Very light partial cutting in the riparian buffers from 1950s on. Clearcuts conducted upslope in late 1990s till the present, cable yarding near streams in steeper areas with tractors used on the rest. Rehab and planting of burned areas. Buffers were never clearcut. Wildfires in the 1930s–1940s.
t7.7	Klamaths	Less managed	Skunk Gulch	1950s–present	30–200+	0.6–10	9–52	PP-10, SP-02, WF-04, DF-24, MC-1, Hwds-60	Original logging started in 1950s, never clearcut, always light selection, road building to access in modern times 1950s, light selection/ high risk salvage continued through the 1970s, selection logging in the 1980s through the 1990s. Tractor based clearcutting with riparian buffers began in 2001. Very light partial cutting including riparian areas from 1950s on. Clearcuts conducted upslope in late 1990s till the present, cable yarding near streams in steeper areas with tractors used on the rest. Rehab and planting of burned areas. Riparian areas were never clearcut. Wildfires visited area 1930s–1940s.
t7.8	Sierras	Managed	San Antonio	1920s–1930s 1950s–present	30–85	0.6–11	9–55	PP-20 SP-15 WF-20 IC-35 Hwds-10	Originally logged around 1920, 1930s: steam donkey logging downhill to the mill near the bottom of the drainage, a near complete clear cut. Road building to access in modern times 1950s, periodic selection and partial cuts conducted by tractor throughout watershed from then until 1990s. Partial cutting in the riparian zones from 1950s on. Clearcuts conducted upslope in 2000s, cableyarding near streams in steeper areas with tractors used on the rest.
t7.9	Sierras	Managed	Pilot	1900s–1930s 1960s–present	30–110	0.6–15	9–61	PP-35 SP-10, WF-35, DF-6, IC-13, Hwds-1	Originally logged around 1930–1940s: steam donkey railroad logging, a near complete clear cut. Road building to access in modern times, some selection/thinnings in the 1960's, tractor based clearcutting with riparian buffers begin in the 1970's. Partial cutting in the riparian zones from 1960s on. Entire drainage is rolling gentle slopes that do not require cable yarding.

t7.10 [a]Redwood.
t7.11 [b]Douglas fir.
t7.12 [c]Western white pine.
t7.13 [d]Hardwoods.
t7.14 [e]Ponderosa pine.
t7.15 [f]Incense cedar.
t7.16 [g]Sugar pine.
t7.17 [h]White fir.

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