Natural and Anthropogenic Controls on Wood Loads in River Corridors of the Rocky, Cascade, and Olympic Mountains, USA

Daniel N. Scott[1*], Ellen E. Wohl[1]
[1]Colorado State University, Department of Geosciences, Fort Collins, CO, USA
[*]Corresponding author: Daniel Scott (dan.scott@colostate.edu)

This is a peer-reviewed manuscript published in *Water Resources Research*. Note that due to copyediting, there may be slight differences between this version and the published version, but the content is almost entirely identical. The final, published version of this manuscript is available via the published DOI on this page.

Abstract

Wood in rivers creates habitat, shapes the morphology of valley bottoms, and acts as a pool of organic carbon (OC). Effective riverine wood management depends on a robust understanding of the spatial distribution of wood throughout river networks. This motivates the analysis of wood load in relation to both reach- and basin-scale processes. We present wood load data coupled with precipitation, forest stand characteristic, land use, and geomorphic data across four basins in the Rocky, Cascade, and Olympic Mountains of the western USA. We compare basins with differing land use within the same climatic region and basins in differing climates and statistically model intra-basin wood load variability. Wood load is a function of metrics that generally describe river corridor spatial heterogeneity, metrics that describe wood storage patterns, and, at a broader scale, metrics that relate to wood supply. From this, we generate a conceptual model to describe controls on wood load across spatial scales. We use this model to propose that spatial heterogeneity and wood storage pattern together determine reach-scale wood trapping efficiency. Trapping efficiency in turn regulates how wood supply to valley bottoms determines wood load. We also find that wood in an undisturbed basin stores significant amounts of OC, and that wood load restoration has the potential to restore significant amounts of OC to valley bottoms. This conceptual model of wood load controls may serve as a framework to guide wood load modeling and restoration at multiple scales.

Key Points

- Wood load in 4 basins is controlled by wood supply, spatial heterogeneity, and storage pattern
- A paired basin study reveals logging to have reduced wood loads by a factor of two
- Wood acts as a significant OC storage mechanism in valley bottoms, especially in undisturbed systems

Plain Language Summary

Downed wood in rivers creates habitat and nutrients for organisms in streams and on floodplains. Humans have negatively impacted valley bottoms through the removal of downed wood. We measured the amount of downed wood in valley bottoms in four mountain river basins to understand what factors, both local and regional, determine how much wood is stored in river

corridors. We found that at the regional scale, logging, precipitation, and forest characteristics control the supply of wood to valley bottoms. At a more local scale, the shape of the valley bottom and the way in which wood is stored (either as accumulations known as jams or as individual logs) determine how much wood can be trapped in the valley bottom. We present a conceptual model that ties these factors together and can guide our understanding and management of how much wood is in rivers.

1 Introduction

Wood accumulates in rivers via bank erosion and mass movements from hillsides. Because wood can remain stable in the channel and on floodplains, it plays a foundational role in shaping the ecology and geomorphology of valley bottoms. By providing colonization surfaces for periphyton and macroinvertebrates as well as a source of carbon, wood increases microhabitat diversity and provides energy input to macroinvertebrates (Benke & Wallace, 2003; Wondzell & Bisson, 2003). By shaping the location, abundance, and geometry of pools and altering bed texture (Gomi et al., 2003; Montgomery et al., 1996, 2003), wood can regulate habitat abundance and diversity for fishes (Jones et al., 2014; Nagayama et al., 2012). Wood also serves as a pool of organic material (Naiman et al., 1987; Osei et al., 2015; Sutfin et al., 2016), providing a source of organic matter as it breaks down and impacting terrestrial organic carbon (OC) cycling (Elosegi et al., 2007; Wohl, Hall, et al., 2017). The potentially substantial role of wood in storing OC motivates quantification of wood loads not only in terms of wood volume per unit area, but also as an estimated OC stock (mass per unit area).

Wood loads are a function of channel geometry, land use, bioclimatic regime, and geomorphic processes (Wohl, Lininger, et al., 2017). Unit wood volume in valley bottoms sometimes correlates inversely with channel width and drainage area (Beechie & Sibley, 1997; Bilby & Ward, 1989, 1991; Wohl, Lininger, et al., 2017), although this correlation has been observed to be direct in some cases and is strongly dependent on bioclimatic region and riparian forest characteristics (Burton et al., 2016; Wohl, Lininger, et al., 2017). Wood loads have little consistent relation to channel characteristics across bioclimatic regions, but individual regions and watersheds do display significant trends, allowing wood load to be predicted by variables describing geomorphic, ecologic, and anthropogenic conditions (Hough-Snee et al., 2015; Wohl, Lininger, et al., 2017). While mechanisms influencing wood transport and storage have been explored in flume environments (Bocchiola et al., 2006; Braudrick et al., 1997; Davidson et al., 2015), we still lack a good understanding of how well experimental results translate to natural conditions. Such a mechanistic understanding is necessary to explain differences between bioclimatic regions (e.g., why wood load and drainage area sometimes correlate directly and sometimes inversely) and explain wood load spatial distribution across scales. This motivates us to seek a mechanistic understanding of the controls on wood load across spatial scales.

By regulating storage pattern and mobility, wood jams are a potential mechanistic control on wood transport and wood load. Wood jams are generally more stable than dispersed wood pieces within a given reach (Dixon & Sear, 2014; Ruiz-Villanueva et al., 2016; Wohl & Goode, 2008). However, wood jams are not uniformly distributed throughout river networks (Benda, 1990; Cadol et al., 2009; Marcus et al., 2002; Pfeiffer & Wohl, 2018). This implies that the importance of wood jams and their impacts on wood transport may vary with network position, likely due to differences in piece mobility, which is strongly regulated by stream size relative to the length of wood pieces (Gurnell et al., 2002; Kramer & Wohl, 2016). This motivates an analysis of the importance of jams in regulating wood loads relative to other variables that might impact wood loads.

Forest management, especially in the form of timber harvest, is one of the most widespread human impacts on forests in mountainous regions. Logging commonly impacts wood in valley bottoms by influencing both riparian recruitment rates and the rate at which mass movements transfer wood from hillslopes to rivers. Logging and associated road-building increase the rate of mass wasting on steep slopes (Guthrie, 2002; Jakob, 2000; Roberts et al., 2004; Sidle et al., 2006; Wolter et al., 2010), potentially increasing the delivery of wood to floodplains and channels. However, the widespread wood removal and streamside harvesting of wood associated with clearcutting in many regions has a net effect of reducing wood loads and reducing wood trapping ability by reducing in-stream roughness and spatial heterogeneity (Hyatt & Naiman, 2001; Ruffing et al., 2015; Wohl, 2014). This loss of roughness can act as a negative feedback on wood storage, leading to high rates of wood export from the system even after riparian corridors have reforested (Bilby, 1984). The impact of logging on in-stream wood has been demonstrated dominantly through the loss of large wood pieces (Bilby & Ward, 1991; Ralph et al., 1994), which could reduce the occurrence of relatively stable wood jams. Past examinations of the effects of logging have commonly used data from individual reaches in a variety of basins with differing conditions (and potentially confounding variables). This motivates a more rigorous examination of the effects of logging across the entirety of river networks.

1.1 Objectives

Here, we seek to move towards a mechanistic and multi-scale understanding of the controls on wood loads by quantifying wood loads across a diverse set of mountain river basins and modeling relationships between those wood loads and the natural and anthropogenic (namely, logging) processes that impact them. To our knowledge, we provide the first field-based quantification of wood load across the entirety of our four study basins, allowing a rigorous examination of the intra-basin trends in wood load from headwaters to basin outlet. By quantifying wood loads and using published data on wood density and OC content, we also seek to apply our examination of wood load variability to variability in wood OC storage.

Previous broad-scale studies of wood load spatial variability (Hough-Snee et al., 2015; Wohl, Lininger, et al., 2017) generally conclude that wood loads can be conceptualized at either broad (inter-basin) or local (intra-basin) scales by taking into account either bioclimatic or site-specific variables (e.g., land use, channel geometry), respectively. However, a conceptual model to describe wood load spatial distribution that applies at all scales has yet to be developed. We use our extensive field dataset and statistical analyses to suggest that a single conceptual framework can be used to guide understanding of wood load spatial variability both within (intra-basin) and between (inter-basin) river basins.

We use statistical modeling of field-sampled wood load data from four mountain river basins in three distinct regions across the western USA to determine the dominant controls on wood load both within each basin (intra-basin) and between basins (inter-basins). By considering wood supply and mechanistic variables relating to reach-scale wood trapping efficiency, we develop a novel conceptual understanding of wood load spatial variability that applies to multiple scales. This conceptual model explains our results and provides a basis for further testing of multi-scale controls on wood load spatial distribution in river networks.

2 Methods

2.1 Field Sites

Our choice of study basins maximizes variability within the western United States in factors that may influence wood loads (forest stand characteristics, valley morphology, climate, etc.), allowing for a robust analysis of wood load spatial variability. We quantified basin-scale wood load in the Big Sandy basin in the Wind River Range of Wyoming, the Middle Fork (MF) Snoqualmie basin in the central Cascade Mountains of Washington, and the Sitkum and South Fork (SF) Calawah River basins in the Olympic Mountains of Washington (Figure 1). These basins represent three distinct bioclimatic and geomorphologic regions, ranging from the semi-arid Middle Rockies to the wet, glacially influenced Cascades and more fluvially dominated basins in the Olympics. Mean annual precipitation, relief, drainage area, and mean basin slope for each study basin are given in Table 1.

We performed a paired basin study using the Sitkum and SF Calawah basins to examine the effects of basin-wide clearcut timber harvest. These two basins are of similar network geometry (Figure 1) and are both underlain by marine sedimentary rocks (Gerstel & Lingley Jr., 2000). Forests in both basins are dominated by Douglas fir (*Pseudotsuga menziesii*), Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*). The SF Calawah lies entirely within the boundary of Olympic National Park and has not experienced forest harvest or road building, in contrast to the Sitkum, which has been clearcut extensively since the 1940s (orange overlay in Figure 1). Road building and clearcut timber harvest were widespread in the Sitkum until the 1990s, with 15 m (50 ft) riparian buffers being implemented on many reaches in 1975. Currently, forests are dominantly being thinned and roads are being decommissioned to enhance forest habitat and reduce mass movement frequency. The result of this land use has been the loss of large trees able to be recruited to streams by bank and hillslope failure (Pacific District Olympic National Forest, 2012).

We also present data from the MF Snoqualmie and Big Sandy Rivers to examine a bioclimatic contrast that allows us to examine wood loads in regions with differing precipitation, forest characteristics, and network structure. The MF Snoqualmie exhibits glaciogenic topography, with streams ranging from steep, debris flow dominated headwater channels to lower gradient, wide, laterally unconfined channels in its lower reaches, and has been extensively logged in its lower elevation reaches. The elevation range in the MF Snoqualmie generates a strong vegetation gradient. The talus, active glaciers, and alpine tundra at the highest elevations grade to subalpine forests dominated by mountain hemlock (*Tsuga mertensiana*) (above approximately 1500 m), but also including Pacific silver fir (*Abies amabalis*) and noble fir (*Abies procera*) grading into the montane zone (above approximately 900 m). At lower elevations, uplands and terraces are covered by Douglas fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*), whereas active riparian zones are dominated by red alder (*Alnus rubra*) and bigleaf maple (*Acer macrophyllum*).

