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Wood controls on pool spacing, step characteristics and sediment storage in headwater streams of the northwestern Cascade Mountains

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ABSTRACT

Wood influences channel morphology in headwater streams by creating steps and pools in the longitudinal profile and trapping sediment. We used field data from 32 headwater stream reaches in the northwestern Cascade Mountains to test the hypotheses that 1) larger diameter classes of large wood (LW, defined as pieces with diameter > 10 cm and length > 0.5 m) are critical step-keying materials in headwater channels despite narrow channel widths (1–4 m), 2) wood-keyed steps trap more sediment than clast- and root-keyed steps, and 3) the negative relationship between LW frequency and the distance between pools observed elsewhere in large streams extends to headwater streams. We found that the frequency of step key pieces peaked in the 20–40 cm diameter class. Similarly, 40–100 cm diameter pieces were disproportionately associated with key-piece function compared to their overall association with step formation (wood with diameter < 10 cm was an important step-keying material in channels of width < 2 m). Steps keyed by wood were significantly more likely to store sediment than clast- or root-keyed steps. In contrast to previous work that did not detect a relationship between wood loading and pool habitat in step-pool channels, pool spacing ranged between ~17 and 1.5 channel widths with an apparent relationship described by a negative exponential function of LW frequency (RMSE = 2.85 channel widths/pool), although the range of LW frequency and the functional relationship were different than those of lower gradient channels. Additionally, linear and nonparametric models demonstrate that sediment storage and step and pool characteristics are related to wood loading and stand history with important distinctions based on channel width. These results confirm the importance of maintaining riparian buffers sufficient to provide functional wood to headwater streams.

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1. Introduction

Wood influences physical and biological processes in large and small streams by reducing the velocity of flowing water, trapping sediment and fining the substrate behind in-channel obstructions, and diversifying channel morphology (Swanson et al., 1982; Buffington and Montgomery, 1999; Fausch and Northcote, 1992; Abbe and Montgomery, 1996; Faustini and Jones, 2003; MacFarlane and Wohl, 2003; Wilcox et al., 2011; Wohl and Scott, 2017). In headwater streams, which are usually narrower and steeper than their downstream counterparts, wood creates morphological diversity through the formation of steps and pools in the longitudinal profile that meter the movement of sediment and cool water to downstream reaches, among other functions (Gomi et al., 2001; Jackson and Sturm, 2002; Pfeiffer and Wohl, 2018). Additionally, pools provide critical wetted habitat for amphibians and macroinvertebrates during low flow conditions when other portions of the channel go dry (Hunter et al., 2005; Olson and Weaver, 2007; Bogan et al., 2015). Because maintenance of morphological complexity in small streams is critical for aquatic habitat and the fate of stored sediment in the stream network, and because small, steep channels may represent as much as 80% of the channel network by length (Stock and Dietrich, 2003; Benda et al., 2005), a large body of research has focused on characterizing relationships between wood and the channel processes that promote the creation and maintenance of steps and pools (Wohl et al., 1997; Gomi et al., 2003; Jackson and Sturm, 2002; May and Gresswell, 2003; Faustini and Jones, 2003; Lienkaemper and Swanson, 1987; MacFarlane and Wohl, 2003).

Both wood- and clast-keyed steps provide numerous functions in small streams (Jackson and Sturm, 2002). Steps function as grade control elements which cause plunging flow and pool scour (Abrahams et al., 1995; Church and Zimmermann, 2007). Steps may also serve as roughness elements that help to slow the flow of water in the absence of significant elevation drop or pool scour, acting to fine the bed substrate and limit sediment transport during high flows. Additionally, steps may retain sediment volumes exceeding many

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times the annual sediment export from such streams (Megahan, 1982). However, the relative functionality of wood- versus clast-keyed steps remains poorly examined, leaving open important questions regarding the role of wood in headwater channels. For example, whether clast-keyed steps are equally effective as wood-keyed steps at metering sediment and causing pool scour is important for assessing the consequences of management practices that reduce wood recruitment.

One study found a tradeoff in wood and clast size such that steps keyed by smaller wood required the secondary entrainment of larger clasts to perform similar functions to those expected in old growth forests (Scott et al., 2014). This suggests that some fluvial functions may depend on bed load characteristics if the in-channel wood size distribution is altered by forest disturbance. Similarly, it is commonly posited that fine wood (FW, diameter 2–10 cm), or the smaller size classes of LW (i.e. diameter < 40 cm) may function as step-forming agents in small streams due to low fluvial power and the jamming effect of closely-spaced channel banks (Jackson and Sturm, 2002). By the same token, LW pieces are non-functional where they span the channel banks and do not interact with flows (Hassan et al., 2005; Jones et al., 2011). However, few studies of headwater streams have examined the size distribution and composition (clast, wood, or root) of all step keying elements, as opposed to that of functional (or even step-forming) wood in general. While it is well known that smaller-sized wood may be more functional in smaller streams for the reasons stated above, less is known about the size distribution required to form key pieces in headwater streams, hampering efforts to target riparian management strategies to the step-forming requirements of small streams.

Additionally, pools are commonly associated with LW in low to moderate gradient channels due to scour behind LW obstructions (Beechie and Sibley, 1997). The distance between pools has been shown to decrease with increasing LW loads (Montgomery et al., 1995) and the specific functional relationship depends on channel gradient, with steeper channels having a greater dependence on LW loading to form pools (Beechie and Sibley, 1997). However, the Beechie and Sibley study focused on low- to moderate-gradient (0.001-0.05 m/m) salmonid bearing streams, and the Montgomery study included only six step-pool channels. In principle, if wood is responsible for creating steps in the longitudinal profile of steep streams (Gomi et al., 2003), and pools are associated with steps due to plunging flow over step crests (Chin and Wohl, 2005), wood loading should be expected to reduce pool spacing in small channels as long as flows are sufficient to cause scour at the base of steps (Jackson and Sturm, 2002). However, it is also possible that headwater channels in forested drainage basins contain such large numbers of wood pieces that pool formation is not related to wood frequency. This would imply a threshold effect in pool spacing dependent on wood frequency and channel size, and could explain the lack of a relationship found by Montgomery et al. (1995) in step-pool channels.

Despite the clear management implications regarding riparian forest protections from logging and the ubiquitous nature of headwater channels in forested areas, the relationship between wood and pool spacing has been tested only to a limited degree in small streams. One study found a linear relationship between LW loading (in units of pieces/channel length/channel width) and the percent channel length composed of pools but not with pool frequency, suggesting LW may control pool size but not the number of pools (Jackson and Sturm, 2002).

In this paper, our goal is to investigate key unknowns regarding the functional role of wood in creating and maintaining morphological diversity in headwater streams of the northwestern Cascade Mountain range. This subregion of the Cascade Mountains is surprisingly absent from the wood and headwater channel processes literature despite the large forest land base, steep and active landscape, and importance to regional salmonid productivity and recovery (SRSC and WDFW, 2005). Specifically, we test the hypotheses that 1) medium to large size classes of LW are especially effective as step key pieces in forested headwater streams, despite the common involvement of FW in the formation of wood steps; 2) wood, and LW in particular, is a more effective step-keying material than clasts or roots in terms of its ability to store sediment; and 3) the distance between pools is reduced by increasing LW loading as has been observed for larger fish-bearing streams. To investigate these hypotheses, we present detailed channel and wood surveys from 32 headwater stream reaches in the Skagit and Samish River basins of Washington State, USA, and augment the analysis with statistical models elucidating general relationships between wood and channel and basin characteristics. Although we focus on the northwestern Cascade Mountain range and present findings specific to that region, our results support the implementation of riparian buffer strategies for headwater streams in forested drainage basins in other settings as well.