The Big Sandy also exhibits glaciogenic topography, but is much drier than the MF Snoqualmie. While higher elevations (above approximately 3100 m) are characterized by herbaceous alpine tundra, the subalpine zone (approximately 2900 to 3100 m) is characterized by forests of whitebark pine (*Pinus albicaulis*), Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*). The montane zone (approximately 2600 m to 2900 m) is comprised dominantly of lodgepole pine (*Pinus contorta*). Only a small portion of this basin (approximately 1%) resides below 2500 m, where shrub steppe begins to dominate (Fall, 1994). Forests in this basin are patchy, with substantial grassy parklands and meadows.

To simplify our presentation of results and highlight contrasts between these basins, we categorize these basins by land use, climate, and geomorphic legacy. We term the MF Snoqualmie, with its wet climate, and glacially carved lakes and broad valley bottoms as the *wet glaciogenic* basin. In contrast, we term the Big Sandy, with its semi-arid climate, and broad, glacially carved valley bottoms as the *semi-arid glaciogenic* basin. Finally, we term the Sitkum and SF Calawah, which exhibit the wettest climate, but most fluvially incised, narrow valley bottoms as the *wet fluviogenic* basins. We further subset the Sitkum as the *logged* wet fluviogenic basin and the SF Calawah as the *unlogged* wet fluviogenic basin (Figure 1).

2.2 Study Design and Sampling

We sampled basins in summer 2016 (both wet fluviogenic basins and the semi-arid glaciogenic basin) and summer 2017 (wet fluviogenic basin). Sampling during the summer ensured that there were no large, wood-transporting floods during sampling, such that our data represent an estimate of the wood load in each basin at a single time. We collected a total of 148 reach-scale (each reach is 100 m or 10 channel widths long, whichever was shorter) samples of valley bottom wood load across all four study basins.

We used stratified random sampling to generate an unbiased sample of wood load measurement sites in each basin. In the semi-arid glaciogenic basin, we used a combination of a 10 m DEM and satellite imagery to manually map the extent of the valley bottom along the entire stream network, with the objective of delineating confined and unconfined valley sections. We defined unconfined valley bottoms as those in which channel width occupied no more than half the valley bottom, and confined valley bottoms as those in which channel width occupied greater than half the valley bottom. We then stratified the stream network by five drainage area classes to ensure uniform sampling throughout the basin. This produced two stratifications, one of drainage area and the other of confinement. In the wet basins, the dense vegetation prevented us from manually mapping valley bottoms as we did in the semi-arid basin. Thus, in the wet fluviogenic basins, we sampled uniformly across stream orders (Strahler, 1957) in order to sample a relatively even distribution of channel and valley widths. We stratified the wet glaciogenic basin stream network by slope into four strata. We chose to not measure wood loads in parts of the network steeper than 0.30 m/m as classified by a 10 m DEM because our initial field reconnaissance indicated that many such channels were dominated by colluvial processes as opposed to fluvial processes, although field-based measurements indicated that some study sites were locally steeper than this threshold. Within each slope strata, we randomly selected ten reaches for sampling wood load.

In all four basins, but especially in the wet fluviogenic basins, we were unable to reach all randomly sampled sites due to time constraints. This resulted in the subjective selection of sites that were accessible and that we felt maintained as unbiased a sample as possible. Total numbers of sites and the proportion of sites that were subjectively chosen are listed in Table S1.

2.3 Reach-Scale Field Measurements

Table S1 summarizes which measurements were collected in each basin. Within each reach, we quantified wood volume in wood jams (accumulations of 3 or more pieces touching one another) using a census approach, measuring the length, width, and height of a rectangular prism that best fit the jam (i.e., these geometric measurements did not correspond to flow direction) and visually estimating the porosity (Thevenet et al., 1998). Although this method is not as accurate as dismantling jams to measure every wood piece (e.g., Manners et al., 2007), our consistency in this method (i.e., only a single person made all estimates using consistent methodology) likely minimizes systematic bias. Within each reach, we quantified wood volume in dispersed pieces greater than 10 cm diameter using a combination of two methods, depending on the nature of wood within the reach and channel confinement. For confined valleys with numerous wood pieces dominantly oriented perpendicular to the valley axis, we used an adapted form of a line-intersect sampling strategy (Van Wagner, 1968; Wallace & Benke, 1984) whereby the line was fit to the channel centerline (Warren et al., 2008). We measured the diameter of every wood piece intersected by the line, then calculated wood volume using the formula given by Van Wagner (1968). For unconfined reaches with sufficiently low wood piece abundance, we measured the diameter and length of each wood piece in the reach, calculating piece volume as if each piece was a cylinder. In the wet glaciogenic basin, some unconfined floodplains were wide enough that a census of pieces and jams was impractical, so we performed a census within the channel, then performed a single line intersect transect across the floodplain perpendicular to the valley axis to quantify floodplain wood load (Van Wagner, 1968).

We assigned a decay class to each reach that describes all the pieces and jams in each reach using the visual decay classification of Harmon et al. (2011). This allowed us to estimate an average wood density using the downed dead softwood densities for each decay class listed in Table 5 of Harmon et al. (2011). With an average wood density and volume per reach, we calculated wood mass as the product of density and volume. We used the length of each reach and the valley bottom width to compute a wood mass per unit area of valley bottom.

At each reach, we measured channel geometry and other characteristics using a TruPulse 360 laser rangefinder (Scott et al., 2016), although our measurements were not consistent across all basins because field protocol evolved during the course of the study (Table S1). In the wet glaciogenic basin, we categorized channels by planform and dominant bedform (Montgomery & Buffington, 1997). We defined planforms as either: straight, where the channel was generally confined and significant lateral migration was not evident; meandering, where lateral migration was evident but only a single channel existed; anastomosing, where vegetated islands separate multiple channels; and anabranching, where a single dominant channel existed with relict channels separated by vegetated islands. For the purposes of statistical modeling, we also classified channels as being either multithread (anastomosing or anabranching) or single thread (straight or meandering). Because logging records are inconsistent and likely inaccurate in the wet glaciogenic basin (based on the frequent observation of past logging activity where none was recorded in Forest Service records), we noted whether signs of logging, such as cut stumps, cable, decommissioned roads or railroads, or other logging-associated tools were found near the reach. We also looked for forest stand characteristics that commonly result from clearcut logging: even-aged stands, monocultures, and a lack of undergrowth compared to unlogged forests. These observations, and our resulting classification of reaches as being logged or unlogged, are limited to the forests immediately surrounding the reach.

2.4 GIS and Derivative Measurements

A 10 m DEM was utilized for all topographic measurements. We collected the following data for each reach using a GIS platform: elevation, drainage area, land cover classification and canopy cover from the National Land Cover Database (Homer et al., 2015), and the mean slope of the basin upstream of each reach. Utilizing drainage area at each reach and field-measured slope, we calculated an estimated stream power as the product of drainage area, slope, and basin-averaged precipitation.

We calculated a wood jam density to measure the abundance of wood jams in each reach as the number of jams divided by the length of each reach. Following Kramer and Wohl (2016), we calculated a dimensionless maximum piece length for each reach (L^*) as the maximum piece length in the reach divided by the bankfull width, for all reaches except those in the semi-arid glaciogenic basin, where bankfull width was not measured. All wood masses were normalized by unit area using the average valley width and length of each reach. For purposes of estimating OC storage in wood, we assumed that half of the measured wood mass was carbon (Lamlom & Savidge, 2003). Variability in wood OC content ranges from 47.21% to 55.2% for conifers (Lamlom & Savidge, 2003), the dominant division of trees present in our study basins. As such, an assumption of 50% OC content is likely a conservative estimate of actual OC content and is a suitable approximation for making first-order estimations of wood OC stock (e.g., Sutfin et al., 2016; Wohl et al., 2012).

2.5 Statistical Analyses

All statistical analyses were performed using the R statistical computing software (R Core Team, 2017). Due to differences in variables measured for each region, we conducted modeling based on model groups with consistent measurements. We modeled wood load in the wet glaciogenic (sample size, $n = 46$) and semi-arid glaciogenic ($n = 52$) basins individually as well as across both fluviogenic basins combined ($n = 50$). Because of the lack of variation in hypothesized predictor variables in other basins, we only modeled the proportion of wood in jams in the wet glaciogenic basin. We note that although this modeling predicts wood load as a mass per unit area, we observe a Pearson correlation coefficient with a 95% confidence interval between 0.98 and 0.99 between wood mass per unit area and wood volume per unit area. We also tested each final model using wood volume as a predictor to ensure that results reported here are equally applicable to wood volume and wood mass.

Our modeling strategy starts with univariate analysis between each hypothesized predictor and the response, utilizing mainly comparative Wilcoxon rank-sum tests (Wilcoxon, 1945) or Spearman correlation coefficient statistics. During this filtering, we also view boxplots or scatterplots as appropriate to discern which variables appear to have anything other than a completely random relationship with the response. We then utilize all subsets multiple linear (for wood load) or multiple logistic (for the proportion of wood stored in jams) regression using the corrected Akaike Information Criterion as a model selection criteria (Wagenmakers & Farrell, 2004). We iteratively transform response variables to ensure homoscedasticity of error terms. When selecting a single best model, we utilize both Akaike weight based importance as well as parsimony to select a final, reduced model. We consider sample sizes, p values, and effect magnitudes (odds ratios for logistic regression and slope coefficients for linear regression) in our discussion of variable importance. All other statistical analyses presented here are comparative statistics utilizing Wilcoxon rank-sum tests or pairwise equivalent using a Holm multiple-comparison correction (Holm, 1979) to accommodate generally skewed distributions. Unless otherwise noted, we present 95% confidence intervals to represent variance on population estimates.

3 Results

3.1 Controls on Wood Load

Median wood load is significantly different between all study basins except for the wet glaciogenic and logged wet fluviogenic basins (Figure 2, Table S2). Wood load is highest in the unlogged wet fluviogenic basin, followed by the wet glaciogenic and logged wet fluviogenic basins, followed by the semi-arid glaciogenic basin. Although not shown here, trends in wood volume between basins track very similarly to those in wood mass (Figure S1). Distributions of wood loads are generally right skewed, especially in the fluviogenic basins. For the entire dataset of wood load in each basin, see Dataset S1 (Scott & Wohl, 2018). Table S3 shows the variables tested to understand controls on wood load and a summary of results for each model.

Multiple linear regression modeling of wood mass per unit area in the wet glaciogenic study basin reveals jam density (number of jams per meter), elevation, estimated stream power, and confinement to be significant controls on wood load (adjusted $R^2 = 0.40$, $p < 0.0001$). For this model, a cube root transformation (to accommodate 0 values) is found to be appropriate, so all slope coefficients relate to a unit increase in the cube root of wood load. We note that the cube root of wood load, while uninterpretable in itself, is likely analogous to a wood length per unit area, if mass and volume are taken to be highly correlated (which they are in our data, see section 2.5) A higher jam density (units of jams/m stream, $\beta = 9.04 \pm 8.16$) and higher estimated stream power (units of m^3, $\beta = 2.13 \text{ X } 10^{-8} \pm 2.06 \text{ X } 10^{-8}$) result in higher wood loads, whereas higher elevations result in lower wood loads (units of m, $\beta = -1.20 \text{ X } 10^{-3} \pm 7.38 \text{ X } 10^{-4}$). Unconfined streams are found to generally store less wood ($\beta = -.48 \pm 0.44$); all other predictors held constant. We note that the effect (β) of stream power on wood load is extremely small, despite its significance in the model. From this, we conclude that although stream power likely has some relation to wood load, its effect is so much smaller than other controls that it is negligible.

Similarly, in the semi-arid glaciogenic basin, jam density, elevation, and confinement in addition to median piece length are found to be significant predictors of wood load (adjusted $R^2 = 0.77$, $p < 0.0001$). However, we find that piece length and confinement were strongly related, leading to multicollinearity in any model including both variables. Comparing models similar to the above model but with either confinement (adjusted $R^2 = 0.59$, $p < 0.0001$) or piece length (adjusted $R^2 = 0.71$, $p < 0.0001$) removed, the model that includes confinement explains much more of the variance in wood load. As such, we conclude that confinement is likely the dominant control on wood load over piece length, and eliminate piece length from the final model. Thus, our final model of wood load in the semi-arid glaciogenic basin includes only jam density, elevation, and confinement as significant predictors of the cube root of wood load. Reaches with higher jam densities (units of jams/m, $\beta = 14.38 \pm 6.94$) and lower elevations tend to store more wood (units of m, $\beta = -0.0012 \pm 0.00048$). Like the wet glaciogenic basin, unconfined reaches store significantly less wood than confined reaches ($\beta = -0.74 \pm 0.20$).

The logged wet fluviogenic basin contains half as much wood as the unlogged wet fluviogenic basin (section 3.1.1). After accounting for logging, channel slope and jam density are significant predictors of the cube root of wood load (adjusted $R^2 = 0.34$, $p < 0.0001$) in these basins. Reaches with higher channel slope (units of m/m, $\beta = 2.66 \pm 0.62$) and more jams tend to store more wood (units of jams/m, $\beta = 19.13 \pm 1.63$).

In summary, we find that jam density, elevation, and confinement in the glaciogenic basins; and logging, slope, and jam density in the fluviogenic basins control wood load. We broadly categorize these variables into those that describe wood supply to valley bottoms (elevation and logging) and those that describe reach-scale wood trapping efficiency (jam density, confinement, and slope).

3.1.1 Effects of Logging on Wood Loads

Comparing the logged wet fluviogenic (extensively clearcut) to the unlogged wet fluviogenic basin (relatively pristine), we find that wood loads are a factor of 2 greater in the unlogged basin (Figure 2, Table S2). Other variables such as bankfull width, slope, wood jam density per unit stream length, median and maximum piece length and diameter do not significantly differ between basins (p values for comparisons are 0.70, 0.24, 0.47, 0.26, 0.19, 0.43, 0.70, respectively). We do note maximum piece diameter may be lower in the logged wet fluviogenic basin, and that we may lack the sample size to note this effect. The only factor that is significantly different between basins is elevation, which is significantly higher in the logged wet fluviogenic basin ($p < 0.001$). However, we note that elevation was not found, either through univariate analysis ($p = 0.56$) or model selection, to be a meaningful predictor of wood load when modeling controls on wood load across samples in both fluviogenic basins, likely due to the lack of variation in forest stand characteristics with elevation in these basins.

Because historic logging records are largely inaccurate in the wet glaciogenic basin, we use our observational mapping of logging to understand logging extent and attempt to understand how variation in logging impacted wood load. We find that with very few exceptions, all sites at low elevations experienced some form of timber harvest, likely within the last century. When considering all sampled reaches in the basin in a univariate analysis, we find that sites with logging apparently contain more wood than sites with no logging nearby ($p = 0.04$). However, we also find that logging is strongly correlated with elevation, such that the median elevation of logged sites (446^{+71}_{-119} m) is less than half that of unlogged sites (989^{+173}_{-66} m). Elevation is a significant predictor of wood load in this basin due to the high range of elevation and forest types. This suggests that the correlation between local logging activity at a reach and enhanced wood loads in this basin is spurious, and that local impacts of logging cannot be evaluated here.

Smithwick et al. (2002) measured potential carbon stores in forests of the Pacific Northwest, including the Washington Cascades and Olympic Mountains. We utilize measurements of downed log OC mass per unit area from Smithwick et al. (2002) to compare our measured wood loads in Washington to upland downed wood loads so as to examine both how fluvial wood storage compares to upland downed wood storage and how logging affects that comparison (Figure S2). We find that the two logged basins likely do not store more wood than their corresponding uplands, whereas the unlogged wet fluviogenic basin may store more wood than nearby uplands.

In summary, logging has significantly decreased wood loads in the logged compared to the unlogged wet fluviogenic basin. Although logging has likely had a similar effect on the wet glaciogenic basin, we cannot evaluate the local effects of logging on that basin.

3.2 Controls on the Proportion of Wood Stored in Jams

Despite wood jam density being a significant predictor in models of wood load, median proportions of wood stored in jams for each basin are all well below 50% (Figure 2b, Table S2). While some reaches store almost all wood as jams, wood is generally not stored as jams in these dominantly small- to moderate-drainage area study reaches.

Multiple logistic regression modeling in the wet glaciogenic basin yields bankfull depth and whether the reach is multithread (a measure of spatial heterogeneity) as significant predictors of the proportion of wood in jams. Multithread channels are significantly more likely than single thread channels to store wood as jams (wood is 1.05 to 23.16 times more likely to be stored in a jam if the reach is multithread) and deeper channels tend to store more wood as jams than shallower channels (wood is 0.94 to 6.12 times more likely to be stored in a jam for every 1 m increase in bankfull depth).

In summary, we find that bankfull depth and channel planform control the proportion of wood stored in jams in the wet glaciogenic basin.

4 Discussion

4.1 Inter-basin Comparisons and the Impacts of Logging on Wood Load

We compare wood loads between basins to examine the effects of climate (comparing the semi-arid to the wet basins) and logging (comparing the logged and unlogged wet fluviogenic basins) on basin-scale wood load. Differences in wood loads between basins (Figure 2a) can be largely explained by differences in precipitation and land use that result in differing forest stand characteristics. The semi-arid glaciogenic basin, with the lowest wood loads, has the correspondingly lowest precipitation and canopy cover ($p < 0.0001$ for comparisons with all other basins). Mean canopy cover in the semi-arid glaciogenic basin is 27% ± 4%, whereas mean canopy cover in the wet glaciogenic, unlogged wet fluviogenic, and logged wet fluviogenic basins are 65% ± 5%, 73% ± 6%, and 72% ± 6%, respectively (uncertainty from a 95% confidence interval on the mean). This likely indicates, and field observations support, that forests in the semi-arid basin are less dense, trees are smaller, and the resulting supply of wood to the channel is lower.

Although the mean slope of the basin upstream of each reach is not a mechanistic predictor of hillslope instability, the semi-arid glaciogenic basin also has, on average, the lowest upstream basin slopes compared to the wet basins ($p < 0.0001$ for comparisons with all other basins). This indicates that landslides that could deliver large pulses of logs to channels are likely much less frequent in the semi-arid basin compared to the wet basins. This is consistent with estimates of upstream basin mean slope in the semi-arid basin being 17° ± 2°, whereas upstream basin slopes in other basins generally hover around 30° (29° ± 1° in the wet glaciogenic, 31° ± 2° in the logged wet fluviogenic, and 29° ± 1° in the unlogged wet fluviogenic basin). Assuming that a hillslope angle of around 30° is a threshold at which landslides become significantly more frequent (Clarke & Burbank, 2010; Larsen & Montgomery, 2012), this indicates that basins in the Pacific Northwest are likely experiencing relatively frequent landslides that potentially input large pulses of logs to valley bottoms (Benda, Veldhuisen, et al., 2003; Benda & Bigelow, 2014). In addition to the significantly denser forests and larger logs, the likelihood of more pulsed inputs to channels in the Pacific Northwest probably explains higher wood loads. Although the semi-arid basin has a lower wood jam density than all other basins ($p = 0.03$ compared to logged wet fluviogenic, 0.005 for unlogged wet fluviogenic, and <0.0001 for wet glaciogenic), it is unclear whether jams are simply less likely to form or whether lack of jams is a result of lower wood loads, which is driven more by the lower supply of riparian trees to the channel.

Logging, in addition to climate, acts as an inter-basin scale control on wood load. Comparing the three wet study basins, the unlogged fluviogenic basin exhibits a significantly higher wood load than the logged glaciogenic and fluviogenic basins. The wet glaciogenic basin exhibits much wider valley bottoms and larger drainage area than the fluviogenic basins, potentially confounding comparison. However, even when we restrict this comparison to reaches with drainage areas lower than the maximum drainage area sampled in the unlogged wet fluviogenic basin (eliminating reaches with high drainage area and wide valley bottoms from the wet glaciogenic basin), the unlogged wet fluviogenic basin still exhibits significantly higher wood loads than the wet glaciogenic basin ($p < 0.0001$) and likely higher wood loads than the logged wet fluviogenic basin (p = 0.06). This indicates that logging (as opposed to valley morphology) is the dominant cause of reduced wood loads in the wet glaciogenic and logged wet fluviogenic basins, both of which exhibit statistically similar wood loads. Considering the similar precipitation and forest stand characteristics throughout most of the basins (the exception being the subalpine and alpine zones of the wet glaciogenic basin), and the observation that both are extensively logged, it seems that wood loads in the wet glaciogenic and logged wet fluviogenic basins are likely lower as a direct result of logging.

We can use comparisons between the three basins in the Pacific Northwest to identify likely mechanisms by which logging has reduced wood loads. While logging can enhance wood supply to valley bottoms by increasing the frequency of landslides that deliver wood (Guthrie, 2002; Jakob, 2000; Roberts et al., 2004; Sidle et al., 2006; Wolter et al., 2010), it generally reduces wood supply decreasing the quantity and size of trees available to be recruited to the stream, especially in the absence of riparian buffers (Bilby & Ward, 1991; Ralph et al., 1994). Logging also reduces in-channel and floodplain roughness if wood is removed or if streams are cleared for tie-drives (anthropogenic floods that serve to flush wood down a channel after harvest). This reduction in macro-scale roughness may reduce wood loads by reducing the frequency of upstream-facing obstacles (e.g., bars, islands, large boulders) on which wood can be trapped during high flows (Hyatt & Naiman, 2001; Ruffing et al., 2015; Wohl, 2014).

Our data indicates that a reduction in wood supply is the most likely mechanism by which logging has reduced wood loads in the logged wet fluviogenic basin, as opposed to a reduction in tree size or a reduction in roughness due to tie-drives. Comparing wood sizes in the logged and unlogged wet fluviogenic basins, there are no significant differences in median (p = 0.43) or maximum (p = 0.70) piece diameter, or median (p = 0.26) or maximum (p = 0.19) piece length, all of which could potentially relate to wood trapping efficiency. However, the logged wet fluviogenic basin consistently has a lower (albeit insignificantly different) estimated median piece size and the possibility remains that wood pieces in the logged basin may be smaller than the unlogged wet fluviogenic basin. We observed no abandoned splash dams and there are no recorded instances of tie-drives in the logged wet fluviogenic basin, so logging probably did not directly affect in-channel roughness. Jam density and the proportion of wood stored in jams does not significantly differ between basins, suggesting that logging has not had a direct impact on the storage patterns of wood in these rivers. We suspect that the combined effect of clearcut harvesting reducing hillslope wood loads and harvest in the riparian zone reducing the supply of wood to the channel results in lower wood loads. Our results indicate a similar reduction in wood load by logging to what has previously been observed in northern wet conifer forests (Wohl, Lininger, et al., 2017). Notably, our study examines the entirety of two otherwise nearly identical basins, lending increased rigor to our comparison relative to past studies.