2. Study area

We collected field data in 32 study reaches within the Skagit River and Samish River drainage basins in northwestern Washington State, USA (Fig. 1). Elevations within the study basins range from sea level to over 3000 m on Mount Baker and Glacier Peak, two Quaternary Cascade volcanos. A regionally-significant fault system, the Straight Creek Suture Zone, separates the igneous and metamorphic core of the Cascade Range to the east from the relatively erodible terrain of the Western Domain of Tabor and Haugerud (1999). Our study sites are all located west of the suture zone, where the geology is dominated by low grade metamorphic rocks (primarily phyllite and greenschist), sandstones, and glacial deposits from both continental and alpine glaciations (Tabor et al., 2003). Regional precipitation is strongly orographic: mean annual precipitation exceeds 5500 mm/yr at the nearby summit of Mount Baker, while average values commonly exceed 3000 mm/yr and may be as low as 1000 mm/yr in the low-lying areas near sea level (PRISM Climate Group, 2010).

The study sites are in low elevation (100–850 m) forests of the Western Hemlock climax zone of Franklin and Dyrness (1973). Dominant tree species in forested uplands include western red cedar (*Thuja plicata*), Douglas-fir (*Psuedotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and red alder (*Alnus rubra*). Old growth western red cedar and Douglas-fir are known for their resistance to decay and large size; LW derived from old conifer trees commonly exceeds one meter in diameter and dead wood can last for 100s of years within the channel (Hyatt and Naiman, 2001). European-American colonizers logged most of the low-elevation old growth forests, greatly reducing average stand ages and potentially altering the size structure of wood within stream channels (Swanson and Lienkaemper, 1978). Today, the forest industry harvests timber from managed stands that in some cases are on their third harvest rotation, although substantial old growth remains within federally-owned portions of the Skagit River basin.

3. Methods

3.1. Site selection

We selected sites spanning a range in channel widths (all <4 m) and gradients within two forest types (unlogged and previously logged mature) and two bedrock types common to the region (sandstone and phyllite) (Fig. 1). Riparian stands in the unlogged sites ranged in age between 170 years and 934 years according to U.S. Forest Service stand age maps. Previously logged sites ranged in age between 29 years and 79 years (WA Department of Natural

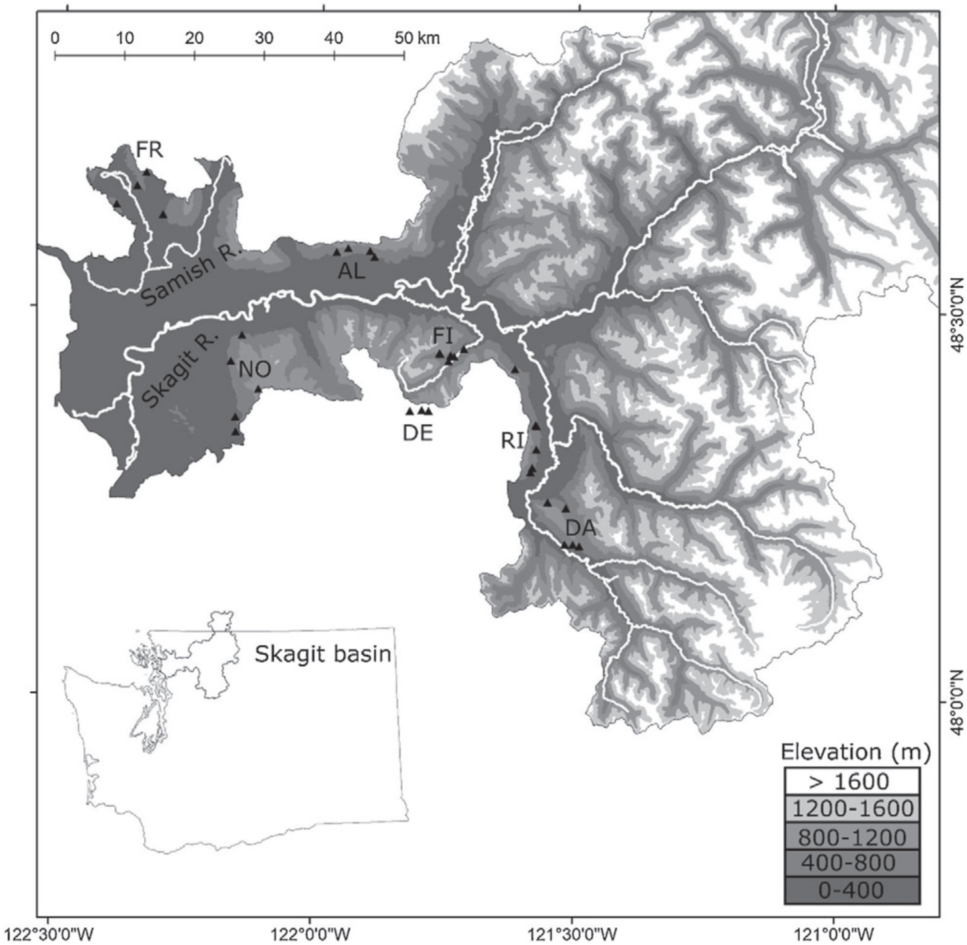

Fig. 1. Location map showing the Skagit and Samish River basins in northwestern Washington State, USA. Major rivers are shown in white (impounded lakes appear as polygons). Site locations within clustered blocks are shown as black triangles, with the letter portion of the site names listed next to each block. The FR sites flow into the Samish River, the DE sites are tributary to the Stillaguamish River, and all other sites are tributary to the Skagit River. Inset shows location within Washington State; the small portion of the Skagit River drainage in British Columbia is excluded from the location map.

Resources, personal communication). Logging practices in that era involved clearcut logging of riparian zones, though sub-merchantable trees and debris were left. We identified the study streams from randomly-selected parcels within tracts of forest land meeting the elevation and bedrock criteria. Once the parcel was field located, we chose for study the first stream found that met the forest age, channel width and gradient criteria. We chose stream segment locations to avoid tributary junctions and abrupt gradient changes. Where possible, we avoided locating sites directly downstream of road crossings to minimize possible sedimentation effects. Segment lengths were 30–50 times the active channel width. All study reaches were confined by adjacent hillslopes and had little to no meandering planform pattern.

3.2. Field surveys

Field data collection involved a channel survey component and a wood inventory. We measured the longitudinal profile of each segment using a surveying level (with tripod), rod and tape measure. We measured the active channel width every 10 m along the long profile and report the means of these measurements. All pools and steps exceeding 10 cm in height were documented along the thalweg profile. We categorized steps by key element (e.g. clast, wood, root) and measured the diameter of the dominant element. We also placed each step into a primary functional category: sediment storage, grade control, or roughness. Sediment storage steps were identified based on the presence of a wedge of sediment upstream of the step-forming element; grade control steps did not have significant sediment accumulations but featured an erosional drop at their base; roughness steps did not trap significant sediment and did not cause localized scour and erosion at the base but nonetheless may add to the overall form resistance of the channel and therefore are geomorphically significant (Curran and Wohl, 2003). For each sediment storage step, we measured the wedge length, two to three wedge widths, and the depth on the step face to calculate an estimated volume of stored sediment, approximated as a half rectangular prism $((L * W * D)/2)$. Where no evidence of the contact between alluvial material and bedrock could be found on the step face, we assumed the step height represented the maximum wedge depth. We recorded volumes of sediment not stored in steps (termed 'non-step storage') in the cases in which accumulations were distinct but not associated with step morphology. For consistency and objectivity, we only recorded sediment storage volumes (in steps and non-step storage) of 0.1 m^3 or greater.