4.2 Controls on Wood Load

Our methodology in each basin differed, making generalization of these results difficult. However, we can draw general conclusions across all basins by considering likely explanations for observed intra-basin variability in wood load.

Jam density clearly controls wood load across all basins, despite the proportion of wood stored in jams being significantly less than half in all basins. This indicates that despite their relatively small proportion of storage, wood jams play a disproportionately large role in determining total wood storage within a reach. This may be due to both the structure of wood jams and their impacts on reach-scale wood mobility. Relatively stable wood jams are hypothesized to significantly decrease the mobility of wood pieces in transport (Beckman &

Wohl, 2014; Kramer & Wohl, 2016). When analyzing the univariate relationship between jam density and wood load in dispersed pieces, only data from the semi-arid glaciogenic basin display a positive Spearman correlation ($p = 0.01$, $\rho = 0.34$ with a 95% confidence interval between 0.06 and 0.57), weakly suggesting that pieces may be more likely to accumulate on jams when more jams are present. We observe a significant positive correlation between jam density and the proportion of wood stored in jams in all basins combined ($p < 0.0001$, $\rho = 0.95$ with a 95% confidence interval between 0.93 and 0.96), as well as in each individual region (all p values < 0.0001, 95% confidence intervals of ρ ranging from 0.74 to 1). This indicates that wood pieces may preferentially deposit on existing accumulations as jam density increases.

The proportion of wood stored in jams in the wet glaciogenic basin is largely controlled by planform and bankfull depth. We were unable to examine controls on the proportion of wood stored in jams for other basins due to a lack of data (see section 2.5). It is likely that multithread reaches, by having greater spatial heterogeneity in terms of flow depth variance and the presence of bar heads and secondary channels, provide relatively immobile objects to anchor wood jams and allow accumulation of racked pieces. This corroborates the interpretation of Wohl et al. (2018), who found that the proportion of wood stored in jams is controlled mainly by whether the reach contains multiple channels and Gurnell et al. (2000), who found that geomorphic complexity directly related to wood retention within a reach. The effect of bankfull depth on the proportion of wood stored in jams could be due to channels with greater bankfull depth being able to transport larger logs at a given discharge, making individual pieces more mobile (Iroumé et al., 2015; Kramer & Wohl, 2016). More mobile pieces transported past jams that are stable for a given flow would likely lead to more wood stored in jams. Although wood jam stability remains a major knowledge gap, our results indicate that spatial heterogeneity, specifically the presence of upstream-facing surfaces on which wood can be trapped during high flows, appears to regulate wood jam dynamics and, in turn, wood load.

The significance of elevation in determining wood load is likely due to trends in forest type with elevation in the glaciogenic basins, as both basins have significant portions of the stream network near and above tree line. As forests become thinner and trees grow more slowly at higher elevations (see section 2.1), the supply of wood from hillslopes to the channel via mass movement probably decreases, leading to a decrease in wood load. Conversely, the homogeneity of forests in the fluviogenic basins (likely due to the relatively low relief in those basins) probably results in little variation in forest stand characteristics, explaining why elevation has no significant effect on wood load in those basins.

In the fluviogenic basins, we are surprised that slope, as opposed to bankfull channel width or dimensionless piece length (L^*) significantly controlled wood load, since we tend to observe what appear to be more dense accumulations of wood in smaller, steeper channels (e.g., Figure S3). Slope directly correlates to wood load in these basins and likely also directly correlates to both channel width and the prevalence of large, relatively immobile roughness elements (e.g., boulders) that can trap wood pieces. Higher gradient channels tend to have more cascade or step-pool morphology and large boulders. These are largely absent from the lower gradient portions of the network, which tend to erode either bedrock or gravel to cobble sized substrate. Large clasts can interact with wood to form relatively stable accumulations in steeper streams (Scott et al., 2014). This, combined with the fact that higher gradient reaches tend to have narrower bankfull widths and corresponding valley widths ($p < 0.0001$, $\rho = -0.59$ with a 95% confidence interval between -0.75 and -0.36), probably leads to higher gradient reaches being both able to trap wood in transport more effectively on large, relatively immobile roughness elements and makes intact trees more likely to be able to span the channel, trapping mobile wood until they begin to break down.

Confinement exerts a consistent and significant control on wood loads in both glaciogenic basins. When wood pieces are able to interact with stable elements of hillslopes such as living trees or stumps, they tend to resist mobilization (Beckman & Wohl, 2014b; Carah et al., 2014, Figure S3). Such interaction is only possible if logs within the channel can reach such elements on the hillside, which is more likely when channels are confined by their valley walls. Unconfined reaches, especially those with less vegetated floodplains (observed in montane meadows in the semi-arid glaciogenic basin or lower gradient reaches of the wet glaciogenic basin with wide gravel bars) may be able to transport wood more readily without the wood being trapped on floodplain or hillslope roughness elements.

It is notable that we are unable to find an effect of L^* on wood load, despite measuring reaches spanning a range of L* values from nearly 0 to 15. However, we find that the presence of wood jams strongly controls wood loads, and the proportion of wood stored in jams is dominantly a function of channel morphology, according to our modeling. Specifically, the relationship between bankfull depth and the proportion of wood in jams may indicate that wood mobility (regulated in part by bankfull depth) influences wood storage pattern. This indicates that L* alone may be insufficient to predict wood mobility. We find that the factors controlling wood load at the reach scale do not appear to be as scale-dependent with respect to piece length and channel width as has been hypothesized (Kramer & Wohl, 2016), but instead are relatively consistent across the ranges of piece length to channel width examined here.

4.3 Conceptual Model of Wood Load in Rivers

We summarize our results and generalize them along with results from previous studies in the form of a conceptual model (Figure 3) to describe the dominant controls on valley bottom wood load at multiple spatial scales. While this conceptual model stems directly from our results, we note that it is represents a hypothesis that is explicitly tested by our analyses. We pose this conceptual model to address the lack of a holistic conceptualization of the controls on wood loads that applies to spatial scales from that of a single reach to entire watersheds or regions. While previous work has suggested that quantifying wood load requires site-specific variables, we instead argue that the following conceptual model should allow for these site-specific variables to be viewed in a way that generalizes the processes affecting wood loads, enabling future evaluation of multivariate models that accurately describe wood load in a variety of settings and at multiple scales.

4.3.1 Wood Supply

Wood supply refers to the wood flux into the channel from mass movement (Benda & Bigelow, 2014; Martin & Benda, 2001) and riparian recruitment via channel migration (Piégay et al., 2017). The contribution of wood from mass movement depends on forest stand characteristics (i.e., the amount of wood growing on hillsides) and the likelihood of mass movements. Such mass movements are much more common in landscapes where hillslopes reach a threshold mean gradient, proposed to be around 30° (Larsen & Montgomery, 2012), such as those found in the Western Cordillera (Benda, Miller, et al., 2003; Benda & Bigelow, 2014). However, mass movement likely contributes only a small proportion of wood flux to channels. Wood likely comes more dominantly from riparian mortality (related to forest stand characteristics and hydroclimatic/disturbance regimes) and bank erosion (Benda & Bigelow, 2014; Piégay et al., 2017). Our results indicating relationships between proxies for forest stand density (elevation at an intra-basin scale and climate or logging at an inter-basin scale) and wood load support the idea that land use and hydroclimatic regime determine forest characteristics and resulting wood supply (Hough-Snee et al., 2015).

While our analysis does not directly examine recruitment rate, rates of lateral mobility depend primarily on hydrology, geomorphology, and wood and vegetation dynamics (Brooks et al., 2003; Collins et al., 2012; Richard et al., 2005; Wickert et al., 2013). Broadly, higher degrees of spatial heterogeneity (i.e., multi-thread planforms, active lateral migration) may lead to higher rates of wood supply to channels. At the same time, some forms of spatial heterogeneity (discussed below) and recruitment can be direct results of in-channel and floodplain wood. In this way, spatial heterogeneity, mainly channel morphology dynamics, links a feedback between wood load and wood supply to channels (Figure 3).

4.3.2 Trapping Efficiency, a Combination of Storage Pattern and Spatial Heterogeneity

Our results indicate that jam density is a dominant control on wood load. In our conceptual model, storage pattern refers to how wood is stored in the valley bottom: either on floodplains or in the channel and either as jams or dispersed pieces. In addition, the breakdown of wood by physical breakage or decay also influences how wood is stored, because these processes regulate wood size (Gurnell, 2013). Storage pattern likely plays a strong role in determining the stability of a piece of wood, or how long it will reside within a reach. Wood stored on the floodplain should be more stable than wood stored in the channel, because mobilization of floodplain wood requires a higher magnitude (and correspondingly less frequent) flow (Wohl, Cadol, et al., 2018). Wood stored in a jam should be, on average, more stable than dispersed pieces (Wohl & Goode, 2008), due to interactions among pieces of wood, sediment, and in-channel and floodplain roughness elements (Bocchiola et al., 2008). Wood load directly feeds back on storage pattern (Figure 3), as it is likely that a threshold wood load in channels is required for the formation of jams. More work is needed to understand the mechanism by which jam density relates to wood loads.

Spatial heterogeneity refers to floodplain and channel morphologic complexity and ability to impede wood in transport. Essentially, a smooth, simplified channel with little morphologic variability is less likely to provide features that can retain wood in transport than a morphologically complex channel that exhibits upstream-facing surfaces on which wood can be pinned. Such morphologic complexity can come from a variety of mechanisms. For instance, large, relatively immobile boulders (Braudrick & Grant, 2000), living vegetation both within channels (Dunkerley, 2014; Opperman et al., 2008) and on bars and floodplains, and vegetated islands (Bertoldi et al., 2013; Gurnell et al., 2002) can all act as trapping points for wood in transport. These objects can rack key pieces that can generate wood jams and can act as anchors for dispersed pieces that impact them during transport. Heterogeneity in planform (e.g., bars and pools, meanders) can result in wood deposition in shallower zones of flow in larger channels (Gurnell et al., 2000; Wohl, Scott, et al., 2018). Channel geometry relative to wood length (Kramer & Wohl, 2016; Shields et al., 2006) can determine how likely wood pieces are to span the channel or ramp up on a bank (Wohl, 2013), increasing their resistance to mobilization. While more spatially heterogeneous multithread channels do not significantly store more wood in our modeling, we do find that multithread channels store higher proportions of wood in jams, which may influence wood load via jam density.

Interpreting our results in the context of similar studies on larger rivers with wider channels relative to log lengths reveals how stream size may influence the nature of spatial heterogeneity. The small to medium streams studied here are generally more confined (i.e., logs interact with banks frequently) and spatial heterogeneity is commonly in the form of bedform variability, large boulders, and bankside vegetation that can trap wood ramped on floodplains and valley walls. Larger streams display spatial heterogeneity dominantly in the form of bars and mid-channel islands that generate shallow flow regions that tend to trap wood (Gurnell et al., 2000; Wohl, Scott, et al., 2018). Our observed positive correlation between slope and wood load in the fluviogenic basins likely reflects the fact that streams in these basins are uniformly confined by their valley walls, allowing bankside spatial disparities to trap wood, and making large boulders or bedforms the dominant wood trapping mechanisms that can trap wood and maintain jams (Scott et al., 2014). Such morphologic roughness features are likely more common in higher gradient channels in those basins (Aberle & Smart, 2003). For the glaciogenic basins, the relationship between slope and wood load is insignificant, likely reflecting the fact that both boulders, bankside disparities, and bedforms as well as planform irregularity, bars, and in-stream vegetation contribute to wood trapping. In those basins, more confined reaches likely allow wood to interact more strongly with bankside heterogeneities, leading to high wood loads.

Vegetation patch dynamics regulate riparian forest stand characteristics (a feedback between spatial heterogeneity and wood supply) as well as the potential for wood to be impeded in transport, especially on bar or floodplain surfaces (Fetherston et al., 1995). Wood in the channel can determine vegetation patch dynamics by affecting the formation of hard points in the valley bottom (Collins et al., 2012), acting as a feedback between wood load and spatial heterogeneity (Figure 3). Lateral mobility is a function of both how effective the river is at eroding its banks and depositing bars as well as the limitations exerted by valley walls or anthropogenic confinement. Our observation that confinement is a strong control on wood load, whereby more confined channels have higher wood loads (Wyżga et al., 2017), however, suggests that greater lateral mobility may result in decreased wood trapping efficiency, despite potential increases in recruitment rate. The exception to this may be found in the case of larger rivers (Gurnell et al., 2000; Wohl, Scott, et al., 2018), where wider reaches may have more bars and islands on which wood can be retained.

With our conceptual model, we propose that wood load is a function of how much wood is deposited within a reach and its residence time, and is controlled by characteristics that affect storage patterns, spatial heterogeneity, and the supply of logs to the channel. Together, spatial heterogeneity and storage pattern determine trapping efficiency, or the wood retentiveness of a reach. This conceptual model relates these characteristics to wood load and facilitates discussion of how wood load feeds back on storage pattern and spatial heterogeneity, which in turn feeds back on supply.

4.4 Valley Bottom Wood Contribution to the Riverine OC Pool

A recent compilation of wood OC storage in temperate rivers shows that, with one exception, most past quantifications of wood OC stock are in the range of 1 to 150 Mg C/ha (Sutfin et al., 2016). Comparing the first-order estimates from our study basins to other values from temperate regions contextualizes the impact of logging on the wood OC stock. In the semi-arid glaciogenic basin, with much of its area near or above tree line, wood plays a minor role in storing carbon (95% confidence interval on median between 0.0 and 2.5 Mg C/ha). In contrast, wet basins in the Pacific Northwest demonstrate substantial OC storage in the form of wood (95% confidence interval on median between 2.7 and 27.9 Mg C/ha). Notably, wood OC storage in the unlogged wet fluviogenic basin (95% confidence interval on median between 67.4 and 229.5 Mg C/ha) is high compared to most temperate rivers (Sutfin et al., 2016), many of which have been impacted by anthropogenic wood removal or a loss of wood supply (Wohl, 2014;

Wohl, Lininger, et al., 2017). This highlights the potential wood OC storage contribution of undisturbed temperate watersheds. The factor of 2 decrease in wood load between the unlogged and logged wet fluviogenic basins in the context of the large extent of anthropogenic disturbances to mountain river basins implies that wood OC storage in mountain river basins has been significantly impacted by anthropogenic disturbance, and that restoration of wood load may have a significant impact on valley bottom OC storage (Lininger et al., 2017).

Understanding the spatial variability in wood residence times is now essential to guide wood load management in the context of climate change and efforts to retain carbon on the landscape. While most wood found in channels is likely less than 50 years old, wood stored in floodplains can reach ages on the order of $10^2 – 10^3$ years (Guyette et al., 2002, 2008; Hyatt & Naiman, 2001; Nanson et al., 1995; Webb & Erskine, 2003). Despite this high variability, wood is likely a significant contribution to the valley bottom carbon pool (Naiman et al., 1987; Sutfin et al., 2016; Wohl et al., 2012). It is important to better quantify how long the substantial riverine wood OC pool resides on the landscape, and its eventual fate after it leaves a watershed (either by export or decay). For example, in the case of the Olympic mountains, it is unknown whether wood is more recalcitrant in mountain river basins or as driftwood in the near-shore environment (Schwabe et al., 2015; Simenstad et al., 2003).

5 Conclusions

We present quantifications of wood load across the entirety of four river basins across the western U.S. to understand intra- and inter-basin variability in wood load spatial distribution. Our modeling shows that wood jam density, confinement, elevation, and slope are strong controls on wood loads. Comparing basins with differing land use and those with differing climate reveals the strong impact of wood supply on wood loads.

Interpreting these results in the context of past studies allows us to conceptualize wood load through the interaction of wood supply to the valley bottom and the efficiency of the valley bottom at trapping wood delivered to it (Figure 3). We find that differences in wood load between basins with varying precipitation and forest stand characteristics are likely the result of factors influencing wood supply. Local geomorphic factors such as wood storage pattern and valley bottom morphology best explain reach-scale variation in wood load This implies that wood load modeling must take into account effects operating at varying spatial scales. Importantly, our results suggest that after accounting for basin-scale variation in variables such as precipitation and forest characteristics, relatively consistent factors control wood load at the reach-scale, namely those that describe spatial heterogeneity and wood storage pattern. We hypothesize that while every basin is different (Hough-Snee et al., 2015), future multivariate predictive models based on this multi-scale conceptualization of wood load controls will likely be able to accommodate inter-basin variability and predict wood load at the reach scale in a variety of hydroclimatic regions. All factors influencing wood supply and trapping efficiency listed in Figure 3 are quantifiable in both field and flume environments. As such, future statistical analyses, predictive modeling, and experimentation should be able to use the conceptual model we propose as a starting point for determining relevant variables across spatial scales to be used in multivariate modeling of wood load.

The factor of two difference between wood loads in the logged and unlogged wet fluviogenic basins demonstrates the severe impact of clearcut logging with no riparian buffer and provides a clear representation of the potential enhancement of the river corridor that could be achieved by watershed-scale restoration. Restoration actions currently underway in the logged wet fluviogenic basin (Pacific District Olympic National Forest, 2012) focus on addressing the wood supply deficiency that likely causes this wood-poor state. However, our conceptual model suggests that addressing the wood supply impacts of logging at the basin scale will likely only be successful if trapping efficiency is addressed, such that wood is retained within the basin. On a positive note, our comparisons do not suggest that the valley bottom morphology or the density of wood jams differs significantly between these two basins, indicating that the logged wet fluviogenic basin may have similar trapping efficiency to the unlogged wet fluviogenic basin.

In terms of OC storage in valley bottoms, we demonstrate that, especially in wood-rich, undisturbed river networks, wood provides a high magnitude pool of OC. This OC pool may persist for 10^3 years (Guyette et al., 2002; Hyatt & Naiman, 2001), although wood residence time is a major knowledge gap.

Acknowledgements

This work was funded by NSF grant EAR-1562713 and a National Geographic Society Young Explorer Grant. We thank the Quileute tribe and Olympic National Park for access to field sites in the Olympics. We thank Ellen Daugherty for extensive assistance in field work and Katherine Lininger for stimulating discussion that improved the manuscript. Comments from three anonymous reviewers and Charles Luce significantly improved the manuscript. All data supporting the analyses presented here can be found in Dataset S1 as well as the CSU Digital Repository (https://hdl.handle.net/10217/186057, Scott & Wohl, 2018).

References

Aberle, J., & Smart, G. M. (2003). The influence of roughness structure on flow resistance on steep slopes. *Journal of Hydraulic Research*, *41*(3), 259–269.

Beckman, N. D., & Wohl, E. (2014). Effects of forest stand age on the characteristics of logjams in mountainous forest streams. *Earth Surface Processes and Landforms*, *39*(11), 1421–1431. https://doi.org/10.1002/esp.3531

Beechie, T. J., & Sibley, T. H. (1997). Relationships between Channel Characteristics , Woody Debris , and Fish Habitat in Northwestern Washington Streams. *Transactions of the American Fisheries Society*, *126*(2), 217–229. https://doi.org/10.1577/1548-8659(1997)1262.3.CO

Benda, L. (1990). The influence of debris flows on channels and valley floors in the Oregon Coast Range, U.S.A. *Earth Surface Processes and Landforms*, *15*(5), 457–466. https://doi.org/10.1002/esp.3290150508

Benda, L., & Bigelow, P. (2014). On the patterns and processes of wood in northern California streams. *Geomorphology*, *209*, 79–97. https://doi.org/10.1016/j.geomorph.2013.11.028

Benda, L., Veldhuisen, C., & Black, J. (2003). Debris flows as agents of morphological heterogeneity at low-order confluences, Olympic Mountains, Washington. *Bulletin of the Geological Society of America*, *115*(9), 1110–1121. https://doi.org/10.1130/B25265.1

Benda, L., Miller, D., Sias, J., Martin, D., Bilby, R., Veldhuisen, C., & Dunne, T. (2003). Wood Recruitment Processes and Wood Budgeting. *American Fisheries Society Symposium*, *37*(January), 49–73.

Benke, A. C., & Wallace, B. (2003). Influence of Wood on Invertebrate Communities in Streams and Rivers Wood-Created Habitat. *American Fisheries Society Symposium*, *37*, 149–177.

Bertoldi, W., Gurnell, A. M., & Welber, M. (2013). Wood recruitment and retention: The fate of eroded trees on a braided river explored using a combination of field and remotely-sensed data sources. *Geomorphology*, *180–181*, 146–155. https://doi.org/10.1016/j.geomorph.2012.10.003

Bilby, R. E. (1984). Removal of Woody Debris May Affect Stream Channel Stability. *Journal of Forestry*, (October), 609–613.

Bilby, R. E., & Ward, J. W. (1989). Changes in Characteristics and Function of Woody Debris with Increasing Size of Streams in Western Washington. *Transactions of the American Fisheries Society*, *118*(4), 368–378. https://doi.org/10.1577/1548-8659(1989)118<0368:CICAFO>2.3.CO;2

Bilby, R. E., & Ward, J. W. (1991). Characteristics and Function of Large Woody Debris in Streams Draining Old-Growth, Clear-Cut, and Second-Growth Forests in Southwestern Washington. *Canadian Journal of Fisheries and Aquatic Sciences*, *48*(12), 2499–2508. https://doi.org/10.1139/f91-291

Bocchiola, D., Rulli, M. C., & Rosso, R. (2006). Transport of large woody debris in the presence of obstacles. *Geomorphology*, *76*, 166–178. https://doi.org/10.1016/j.geomorph.2005.08.016

Bocchiola, D., Rulli, M. C., & Rosso, R. (2008). A flume experiment on the formation of wood jams in rivers. *Water Resources Research*, *44*(2), 1–17. https://doi.org/10.1029/2006WR005846

Braudrick, C. A., & Grant, G. E. (2000). When do logs move in rivers? *Water Resources Research*, *36*(2), 571–583. https://doi.org/10.1029/1999WR900290

Braudrick, C. A., Grant, G. E., Ishikawa, Y., & Ikeda, H. (1997). Dynamics of Wood Transport in Streams: A Flume Experiment. *Earth Surface Processes and Landforms*, *22*, 669–683.