During the channel surveys we noted apparent pool locations based on criteria of locally inverted bed slope and measurable residual depth. Following data entry, we made the final determination of pool status after considering the wide range of definitions of what constitutes a pool (see Montgomery et al., 1995). Purely morphological definitions are reliant on the literature of lower gradient pool-riffle channels; all employ some form of negative deviation from the channel bed mean elevation, slow relative flow at low to moderate discharges, and/or relatively flat water surfaces (Leopold et al., 1964; Keller, 1971; O'Neill and Abrahams, 1984; Montgomery et al., 1995). Most definitions imply local scour around wood, clast, or bedform obstructions. Habitat-based definitions have included criteria of 10 cm residual depth (Pleus et al., 1999), a number largely informed by the requirements for juvenile salmonids. Several studies have also employed a criterion for pool depth scaled to mean bankfull or active channel width (Wood-Smith and Buffington, 1996; Jackson and Sturm, 2002), presumably under the justification that smaller pools may be functionally important in smaller channels. There is also a class of papers that distinguishes pools (and steps) based on the hydraulics of plunging flow (Church and Zimmermann, 2007, and references therein). In these studies, pools are differentiated from steps largely by the transition between critical or supercritical flow over step crests into subcritical flow in the pools (Chin and Wohl, 2005). Fluctuations in hydraulic state are determined by channel gradient, relative roughness and flood stage in addition to channel morphology (Church and Zimmermann, 2007).

We sought a definition for pool that does not depend on water surface elevations or hydraulic measurements, and that is easily identifiable in the field. We identified pools as being channel units with a negatively-sloping bed surface and a residual depth of at least 5 cm. The depth criterion was meant to ensure the negative slope of the profile because positively sloping riffle units were common; pools should be distinguished by at least some scour due to plunging flow at the base of a step. Moreover, negatively sloping units (even of shallow depth) are expected to function geomorphically in small streams to trap sediment on the waning limb of flood stages. From a habitat perspective, all of the channels in this study were above the known fish range (including resident populations); therefore, we follow Jackson and Sturm (2002) in believing the 10 cm residual depth criterion to be overly restrictive for small channels.

To calculate step (pool) spacing, we divided the total reach length by the number of steps (pools) in the reach that met our criteria to find the average distance between steps (pools). Then, we divided the average distance by the active channel width to find the number of channel widths per step (pool) (Montgomery et al., 1995; Beechie and Sibley, 1997; Jackson and Sturm, 2002). We excluded reaches that had fewer than three pools from the pool spacing analysis because the presence of only one or two pools is insufficient to quantify typical spacing in that channel. Similar to Church and Zimmermann (2007), we defined tread length as the distance between steps regardless of the morphology of that distance. For example, a tread could be composed of pool, riffle, or cascade units.

Additionally, we collected a census of all pieces of wood greater than 2 cm in diameter and 50 cm long, recording diameter class and functional category. We placed diameter class breaks at 2 cm, 5 cm, 10 cm, 20 cm, 40 cm, and 100 cm. Large wood consisted of all pieces 10 cm diameter or greater; fine wood consisted of diameter classes 2–5 cm and 5–10 cm, similar to Gomi et al. (2001).

We tallied all wood pieces into the functional categories—'step', 'bank', 'roughness', 'loose', and 'spanning'—based on position with respect to the channel margins and fluvial interaction. Step-forming pieces were involved in the support of a step in the thalweg profile (note that step key pieces were a subset of the many pieces classified as 'step' and were also measured in the longitudinal profile); wood classified as 'bank' primarily acted to support or armor the channel banks. 'Roughness' pieces were found within the channel margins but were anchored in some way, allowing for these pieces to resist flow energy; in contrast, 'loose' pieces existed between channel banks but were untethered to banks or the channel bed. 'Spanning' pieces had both ends resting beyond the channel margins and were suspended above the channel surface at high flows; these pieces had little opportunity to interact with in-channel flows. We aggregated 'step', 'bank', and 'roughness' pieces as geomorphically 'functional' and 'loose' and 'spanning' pieces as 'non-functional'.

3.3. Statistical methods

To explore relationships between wood and ecological and geomorphic characteristics of the study reaches, we developed linear regression models for 14 important habitat and fluvial functional variables (listed in Appendix A) with the Statsmodels statistical package (www.statsmodels.org) in Python 2.7. Because our goal was a general exploration of the dataset (not a rigorous predictive model from a machine learning perspective), and due to our relatively small sample size, we included data from all sites in the model training stage and report model results on the training data.

The set of potential independent variables was composed of contributing drainage area, reach averaged channel gradient, the product of drainage area and gradient (a proxy for stream power), active channel width, hillslope gradient, harvest legacy (unlogged or previously logged), geology (phyllite or sedimentary), stand age, LW frequency, and FW frequency. The categorical variables harvest legacy and geology were first transformed to dummy variables (previously logged and phyllite set to one, unlogged and sedimentary set to zero). We removed predictor variables that were included in the dependent variable (e.g. we removed active channel width from the model for channel widths per pool). For each dependent variable, we performed a version of stepwise linear regression in which we developed a model for the entire powerset of the independent variables (every combination of independent variables, excluding models that only included the intercept term), and picked the model with the lowest Akaike Information Criterion.

Prior evidence suggests that channel widths per pool is a non-linear function of LW abundance in some settings (Montgomery et al., 1995); therefore, we fit exponential and power-law curves to the pool spacing data as a function of LW frequency and examined the fits using the root mean square error (RMSE). Additionally, we split the sites into large and small active channel width categories using $W = 2.0$ m as the cutoff and examined differences in the distributions of the same dependent variables from the linear regression analysis. We measured differences in the distributions of these metrics using the nonparametric two-sample Kolmogorov-Smirnov (K-S) test, which is sensitive to both the mean and location of the two distributions. Due to the inherent scatter in the data, we regarded a p-value of 0.1 or lower to indicate statistical significance in the K–S tests as well as for the variables in the linear regression models.

4. Results

Study reaches spanned a range of contributing drainage areas (0.6–22.4 km^2), active channel widths (1.1–3.9 m), and channel gradients (0.09–0.58 m/m) (Appendix B). Median step height per segment ranged from 0.20 m to 0.95 m. Large wood frequency ranged from 0.54 pieces/m to 3.51 pieces/m (mean = 1.31 pieces/m), and FW ranged from 1.10 pieces/m to 4.90 pieces/m (mean = 2.63 pieces/m).

When comparing across wood diameter categories, we noted contrasting patterns between piece frequency and metrics of geomorphic functionality (Fig. 2). Specifically, we observed a systematic downward trend in the frequency of wood pieces and step-associated wood pieces with increasing wood diameter (Figs. 2A, B); in contrast, there was a distinct peak in the median and 75th percentile of step key pieces in the 20–40 cm diameter class (Fig. 2C). The 40–100 cm and 10–20 cm diameter classes were the next-most important step-keying wood sizes (in order of decreasing median frequency). Moreover, the ratio between

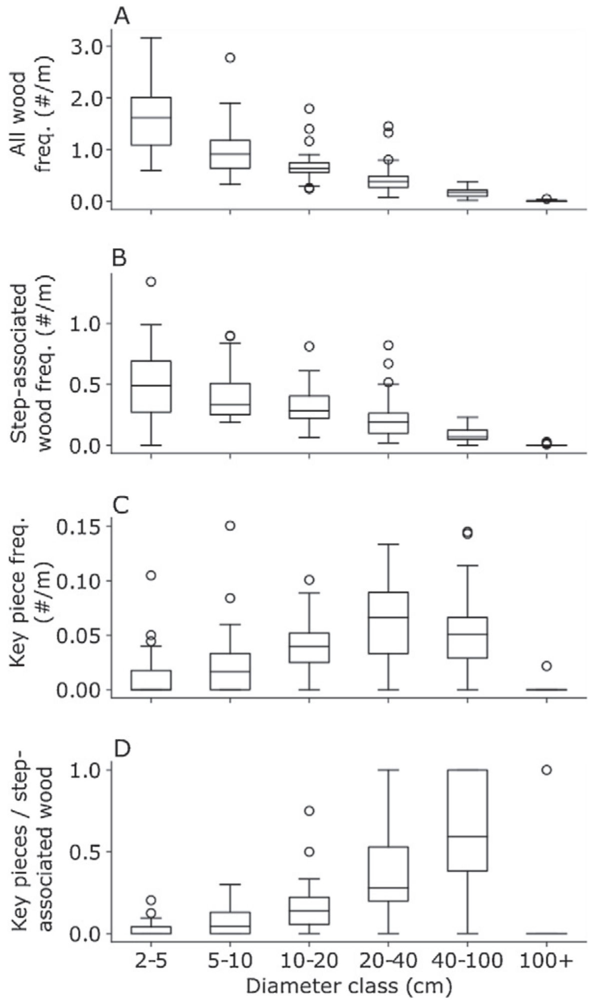

Fig. 2. The distributions by diameter class of: A) total wood frequency, B) step-associated wood frequency, C) step key piece frequency, and D) the ratio of the number of key pieces to the number of step-associated pieces. All frequencies have units of pieces per meter of channel length. All wood that is involved in step formation is included in the distributions in B; in contrast, only the individual key pieces are included in C. The central line in each box shows the median, the upper and lower edges of the boxes show the margins of the inners quartiles, and the small circles are outliers.

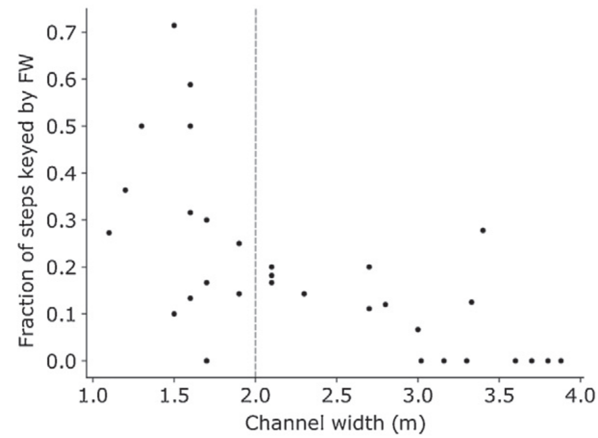

Fig. 3. The fraction of steps keyed by fine wood (FW) in each study reach as a function of the active channel width. Grey dashed line (at 2.0 m channel width) represent a potential threshold above which the fraction of steps keyed by small wood is greatly diminished.

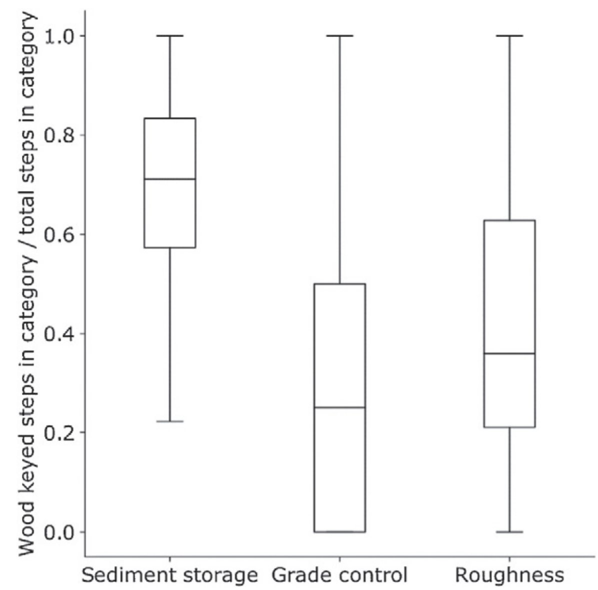

Fig. 4. The distribution of the proportion of wood-keyed steps versus steps keyed by clasts and roots in sediment storage, grade control, and roughness functional categories. See the text for a definition of the categories and for the results of significance tests between each distribution.

key piece frequency and step-associated wood frequency peaked in the 40–100 cm diameter class, followed by the 20–40 cm diameter class (Fig. 2D). This indicates that the 40–100 cm diameter class has the greatest potential to form key pieces relative to the total piece count associated with step formation in that diameter class.

Although FW was common in all channels (Appendix B), the fraction of steps keyed by FW appeared to exhibit a threshold behavior related to channel width: there was a high degree of variability in the fraction of steps keyed by FW for channel widths less than ~2 m (Fig. 3). For channel width larger than ~2 m the variability and the maximum values were greatly diminished. Only two study reaches among the nine reaches wider than 3 m contained any FW-keyed steps (Fig. 3).

As a fraction of the total number of steps in each step category (sediment storage, grade control and roughness), there were significantly more wood-keyed steps in the sediment storage category than in the roughness and grade control categories ($p < 0.001$, two-sample Kolmogorov-Smirnov test; Fig. 4); the distributions of the proportion of wood-keyed steps in the grade control and roughness categories were barely significantly different from each other at the 10% confidence interval ($p = 0.07$). We also found channel-size differences among step categories that are addressed later in this section.

Consistent with Jackson and Sturm (2002), we found that most of the elevation drop of the studied channels occurred on riffle morphological units, not on step-pool pairs (Fig. 5). Exceptions to this finding were sites AL1, DA3, NO3, RI1, and RI6, which all plot above the 1:1 line in a plot of average step height per tread length versus reach-averaged channel gradient (Fig. 5). The latter sites are within the range identified by Abrahams et al. (1995) as exhibiting maximum form resistance in which all elevation drop is accomplished on step-pool pairs. Reaches below the 1:1 line in Fig. 5 had either shorter step heights (implying little pool scour), longer treads between steps, or both. However, all sites except DE2 and FI4 contained pools according to our functional morphological definition, with median residual pool depths exceeding 0.1 m in most sites (Fig. S1). This indicates that pools were significant habitat units in all but two of the streams we studied despite the presence of important stretches of riffle between pools.