Brooks, A. P., Brierley, G. J., & Millar, R. G. (2003). The long-term control of vegetation and woody debris on channel and flood-plain evolution: Insights from a paired catchment study in southeastern Australia. *Geomorphology*, *51*(1–3), 7–29. https://doi.org/10.1016/S0169-555X(02)00323-9

Burton, J. I., Olson, D. H., & Puettmann, K. J. (2016). Effects of riparian buffer width on wood loading in headwater streams after repeated forest thinning. *Forest Ecology and Management*, *372*, 247–257. https://doi.org/10.1016/j.foreco.2016.03.053

Cadol, D., Wohl, E., Goode, J. R., & Jaeger, K. L. (2009). Wood distribution in neotropical forested headwater streams of La Selva, Costa Rica. *Earth Surface Processes and Landforms*, *34*(9), 1198–1215. https://doi.org/10.1002/esp.1800

Carah, J. K., Blencowe, C. C., Wright, D. W., & Bolton, L. A. (2014). Low-Cost Restoration Techniques for Rapidly Increasing Wood Cover in Coastal Coho Salmon Streams. *North American Journal of Fisheries Management*, *34*(5), 1003–1013. https://doi.org/10.1080/02755947.2014.943861

Clarke, B. A., & Burbank, D. W. (2010). Bedrock fracturing, threshold hillslopes, and limits to the magnitude of bedrock landslides. *Earth and Planetary Science Letters*, *297*(3–4), 577–586. https://doi.org/10.1016/j.epsl.2010.07.011

Collins, B. D., Montgomery, D. R., Fetherston, K. L., & Abbe, T. B. (2012). The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion. *Geomorphology*, *139–140*, 460–470. https://doi.org/10.1016/j.geomorph.2011.11.011

Davidson, S. L., MacKenzie, L. G., & Eaton, B. C. (2015). Large wood transport and jam formation in a series of flume experiments. *Water Resources Research*, *51*, 10065–10077. https://doi.org/10.1002/ 2015WR017446

Dixon, S. J., & Sear, D. A. (2014). The influence of geomorphology on large wood dynamics in a low gradient headwater stream. *Water Resources Research*, *50*(12), 9194–9210. https://doi.org/10.1002/2014WR015947

Dunkerley, D. (2014). Nature and hydro-geomorphic roles of trees and woody debris in a dryland ephemeral stream: Fowlers Creek, arid western New South Wales, Australia. *Journal of Arid Environments*, *102*, 40–49. https://doi.org/10.1016/j.jaridenv.2013.10.017

Elosegi, A., Díez, J., & Pozo, J. (2007). Contribution of dead wood to the carbon flux in forested streams. *Earth Surface Processes and Landforms*, *32*(8), 1219–1228. https://doi.org/10.1002/esp.1549

Fall, P. L. (1994). Modern Pollen Spectra and Vegetation in the Wind River Range, Wyoming, U.S.A. *Arctic and Alpine Research*, *26*(4), 383–392.

Fetherston, K. L., Naiman, R. J., & Bilby, R. E. (1995). Large woody debris, physical process, and riparian forest development in montane river networks of the Pacific Northwest. *Geomorphology*, *13*(1–4), 133–144. https://doi.org/10.1016/0169-555X(95)00033-2

Gerstel, W. J., & Lingley Jr., W. S. (2000). *Geologic Map of the Forks 1:100,000 Quadrangle, Washington*.

Gomi, T., Sidle, R. C., Woodsmith, R. D., & Bryant, M. D. (2003). Characteristics of channel steps and reach morphology in headwater streams, southeast Alaska. *Geomorphology*, *51*(1–3), 225–242. https://doi.org/10.1016/S0169-555X(02)00338-0

Gurnell, A. M. (2013). Wood in Fluvial Systems. In J. Schroder & E. Wohl (Eds.), *Treatise on Geomorphology* (Vol. 9, pp. 163–188). San Diego, CA: Elsevier Ltd.

https://doi.org/10.1016/B978-0-12-374739-6.00236-0

Gurnell, A. M., Petts, G. E., Harris, N., Ward, J. V., Tockner, K., Edwards, P. J., & Kollmann, J. (2000). Large wood retention in river channels: The case of the Fiume Tagliamento, Italy. *Earth Surface Processes and Landforms*, *25*(3), 255–275. https://doi.org/10.1002/(SICI)1096-9837(200003)25:3<255::AID-ESP56>3.0.CO;2-H

Gurnell, A. M., Piegay, H., Swanson, F. J., & Gregory, S. V. (2002). Large wood and fluvial processes. *Freshwater Biology*, *47*, 601–619. https://doi.org/10.1046/j.1365-2427.2002.00916.x

Guthrie, R. H. (2002). The effects of logging on frequency and distribution of landslides in three watersheds on Vancouver Island, British Columbia. *Geomorphology*, *43*(3–4), 273–292. https://doi.org/10.1016/S0169-555X(01)00138-6

Guyette, R. P., Cole, W. G., Dey, D. C., & Muzika, R.-M. (2002). Perspectives on the age and distribution of large wood in riparian carbon pools. *Canadian Journal of Fisheries and Aquatic Sciences*, *59*(3), 578–585. https://doi.org/10.1139/f02-026

Guyette, R. P., Dey, D. C., & Stambaugh, M. C. (2008). The Temporal Distribution and Carbon Storage of Large Oak Wood in Streams and Floodplain Deposits. *Ecosystems*, *11*(4), 643–653. https://doi.org/10.1007/s10021-008-9149-9

Harmon, M. E., Woodall, C. W., & Sexton, J. (2011). *Standing and Downed Dead Tree Wood Density Reduction Factors : A Comparison Across Decay Classes and Tree Species*. *Research Paper NRS-15*.

Holm, S. (1979). A Simple Sequentially Rejective Multiple Test Procedure. *Scandinavian Journal of Statistics*, *6*(2), 65–70.

Homer, C. G., Dewitz, J. A., Yang, L., Jin, S., Danielson, P., Xian, G., et al. (2015). Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing*, *81*(5), 345–354.

Hough-Snee, N., Kasprak, A., Rossi, R. K., Bouwes, N., Roper, B. B., & Wheaton, J. M. (2015). Hydrogeomorphic and Biotic Drivers of Instream Wood Differ Across Sub-basins of the Columbia River Basin, USA. *River Research and Applications*, *32*(6), 1302–1315. https://doi.org/10.1002/rra.2968

Hyatt, T., & Naiman, R. J. (2001). The residence time of large woody debris in the Queets River, Washington, USA. *Ecological Applications*, *11*(1), 191–202.

Iroumé, A., Mao, L., Andreoli, A., Ulloa, H., & Ardiles, M. P. (2015). Large wood mobility processes in low-order Chilean river channels. *Geomorphology*, *228*, 681–693. https://doi.org/10.1016/j.geomorph.2014.10.025

Jakob, M. (2000). The impacts of logging on landslide activity at Clayoquot Sound, British Columbia. *Catena*, *38*(4), 279–300.

Jones, K. K., Anlauf-Dunn, K., Jacobsen, P. S., Strickland, M., Tennant, L., & Tippery, S. E. (2014). Effectiveness of Instream Wood Treatments to Restore Stream Complexity and Winter Rearing Habitat for Juvenile Coho Salmon. *Transactions of the American Fisheries Society*, *143*(2), 334–345. https://doi.org/10.1080/00028487.2013.852623

Kramer, N., & Wohl, E. (2016). Rules of the road: A qualitative and quantitative synthesis of large wood transport through drainage networks. *Geomorphology*, *279*, 74–97. https://doi.org/10.1016/j.geomorph.2016.08.026

Lamlom, S. H., & Savidge, R. A. (2003). A reassessment of carbon content in wood: Variation within and between 41 North American species. *Biomass and Bioenergy*, *25*(4), 381–388.

https://doi.org/10.1016/S0961-9534(03)00033-3

Larsen, I. J., & Montgomery, D. R. (2012). Landslide erosion coupled to tectonics and river incision. *Nature Geoscience*, *5*(7), 468–473. https://doi.org/10.1038/ngeo1479

Lininger, K. B., Wohl, E., Sutfin, N. A., & Rose, J. R. (2017). Floodplain downed wood volumes: a comparison across three biomes. *Earth Surface Processes and Landforms*. https://doi.org/10.1002/esp.4072

Manners, R. B., Doyle, M. W., & Small, M. J. (2007). Structure and hydraulics of natural woody debris jams. *Water Resources Research*, *43*(6), 1–17. https://doi.org/10.1029/2006WR004910

Marcus, W. A., Marston, R. A., Colvard, C. R., & Gray, R. D. (2002). Mapping the spatial and temporal distributions of woody debris in streams of the Greater Yellowstone Ecosystem, USA. *Geomorphology*, *44*(3–4), 323–335. https://doi.org/Pii S0169-555x(01)00181-7\rDoi 10.1016/S0169-555x(01)00181-7

Martin, D. J., & Benda, L. (2001). Patterns of Instream Wood Recruitment and Transport at the Watershed Scale. *Transactions of the American Fisheries Society*, *130*, 940–958. https://doi.org/10.1577/1548-8659(2001)130<0940:POIWRA>2.0.CO;2

Montgomery, D. R., & Buffington, J. M. (1997). Channel-reach morphology in mountain drainage basins. *Bulletin of the Geological Society of America*, *109*(5), 596–611.

Montgomery, D. R., Abbe, T. B., Buffington, J. M., Peterson, N. P., Schmidt, K. M., & Stock, J. D. (1996). Distribution of bedrock and alluvial channels in forested mountain drainage basins. *Nature*, *381*(13), 587–589. https://doi.org/10.1038/381587a0

Montgomery, D. R., Massong, T. M., & Hawley, S. C. S. (2003). Influence of debris flows and log jams on the location of pools and alluvial channel reaches, Oregon Coast Range. *Bulletin of the Geological Society of America*, *115*(1), 78–88. https://doi.org/10.1130/0016-7606(2003)115<0078:IODFAL>2.0.CO;2

Nagayama, S., Nakamura, F., Kawaguchi, Y., & Nakano, D. (2012). Effects of configuration of instream wood on autumn and winter habitat use by fish in a large remeandering reach. *Hydrobiologia*, *680*, 159–170. https://doi.org/10.1007/s10750-011-0913-z

Naiman, R. J., Melillo, J. M., Lock, M. A., Ford, T. E., & Reice, S. R. (1987). Longitudinal patterns of ecosystem processes and community structure in a subarctic river continuum. *Ecology*, *68*(5), 1139–1156. https://doi.org/10.2307/1939199

Nanson, G. C., Barbetti, M., & Taylor, G. (1995). River stabilisation due to changing climate and vegetation during the late Quaternary in western Tasmania, Australia. *Geomorphology*, *13*(1–4), 145–158. https://doi.org/10.1016/0169-555X(95)00040-C

Opperman, J. J., Meleason, M., Francis, R. a., & Davies-Colley, R. (2008). "Livewood": Geomorphic and Ecological Functions of Living Trees in River Channels. *BioScience*, *58*(11), 1069. https://doi.org/10.1641/B581110

Oregon State University. (2004). PRISM Climate Group.