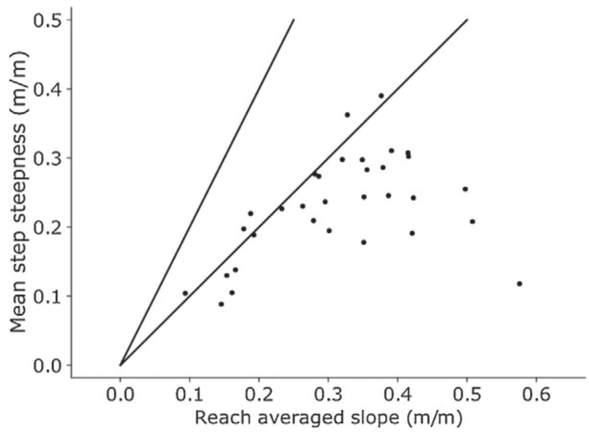

Fig. 5. Mean 'step steepness'—mean (step height/tread length)—as a function of reach averaged channel gradient. 1:1 (lower) and 2:1 (upper) lines are shown.

The distance between pools ranged from 1.46 to 16.6 channel widths per pool, though only two sites exceeded 10 channel widths per pool (Appendix B). The relationship between channel widths per pool and LW frequency was better fit with a negative exponential function (RMSE = 2.85 channel widths per pool) than by power law (RMSE = 3.00 channel widths per pool) or linear (RMSE = 3.11 channel widths per pool) functions (Fig. 6). The measured range in pool spacing is similar to larger Pacific Northwest streams studied by Montgomery et al. (1995) (Fig. 6). However, our channels had higher LW frequencies and therefore greater distances between pools for a given LW frequency (Fig. 6).

Regression modeling results are presented in detail in Appendix A and the best models are summarized in Table 1 (we limit the presentation and discussion of the results to models with an adjusted r^2 greater than 0.33 although all models are included in Appendix A for completeness). The fraction of channel length composed of pools (which is related to pool size as well as number) was best fit by a simple model of drainage area and harvest legacy (adjusted $r^2 = 0.49$), while the best model for pool spacing included reach-averaged channel gradient, hillslope gradient, geology, stand age and FW frequency as predictors (adjusted $r^2 = 0.40$). Models for step characteristics had low predictive power, with only models for FW-keyed step frequency and step height/tread length explaining greater than 33% of the variation in the response. These models relied primarily on basin characteristics predictor variables (drainage area, channel gradient and stream power). Overall, the models for sediment storage had higher predictive power than those for pools or step characteristics (Appendix A). The best models for sediment characteristics included as predictors a range of basin characteristics and disturbance legacy predictors, as well as LW frequency.

Large wood was a positive predictor in models for FW-keyed step frequency, sediment wedge volume, average sediment depth, and non-step storage (Table 1). Harvest legacy was a positively correlated predictor in models for sediment wedge volume and average sediment depth and it was a negative predictor in the model for fraction of channel length composed of pools. Because harvest legacy was quantified in the models by a dummy variable of one for previously logged sites, this can be interpreted to indicate a positive relationship between the legacy of clearcut harvest and total sediment wedge volume and average sediment depth, and a negative relationship with the fraction of channel length composed of pools.

Stand age was a negative predictor in the model for channel widths per pool (older stands were associated with closer pool spacings). Stand age was a positive predictor in models for sediment wedge volume and average sediment depth.

The channels we examined exhibited differences in key variables between large and small channel widths (channel width bins split at 2.0 m ACW) even where active channel width was not included in the best regression model. For example, we found significant differences between large and small channels in channel widths per pool, sediment wedge volume, non-step storage, channel widths per step, FW-keyed step frequency, grade control step frequency, fraction of channel length composed of pools, and roughness step frequency (Table 2 and Appendix C).

5. Discussion and conclusions

5.1. What is the relative role of large and fine wood in the structure of headwater streams?

Our findings are consistent with other studies demonstrating the critical role of LW in creating obstructions that trap and store sediment in small streams (Megahan, 1982; Gomi et al., 2001). However, we have also demonstrated that wood in larger size classes (20–40 cm and 40–100 cm diameter classes) is particularly effective at anchoring steps (Fig. 2C, D). Wood pieces contributing to steps span the full range of size classes and mimic the size distribution of total wood frequency (i.e. Fig. 2A, B), yet key pieces are most represented by medium- to large-sized pieces (Fig. 2C). Moreover, the ratio of key piece frequency and step-associated piece frequency peaks in the 40–100 cm diameter class, suggesting the largest pieces found in our study reaches (excluding the uncommon 100+ cm diameter pieces) had the greatest potential to key steps with respect to the number of step-associated wood pieces in each diameter class. This is important because it suggests that medium to large diameter classes are critical for step formation even in small headwater channels. Furthermore,

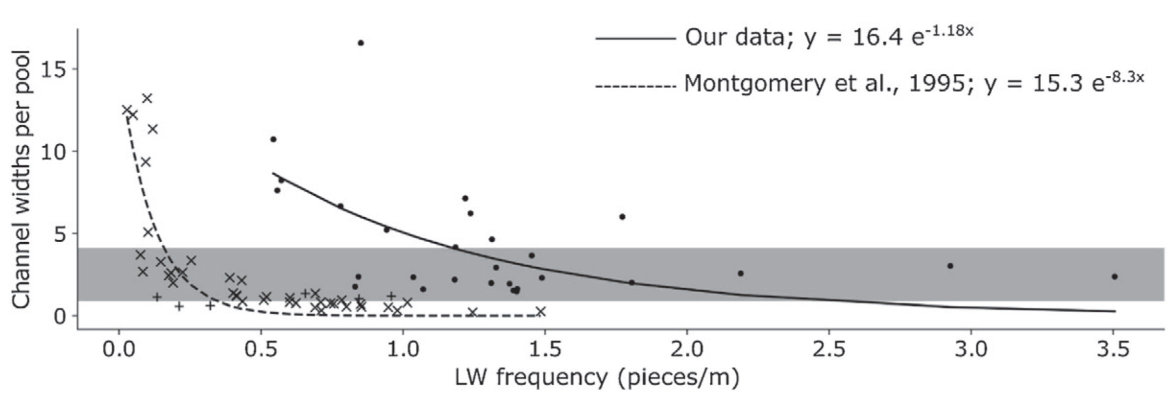

Fig. 6. Channel widths per pool as a function of large wood frequency. Our data (points) are compared to step-pool channels (plusses) and all other channel types (x-marks) from Montgomery et al., 1995. The best-fitting negative exponential models for our data (solid line) and the Montgomery data (dashed line) are shown in the figure. The gray rectangle is the approximate range in channel widths per pool of 1–4 expected for step-pool channels (Chin and Wohl, 2005).

Table 1
Summary of regression results.[*]

		Basin characteristics						Disturbance legacy		Wood loading	
		A	S	A*S	ACW	Hillslope gradient	Geology	Harvest	Stand age	LW frequency	FW frequency
Pools	Frac. chan. length in pools	+						–			
	Channel widths per pool		+			–	–		–		–
Steps	FW-keyed step frequency	–	–	+	–					+	
	Step height/tread length	–		+							
Sediment	Sediment wedge volume/reach length					+	+	+	+	+	
	Avg. sediment depth					+	+	+	+	+	
	Non-step storage/reach length									+	

[*] Plus (minus) indicates a positive (negative) relationship between predictor and response. Only models with $r^2 > 0.33$ are shown.

Table 2
Summary of differences between large and small channels.[*]

Category	Metric	Small channels[1]	Large channels[2]
Step and pool spacing	Channel widths per pool	↑	↓
	Channel widths per step	↑	↓
	Fraction channel length in pools	↓	↑
Sediment metrics	Sediment wedge volume/reach length	↓	↑
	Non-step storage/reach length	↓	↑
Frequency metrics	FW-keyed step frequency	↑	↓
	Grade control step frequency	↑	↓
	Roughness step frequency	↑	↓

[*] Upward-facing arrows indicate increased level of metric relative to other channel size category; downward-facing arrows indicate decreased level of metric. Only models with $p < 0.1$ are shown.
[1] Small channels: ACW < 2.0 m.
[2] Large channels: ACW >= 2.0 m.

wood key pieces with a diameter of 40 cm or greater were responsible for 64% and 37% of the volume of sediment stored in steps in unlogged and previously logged channels, respectively, indicating the largest size classes were responsible for a large portion of the total storage capacity observed in most reaches.