Osei, N. A., Gurnell, A. M., & Harvey, G. L. (2015). The role of large wood in retaining fine sediment, organic matter and plant propagules in a small, single-thread forest river. *Geomorphology*, *235*, 77–87. https://doi.org/10.1016/j.geomorph.2015.01.031

Pacific District Olympic National Forest. (2012). *Sitkum Watershed Restoration Action Plan*.

Pfeiffer, A., & Wohl, E. (2018). Where Does Wood Most Effectively Enhance Storage? Network-Scale Distribution of Sediment and Organic Matter Stored by Instream Wood. *Geophysical Research Letters*, *45*(1), 194–200. https://doi.org/10.1002/2017GL076057

Piégay, H., Moulin, B., & Hupp, C. R. (2017). Assessment of transfer patterns and origins of in-channel wood in large rivers using repeated field surveys and wood characterisation (the Isère River upstream of Pontcharra, France). *Geomorphology*, *279*, 27–43. https://doi.org/10.1016/j.geomorph.2016.07.020

R Core Team. (2017). R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing.

Ralph, S. C., Poole, G. C., Conquest, L. L., & Naiman, R. J. (1994). Stream Channel Morphology and Woody Debris in Logged and Unlogged Basins of Western Washington. *Canadian Journal of Fisheries and Aquatic Sciences*, *51*, 37–51. https://doi.org/10.1139/f94-006

Richard, G. A., Julien, P. Y., & Baird, D. C. (2005). Statistical analysis of lateral migration of the Rio Grande, New Mexico. *Geomorphology*, *71*(1–2), 139–155. https://doi.org/10.1016/j.geomorph.2004.07.013

Roberts, B., Ward, B., & Rollerson, T. (2004). A comparison of landslide rates following helicopter and conventional cable-based clear-cut logging operations in the Southwest Coast Mountains of British Columbia. *Geomorphology*, *61*(3–4), 337–346. https://doi.org/10.1016/j.geomorph.2004.01.007

Ruffing, C. M., Daniels, M. D., & Dwire, K. A. (2015). Disturbance legacies of historic tie-drives persistently alter geomorphology and large wood characteristics in headwater streams, southeast Wyoming. *Geomorphology*, *231*(February), 1–14. https://doi.org/10.1016/j.geomorph.2014.10.029

Ruiz-Villanueva, V., Wyżga, B., Mikuś, P., Hajdukiewicz, H., & Stoffel, M. (2016). The role of flood hydrograph in the remobilization of large wood in a wide mountain river. *Journal of Hydrology*, *541*(April), 330–343. https://doi.org/10.1016/j.jhydrol.2016.02.060

Schwabe, E., Bartsch, I., Błazewicz-Paszkowycz, M., Brenke, N., Chernyshev, A. V., Elsner, N. O., et al. (2015). Wood-associated fauna collected during the KuramBio expedition in the North West Pacific. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *111*(January 2015), 376–388. https://doi.org/10.1016/j.dsr2.2014.08.001

Scott, D. N., & Wohl, E. (2018). Dataset for Natural and Anthropogenic Controls on Wood Loads in River Corridors of the Rocky, Cascade, and Olympic Mountains, USA. Colorado State University Library. https://doi.org/https://hdl.handle.net/10217/186057

Scott, D. N., Montgomery, D. R., & Wohl, E. (2014). Log step and clast interactions in mountain streams in the central Cascade Range of Washington State, USA. *Geomorphology*, *216*, 180–186. https://doi.org/10.1016/j.geomorph.2014.04.004

Scott, D. N., Brogan, D. J., Lininger, K. B., Schook, D. M., Daugherty, E. E., Sparacino, M. S., & Patton, A. I. (2016). Evaluating survey instruments and methods in a steep channel. *Geomorphology*, *273*, 236–243. https://doi.org/10.1016/j.geomorph.2016.08.020

Shields, F. D., Knight, S. S., & Stofleth, J. M. (2006). Large wood addition for aquatic habitat rehabilitation in an incised, sand-bed stream, Little Topashaw Creek, Mississippi. *River Research and Applications*, *22*(7), 803–817. https://doi.org/10.1002/rra.937

Sidle, R. C., Ziegler, A. D., Negishi, J. N., Nik, A. R., Siew, R., & Turkelboom, F. (2006). Erosion processes in steep terrain - Truths, myths, and uncertainties related to forest management in Southeast Asia. *Forest Ecology and Management*, *224*(1–2), 199–225. https://doi.org/10.1016/j.foreco.2005.12.019

Simenstad, C. A., Wick, A., Van de Wetering, S., & Bottom, D. L. (2003). Dynamics and ecological functions of wood in estuarine and coastal marine ecosystems. In S. V Gregory, K. L. Boyer, & A. M. Gurnell (Eds.), *The ecology and management of wood in world rivers* (pp. 265–277). Bethesda, Maryland: American Fisheries Society.

Smithwick, E., Harmon, M. E., Remillard, S. M., Acker, S. A., & Franklin, J. F. (2002). Potential upper bounds of carbon stores in forests of the Pacific Northwest. *Ecological Applications*, *12*(5), 1303–1317. https://doi.org/10.1890/1051-0761(2002)012[1303:PUBOCS]2.0.CO;2

Strahler, A. N. (1957). Quantitative classification of watershed geomorphology. *Transactions, American Geophysical Union*, *38*(6), 915–920.

Sutfin, N. A., Wohl, E., & Dwire, K. A. (2016). Banking carbon: A review of organic carbon storage and physical factors influencing retention in floodplains and riparian ecosystems. *Earth Surface Processes and Landforms*, *60*, 38–60. https://doi.org/10.1002/esp.3857

Thevenet, A., Citterio, A., & Piegay, H. (1998). A new methodology for the assessment of large woody debris accumulations on highly modified rivers (example of two french piedmont rivers). *Regulated Rivers: Research & Management*, *14*, 467–483. https://doi.org/10.1002/(SICI)1099-1646(1998110)14:6<467::AID-RRR514>3.0.CO;2-X

Wagenmakers, E.-J., & Farrell, S. (2004). AIC model selection using Akaike weights. *Psychonomic Bulletin & Review*, *11*(1), 192–196. https://doi.org/10.3758/BF03206482

Van Wagner, C. E. (1968). The line intersect method in forest fuel sampling. *Forest Science*, *14*, 20–26.

Wallace, J. B., & Benke, A. C. (1984). Quantification of Wood Habitat in Subtropical Coastal Plain Streams. *Canadian Journal of Fisheries and Aquatic Sciences*, *41*(11), 1643–1652. https://doi.org/10.1139/f84-203

Warren, D. R., Keeton, W. S., & Kraft, C. E. (2008). A comparison of line-intercept and census techniques for assessing large wood volume in streams. *Hydrobiologia*, *598*(1), 123–130. https://doi.org/10.1007/s10750-007-9144-8

Webb, A. A., & Erskine, W. D. (2003). Distribution, recruitment, and geomorphic significance of large woody debris in an alluvial forest stream: Tonghi Creek, southeastern Australia. *Geomorphology*, *51*(1–3), 109–126. https://doi.org/10.1016/S0169-555X(02)00327-6

Wickert, A. D., Martin, J. M., Tal, M., Kim, W., Sheets, B., & Paola, C. (2013). River channel lateral mobility: Metrics, time scales, and controls. *Journal of Geophysical Research: Earth Surface*, *118*(2), 396–412. https://doi.org/10.1029/2012JF002386

Wilcoxon, F. (1945). Individual Comparisons by Ranking Methods. *Biometrics Bulletin*, *1*(6), 80–83. https://doi.org/10.2307/3001946

Wohl, E. (2013). Floodplains and wood. *Earth-Science Reviews*, *123*, 194–212. https://doi.org/10.1016/j.earscirev.2013.04.009

Wohl, E. (2014). A legacy of absence: Wood removal in US rivers. *Progress in Physical Geography*, *38*(5), 637–663. https://doi.org/10.1177/0309133314548091

Wohl, E., & Goode, J. R. (2008). Wood dynamics in headwater streams of the Colorado Rocky Mountains. *Water Resources Research*, *44*(9), 1–14. https://doi.org/10.1029/2007WR006522

Wohl, E., Dwire, K., Sutfin, N., Polvi, L., & Bazan, R. (2012). Mechanisms of carbon storage in mountainous headwater rivers. *Nature Communications*, *3*, 1263. https://doi.org/10.1038/ncomms2274

Wohl, E., Hall, R. O., Lininger, K. B., Sutfin, N. A., & Walters, D. M. (2017). Carbon dynamics of river corridors and the effects of human alterations. *Ecological Monographs*, *87*(3), 379–409. https://doi.org/10.1002/ecm.1261

Wohl, E., Lininger, K. B., Fox, M., Baillie, B. R., & Erskine, W. D. (2017). Instream large wood loads across bioclimatic regions. *Forest Ecology and Management*, *404*(September), 370–

380. https://doi.org/10.1016/j.foreco.2017.09.013
Wohl, E., Cadol, D., Pfeiffer, A., Jackson, K., & Laurel, D. (2018). Distribution of Large Wood Within River Corridors in Relation to Flow Regime in the Semiarid Western US. *Water Resources Research*, 1–15. https://doi.org/10.1002/2017WR022009
Wohl, E., Scott, D. N., & Lininger, K. B. (2018). Spatial distribution of channel and floodplain large wood in forested river corridors of the Northern Rockies. *Water Resources Research*. https://doi.org/10.1029/2018WR022750
Wolter, A., Ward, B., & Millard, T. (2010). Instability in eight sub-basins of the Chilliwack River Valley, British Columbia, Canada: A comparison of natural and logging-related landslides. *Geomorphology*, *120*(3–4), 123–132. https://doi.org/10.1016/j.geomorph.2010.03.008
Wondzell, S. M., & Bisson, P. A. (2003). Influence of Wood on Aquatic Biodiversity. *American Fisheries Society Symposium*, *37*, 249–263.
Wyżga, B., Mikuś, P., Zawiejska, J., Ruiz-villanueva, V., Kaczka, R. J., & Czech, W. (2017). Log transport and deposition in incised , channelized , and multithread reaches of a wide mountain river : Tracking experiment during a 20-year fl ood. *Geomorphology*, *279*, 98–111. https://doi.org/10.1016/j.geomorph.2016.09.019

Tables

Table 1: Characteristics of study basins. Mean annual precipitation data are from PRISM (Oregon State University, 2004). Relief, drainage area, and mean basin slope are calculated from a 10 m DEM.