The above findings provide an important refinement to the common idea that the larger size classes of LW have little opportunity to functionally interact with small headwater channels due to the mismatch between the length of LW pieces and the width of small channels (e.g. Nakamura and Swanson, 1993). A corollary is that FW and the smaller sizes of LW provide important functionality in small streams. For example, Jackson and Sturm (2002) found that FW contributed to step formation in a similar fashion as the smaller size classes of LW (10–40 cm diameter) and that LW with diameter > 40 cm contributed to step formation in less than 10% of steps. We suspect the discrepancy between that study and our findings is due to our focus on key pieces (contrast Fig. 2B and D), and the fact that most of the streams in the Jackson and Sturm study had a channel width of less than 2 m, comparable to the smaller streams in our study. We also found that FW was a dominant step-keying material in streams narrower than 2 m (Fig. 3).

In most cases, the most functional 20–40 cm and 40–100 cm diameter wood pieces were oriented parallel to the channel or had decayed and broken into pieces short enough to jam between the channel margins. Large wood oriented parallel to the channel was able to act as step-keying material by creating constrictions in the channel that trapped clasts and other pieces of wood. Some pieces of LW formed the key piece in multiple steps.

5.2. Are wood-keyed steps more effective at trapping sediment than clast- and root-keyed steps?

Our results demonstrate that wood-keyed steps are much more likely to store sediment than are clast- or root-keyed steps (Fig. 4). The same is not true for grade control and roughness steps, which are more likely to be keyed by clasts and/or roots than by LW. We suspect this effect is due to the geometry of wood pieces: the length of most wood pieces is large compared to their diameter, increasing the likelihood of jamming between channel banks, which in turn creates stable structures that accumulate sediment and additional pieces of wood (Jones et al., 2011). It is important to note that LW can jam between channel banks at a variety of angles with respect to the channel thalweg (i.e. not all jammed pieces are oriented perfectly perpendicular to the channel). Therefore, LW pieces that are much longer than the channel is wide may still become lodged between banks and interact with the flow. Once wedged into the channel, large step-keying conifer pieces decay slowly, extending the functional life of the structures relative to structures keyed by smaller pieces. Due to the high wood loads in the studied streams, over half (54%) of clast-keyed steps in our dataset included wood as a secondary structural element.

Additionally, we plotted the distributions of the ratio of wood-keyed steps to total steps in each of the three step function categories, stratified by key piece diameter class (Fig. S2). The smallest diameter class (2–5 cm) showed no clear distinction between storage, roughness, and grade control functional categories. In the 5–10 cm diameter class, the median ratio of wood-keyed steps/total steps was elevated slightly in the sediment storage category with respect to the other categories. The median ratio was again slightly higher in the 10–20 cm diameter class, but it was significantly elevated in the 20–40 and 40–100 diameter classes (Fig. S2). This further demonstrates that the medium to larger size fractions of LW are best able to store sediment when compared to the other possible step functions we analyzed.

5.3. How does the relationship between large wood frequency and the distance between pools differ between headwater and larger streams?

Significantly, we have verified the apparent link between LW frequency and pool spacing in the headwater streams studied here (Fig. 6), which heretofore had only been documented in larger, fish-bearing streams (Montgomery et al., 1995; Beechie and Sibley, 1997). The highest values of channel widths per pool (even excluding the single highest value) in our dataset are well above the commonlycited value of 5–7 channel widths per pool for lower gradient streams (Leopold et al., 1964), indicating less frequent pools in our headwater sites at low LW frequencies. The median and mean values (2.7 and 4.3 channel widths per pool, respectively) are similar to the 1–4 channel widths per pool reported for step-pool channels in a range of settings (Chin, 2002; Chin and Wohl, 2005 and references therein).

Interestingly, Montgomery et al. (1995) found no relationship between LW density and pool spacing in the few step-pool channels they studied (Fig. 6). In contrast, at our 32 study sites pool spacing can be predicted by a negative exponential function of LW frequency, albeit with a fair amount of scatter (RMSE = 2.85 channel widths per pool). Interestingly, the functional relationship between LW frequency and pool spacing is much different between the channels in our dataset and those of Montgomery et al. (1995) despite the similarity in intercepts (e.g. 16.4 for our data and 15.3 for the Montgomery data). The Montgomery pool spacing data from pool-riffle, forced pool-riffle and step-pool channels loses most of its sensitivity to LW frequency at values of LW frequency > 0.5 pieces/m; in contrast, our dataset is highly sensitive to LW frequency between values of 0.5 to 1.5 pieces/m, but loses sensitivity at greater values of LW frequency. Both exponential models undershoot the data at the highest values of LW frequency, further emphasizing the lack of sensitivity of pool spacing at high LW frequencies. We acknowledge that some of the discrepancy between the two models may be due to the LW counting criterion used in the two studies (we used a less restrictive criterion of 0.5 m length versus 1 m in the Montgomery paper). Anecdotally, however, most of the LW pieces in our study were longer than 1 m, suggesting that much of the difference between the data and models in Fig. 6 can be explained by channel size and/or gradient. The step-pool channels studied by Montgomery et al. (1995) were clearly much wider and lower gradient environments than the streams we studied, with channel width greater than 4 m—greater than 10 m in half their step pool sites—and gradient less than 0.1 m/m. Taken together, the above observations demonstrate that headwater streams are adjusted to higher wood loads than larger streams lower in the channel network. Wood frequencies that would be considered high in pool-riffle or forced pool-riffle channels would be insufficient to maintain high levels of pool habitat in headwater streams.

The differences between our dataset, the step-pool channels studied by Montgomery et al. (1995) and all other channels studied by Montgomery et al. (1995) suggest there may be two channel size and/or gradient thresholds such that the smallest/steepest and widest/least steep channels in mountain drainage networks of the Pacific Northwest require LW to enhance pool habitat, albeit for differing reasons, while channels of intermediate width and slope do not. The smallest/steepest headwater streams, such as those we studied, are confined by adjacent hillslopes and therefore accomplish flow resistance in the vertical dimension, i.e. by forming steps and pools (Chin, 2002). These channels require wood to form pools because there is not enough fluvial energy to sculpt the largest clastic materials into the classic step-pool arrangement; wood-keyed steps provide needed vertical drop to carve pools into gravel patches trapped by the next lower wood-keyed step. Therefore, wood functions in the smallest headwater channels as in-channel roughness elements as well as the dominant control on form resistance. Pool-riffle channels, such as those studied by Montgomery et al. (1995), are free to meander in the horizontal dimension, thereby accomplishing form resistance at meander bends. In such channels, wood is required to cause pool scour but it is not necessarily the dominant creator of flow resistance. In contrast, intermediate width/gradient channels, such as the step-pool channels studied by Montgomery et al. (1995), are confined by hillslopes but have enough fluvial energy to deform their beds (i.e. create steps and pools by rearranging the clastic components of the stream bed (Church and Zimmermann, 2007)). These channels have very high wood loads but are able to account for the needed resistance to flow through rearrangement of large clasts and the formation of step-pool sequences.

The above observations emphasize the important role wood plays in forcing plunging flow and pool formation in headwater streams, i.e. low LW frequency in our dataset is correlated with distances between pools that are greater than the expected range for step-pool channels, whereas higher LW frequency values appear to be correlated with pool spacings similar to the expected range (Fig. 6).

While our findings are consistent with previous research on the role of riffles in providing much of the elevation drop in small channels (Jackson and Sturm, 2002), we note that plots of average step height divided by tread length versus reach-averaged channel gradient do not necessarily demonstrate a lack of pools. The presence of deep pools could drive data points upward on Fig. 5 (even above the 2:1 line; Church and Zimmermann, 2007); however, the dearth of points above the 1:1 line does not preclude the presence of pools within the stream profile, but does demonstrate that pools may be separated by long stretches of riffle.

5.4. What are the habitat and geomorphic differences between large and small headwater channels?

Our results demonstrate that potential wood function depends on channel size even within the range of stream widths we studied (1–4 m width). For example, in the smaller streams we studied, FW played a significant role in step formation and sediment storage. Channels larger than ~2 m saw a precipitous drop in FW-keyed steps, implying that wood pieces smaller than 10 cm diameter were insufficient in terms of stability, rigidity and/or durability. This effect could also be based largely on piece length relative to channel width (i.e. small-diameter wood pieces are too short to become lodged between channel banks).

Alternatively, wider channels tend to convey larger flows, leading to the requirement that step-keying pieces be larger and stronger. It is likely that both effects play a role. Streams that are wider than 2 m apparently benefit from in-channel wood with diameters of 20 cm or larger to effectively key steps. This is similar to the findings elsewhere (e.g. Chen et al. (2006), Baillie et al. (2008), Chen et al. (2008) and Jones et al. (2011)) documenting a discontinuity in wood stability at approximately 3 m channel width. Our results complement this idea by demonstrating the role for FW in step formation in channels smaller than 2 m width but show the augmented role of large- and medium-sized wood in channels wider than this threshold.

Additionally, we found other important distinctions between the smallest channels in our dataset (those less than 2 m wide) and the larger channels (Table 2, Appendix C). For example, channel morphological diversity (as quantified by step and pool spacing and fraction of channel length in pools) was greater in the larger channels we studied (Table 2). However, grade control and roughness step frequency were lower in channels with active channel width greater than 2 m and sediment storage step frequency was not different between large and small channels. The observation that channel widths per step and step frequency were lower in larger channels indicates that the absolute distance between steps was longer in larger channels, but the distance as a function of channel width was shorter. Similarly, the larger channels stored more sediment in both steps and in non-step storage.

5.5. What are the effects of logging legacy on wood function?

Interestingly, our sites with past logging generally had relatively high wood loads, not dissimilar to unlogged sites (K-S test p-value =

0.37). Arguably, the lack of fresh recruitment in the decades after riparian logging was offset by several possible recruitment mechanisms, including wood introduced directly by logging (Jackson et al., 2001) and subsequent slope instability (Benda et al., 2003a). Original logging practices left behind large amounts of substandard and defective woody material, much of it from slow-decaying western red cedar and Douglas-fir (Swanson et al., 1984; Benda et al., 2002). This legacy wood appears to supplement increasing inputs from second-growth stands.

Our dataset produced a mixed result regarding the effects of harvest legacy on sediment accumulation. On the one hand, the distributions of sediment wedge volume and average sediment depth were not visibly distinguishable in a comparison of boxplots of the data stratified by harvest legacy, nor were they significantly different according to two-sample K-S tests ($p > 0.1$). However, harvest legacy was a positive predictor in the linear models for sediment wedge volume and average sediment depth (Table 1, Appendix A). The presence of harvest legacy in the linear model may reflect interaction with other variables. It is not clear, however, whether harvest legacy affected the linear model results due to increased storage of fine sediment resulting from inputs of slash from logging in the previously logged streams (Jackson et al., 2001, 2007) or increased sediment supply due to destabilized hillslopes (Benda et al., 2003a). Hillslope gradient was also a positive predictor of sediment wedge volume and average sediment depth (Table 1, Appendix A), suggesting the latter effect may have played a role in the selection of harvest legacy in the best-fitting linear model.

Stand age was a positive predictor in models for sediment wedge volume and average sediment depth (Table 1 and Appendix A), suggesting there may be a relationship between sediment accumulation and riparian forest disturbance. One possible mechanism for this correlation is debris flow erosion following disturbance. In this conceptual model of headwater channel evolution in forested drainage basins, in which debris flows are responsible for the majority of sediment transport over century to 1000 year timescales (May and Gresswell, 2003; Gomi et al., 2001), episodic debris flows scour steep channels to bedrock, depositing wood and sediment in flatter downstream runout zones (Benda et al., 2003a, b). Over time, the scoured channels receive periodic inputs of LW, which gradually accumulate sediment and organic material until enough material is present to be evacuated by another debris flow. However, we did not observe evidence for recent (last ~50 years) debris flows in any of our study sites. This suggests either that evidence of debris flow erosion and deposition has been obscured by fluvial processes at all our sites or some other mechanism must be invoked to explain the presence of stand age in the linear models for sediment storage metrics.

Intriguingly, harvest legacy was a negative predictor in the model for fraction of channel length in pools ($p = 0.125$) and stand age was a negative predictor in the model for channel widths per pool ($p = 0.057$). These results can be interpreted to mean that a legacy of clearcut harvest was negatively correlated with total pool habitat and that stand age was negatively correlated with the distance between pools, respectively. This suggests that older, un-logged forests are associated with larger pools and more closely-spaced pool habitat, as has been documented for larger channels (Montgomery et al., 1995). However, unlike the larger streams studied by Montgomery et al. (1995), the unlogged and previously logged streams we studied did not have significantly different LW frequencies, suggesting wood piece counts alone are unlikely to explain the linear relationships between forest type, stand age and pool habitat.

5.6. Concluding remarks

Overall, the stream reaches we investigated had higher wood frequencies than those published for other sub-regions within the Washington Cascade Mountains and Coast Ranges (including when controlling for minimum size requirements). For example, Jackson and Sturm (2002) compiled data from various studies of LW loading in channels with a range in widths. They showed that many small headwater streams in the Washington Coast Ranges had higher wood frequencies than larger channels. However, their maximum LW frequency was ~1.6 pieces/m, approximately half that of our dataset. Future work should more fully investigate regional patterns of LW loading and potential differences in sediment storage and channel morphology (Hassan et al., 2005).

Taken together, the data presented herein support the concept that riparian buffers are important for maintaining wood recruitment processes that support habitat formation in non-fish-bearing streams on managed timberlands. Headwater streams are granted partial, if any, protections from forest management practices in many jurisdictions around the world. For example, headwater streams are partially protected in Washington State by the 2001 Forest Practice Rules, which are designed to maintain water quality and other watershed functions while allowing for clearcut logging adjacent to portions of perennial stream reaches (U.S. Fish and Wildlife Service et al., 1999). This requirement allows for approximately 50% of the stream length in perennial non-fish-bearing streams to be harvested without a buffer (seasonal streams may be entirely un-buffered). However, our results suggest that this arrangement may significantly impact sediment dynamics and pool formation in headwater stream channels if the amount or size distribution of wood inputs are reduced.