Basin	**Mean Annual Precipitation (m)**	**Relief (m)**	**Drainage Area (km^2)**	**Mean Basin Slope (%)**
Logged Wet Fluviogenic	3.61	1024	112	49
Unlogged Wet Fluviogenic	3.67	1024	85	45
Wet Glaciogenic	3.04	2079	407	60
Semi-arid Glaciogenic	0.72	1630	114	25

Figures

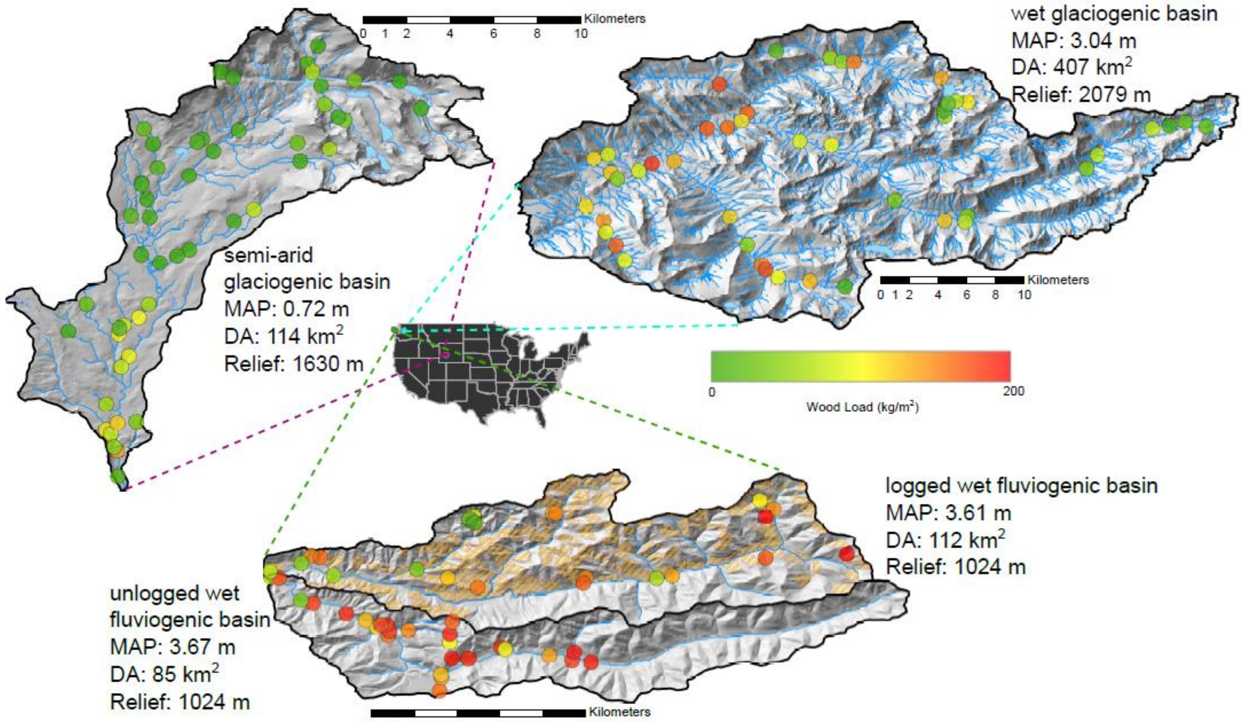

Figure 1: Map showing the location, topography, sampling sites, and stream network of the sampled basins. Clockwise, from upper left: Big Sandy watershed, Wyoming; MF Snoqualmie watershed, Washington; Sitkum (north) and SF Calawah (south) watersheds, Washington. Circles represent sampling locations at which wood loads were measured, and are colored by wood load. The orange overlay in the Sitkum basin shows areas that have experienced recorded clearcut timber harvest. Mean annual precipitation (MAP), drainage area (DA), and relief are given for each basin.

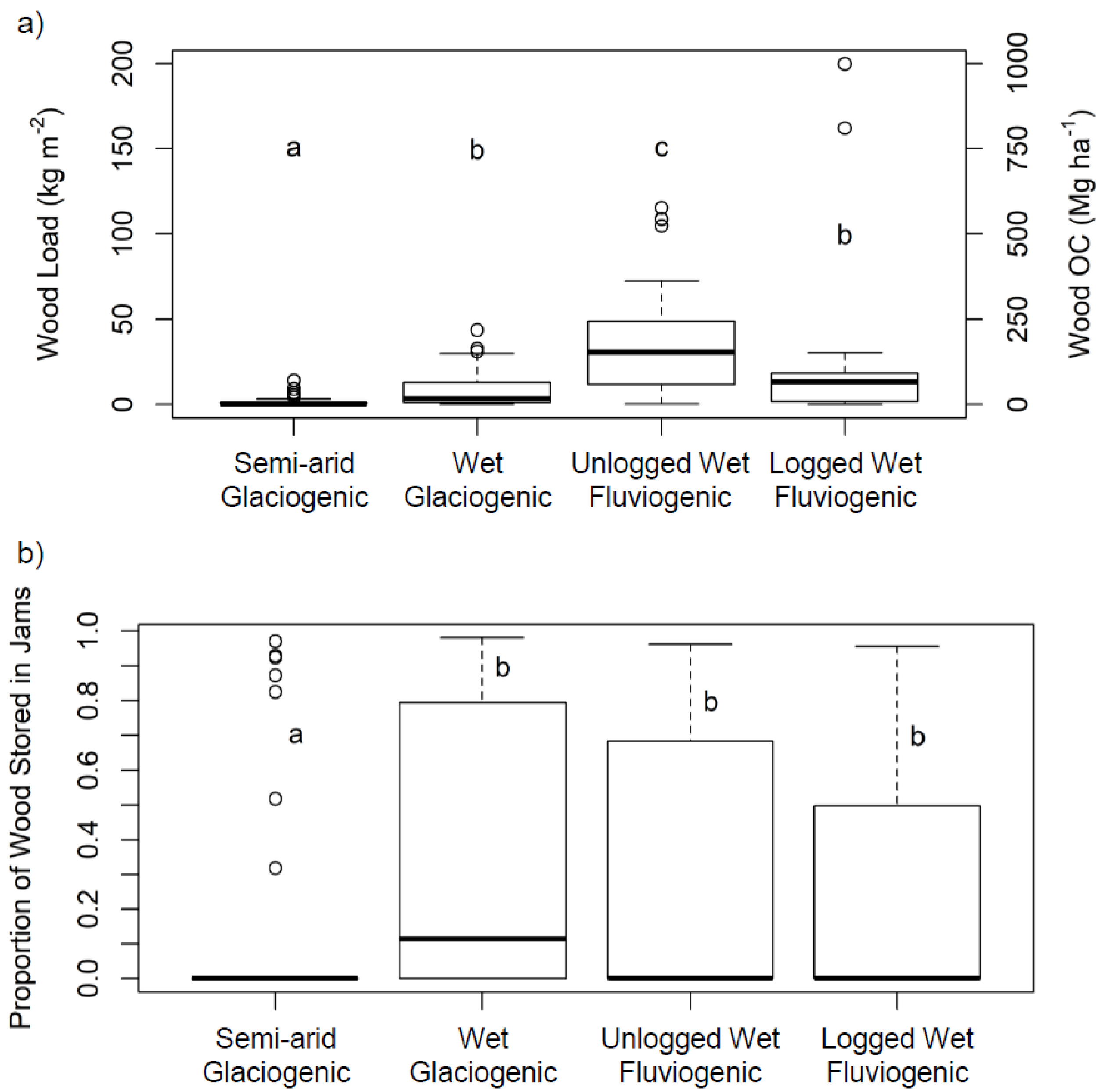

Figure 2: Boxplot of wood load and OC storage in wood (a) and the proportion of wood stored in jams (b) by study basin. Bold line represents median. Box top and bottom represent 75th and 25th percentile, respectively. Ends of dashed lines represent 1.5 times the interquartile range. Circles represent outliers. Letters show significantly different groups at a 95% confidence level. Data shown here are summarized in Table S2, and translated to wood volume for comparison in Figure S1.

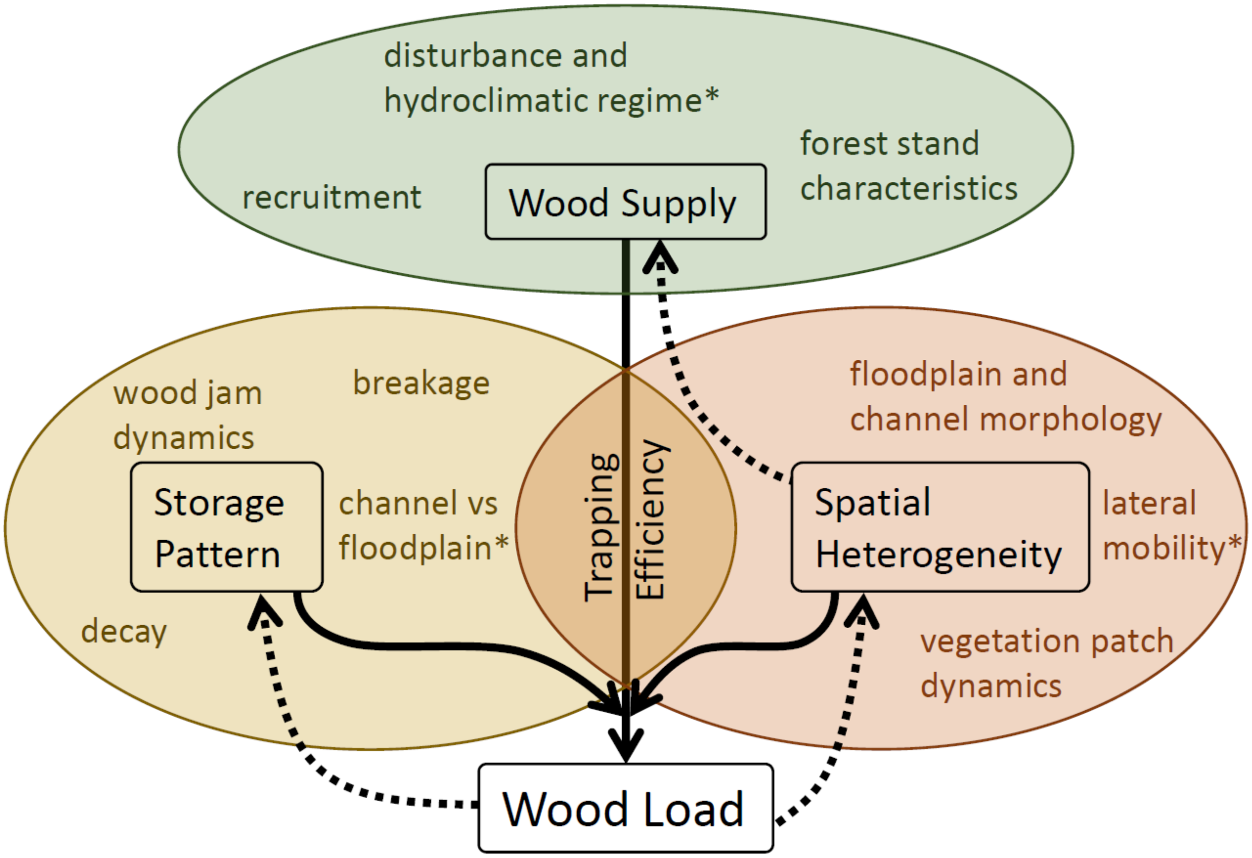

Figure 3: Conceptual model of controls on valley bottom wood load. Colored text within the ellipse surrounding each control indicates the processes that regulate that control. Dotted arrows represent feedbacks. Asterisks indicate processes that may determine other processes within each ellipse. Wood supply regulates wood load through the filter of trapping efficiency. That is, trapping efficiency is the first-order, local control on wood load, whereas wood supply is a broader, basin-scale limit on maximum wood load. This model can be used to explain differences in wood loads between basins (mainly related to wood supply), the effects of anthropogenic activities or changing climate, and variation within a single basin. See section 4.3 for details.