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Appendix A. Linear regression results.*

Category	Dependent variable	r^2 (adj.)	p (F stat.)	Independent variables	p (ind. variables)
Pools	Fraction channel length in pools	0.49	<0.001	A	<0.001
				Harvest	(0.125)
	Channel widths per pool	0.4	0.0032	S	0.006
				Hillslope gradient	(0.01)
				Geology	(0.004)
				Stand age	(0.057)
				FW frequency	(0.133)
Steps	FW-keyed step frequency	0.41	0.0016	A	(0.022)
				S	(0.008)

(continued on next page)

(*continued*)

Category	Dependent variable	r^2 (adj.)	p (F stat.)	Independent variables	p (ind. variables)
				A*S	0.036
				ACW	(0.004)
				LW frequency	0.04
	Step height/tread length	0.33	0.0013	A	(0.001)
				A*S	<0.001
	SS step frequency	0.25	0.012	A	0.065
				Geology	0.073
				LW frequency	0.003
	RG step frequency	0.25	0.0056	A	0.168
				Hillslope gradient	(0.03)
	Percent steps keyed by wood	0.12	0.031	LW frequency	0.031
	Channel widths per step	0.25	0.0056	Hillslope gradient	0.026
				FW frequency	(0.003)
	Percent steps keyed by clasts	0.03	0.177	A*S	(0.177)
	GC step frequency	0.16	0.014	ACW	(0.014)
	LW-keyed step frequency	0.03	0.167	A	(0.167)
Sediment	Sediment wedge volume/reach length	0.56	0	Hillslope gradient	0.012
				Harvest	0.178
				Stand age	0.023
				LW frequency	0.001
	Avg. sediment depth	0.41	0.0019	Hillslope gradient	0.027
				Harvest	0.042
				Geology	0.059
				Stand age	0.003
				LW frequency	0.154
	Non-step storage/reach length	0.28	0.001	LW frequency	0.001

*P-values in parentheses indicate a negative relationship with the response variable. SS = sediment storage; GC = grade control; RG = roughness; A = contributing drainage area; S = reach-averaged channel gradient; ACW = active channel width.

Appendix B. Site characteristics

Site	Forest*	Drainage area (km^2)	Gradient (m/m)	ACW** (m)	Reach len (m)	H/L§ (m/m)	Mean step height (m)	Mean pool depth (m)	# pools	# steps	Sed. Volume (m^3/m)	LW freq. (#/m)	FW freq. (#/m)
AL1	P-L	3.18	0.19	1.7	52.2	0.22	0.28	0.10	13	30	0.02	0.84	1.92
AL2	P-L	2.60	0.39	1.7	60.7	0.26	0.45	0.11	5	23	0.05	1.22	1.70
AL3	P-L	8.40	0.29	2.8	90.0	0.27	0.40	0.10	22	46	0.16	1.40	2.99
AL4	P-L	7.83	0.42	3.6	110	0.30	0.60	0.15	14	40	0.06	1.18	1.76
DA1	U-L	0.89	0.28	1.6	59.4	0.21	0.34	0.09	8	25	0.12	1.31	2.71
DA2	U-L	8.26	0.16	2.3	80.6	0.11	0.49	0.17	12	15	0.06	1.33	3.57
DA3	U-L	4.46	0.38	1.9	60.7	0.39	0.87	0.22	20	25	0.09	1.07	3.81
DA4	P-L	6.84	0.38	2.7	90.0	0.29	0.76	0.19	13	24	0.26	2.19	3.90
DA5	U-L	13.72	0.35	3.9	120.0	0.18	0.65	0.17	16	22	0.08	1.38	2.04
DE1	U-L	1.21	0.39	2.1	63.2	0.31	0.50	0.12	5	28	0.09	1.77	2.91
DE2	P-L	3.32	0.42	3.7	114.0	0.24	0.58	0.13	1	35	0.10	1.68	1.68
DE3	P-L	0.60	0.51	1.5	50.6	0.21	0.45	None	0	20	0.02	0.89	1.56
DE4	P-L	5.93	0.26	3.3	105.3	0.20	0.59	0.25	16	26	0.15	1.31	2.46
FI1	U-L	1.22	0.41	1.6	58.5	0.31	0.49	0.10	10	28	0.09	1.45	2.67
FI2	U-L	3.05	0.50	1.7	70.0	0.25	0.95	0.17	5	8	0.12	0.57	1.10
FI3	P-L	1.97	0.30	1.6	59.8	0.23	0.37	0.10	6	26	0.09	1.24	3.36
FI4	P-L	2.19	0.42	1.7	60.3	0.19	0.36	None	0	23	0.05	1.18	4.86
FI5	U-L	22.26	0.30	3.3	105.8	0.19	0.66	0.19	16	12	0.18	1.81	2.49
FI6	U-L	3.22	0.32	3.0	90.0	0.30	0.52	0.15	13	42	0.06	1.49	2.72
FR1	P-L	1.96	0.15	1.5	50.0	0.09	0.21	0.16	5	12	0.01	0.78	3.64
FR2	P-L	0.78	0.35	1.1	45.0	0.24	0.38	0.13	2	18	0.02	0.78	3.29
FR3	P-L	7.92	0.15	2.1	63.7	0.13	0.32	0.13	13	15	0.08	1.04	2.39
NO1	P-L	1.52	0.28	1.3	64.6	0.28	0.28	0.07	3	38	0.01	0.85	1.83
NO3	P-L	10.72	0.09	1.9	63.3	0.10	0.36	0.18	8	13	0.06	1.18	2.24
NO4	P-L	5.10	0.19	3.8	114.8	0.19	0.45	0.16	10	30	0.12	2.93	3.92
NO5	P-L	5.85	0.36	3.4	104.7	0.28	0.55	0.12	13	45	0.22	3.51	4.88
RI1	U-L	0.75	0.18	1.6	61.0	0.20	0.32	0.14	5	23	0.01	0.56	1.44
RI2	U-L	1.79	0.35	1.2	51.5	0.30	0.36	0.12	4	28	0.04	0.54	1.24
RI3	P-L	9.81	0.23	3.0	92.0	0.23	0.56	0.19	19	28	0.15	1.40	2.39
RI4	P-L	1.98	0.58	2.1	65.8	0.12	0.78	0.16	6	8	0.07	0.94	1.44
RI5	U-L	11.12	0.17	2.7	80.6	0.14	0.47	0.18	17	19	0.08	0.83	1.19
RI6	U-L	22.4	0.33	3.2	96.5	0.36	1.09	0.24	20	28	0.08	1.39	4.11

* P-L = previously logged; U-L = unlogged.
** Active channel width.
§ Mean step height/mean tread length. Tread is the distance between steps, including pools, riffles and cascades.

Appendix C. Results from two-sample Kolmogorov-Smirnov tests comparing large and small channels

Metric	p-value*
Channel widths per pool	0.00042
Sediment wedge volume/L	(0.00074)
Non-step storage	(0.0094)
Channel widths per step	0.0159
FW-keyed step frequency	0.028
Grade control step frequency	0.036
Fraction channel length in pools	(0.044)
Roughness step frequency	0.065
Average sediment depth	(0.28)
Sediment storage step frequency	0.57
Step height/tread length	0.78
Percent wood-keyed steps	(0.78)
Percent clast-keyed steps	0.81
LW-keyed step frequency	0.98

*Values in parenthesis indicate the median of the large channels was greater than the median of the small channels. Models with $p < 0.10$ are interpreted as statistically significant.

Appendix D. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.geomorph.2019.106898.

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