Effects of riparian buffer width on wood loading in headwater streams after repeated forest thinning

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ABSTRACT

Forested riparian buffer zones are used in conjunction with upland forest management, in part, to provide for the recruitment for large wood to streams. Small headwater streams account for the majority of stream networks in many forested regions. Yet, our understanding of how riparian buffer width influences wood dynamics in headwater streams is relatively less developed compared to larger fish-bearing streams. The effects of riparian buffer width on instream wood loading after thinning can be difficult to discern due to the influence of basin characteristics and reach-scale geomorphology on wood recruitment, breakage and redistribution. We assessed the relationships between instream wood loading, geomorphology and riparian buffer width in small headwater streams after upland thinning. Then we examined the distances between pieces of stream wood and their sources, or the distance from which wood volumes were recruited to these streams. Data were collected along 34 stream reaches at six different sites in a replicated field experiment, comparing three no-harvest streamside buffer treatments (∼6-m, 15-m minimum, and ∼70-m widths). At each site, second-growth forests were thinned first to 200 trees per ha [tph] and ∼10 years later to 85 tph, alongside an unthinned reference unit (∼400 tph). We measured wood loading (m^3/100 m) four times: (1) prior to thinning; (2) year 5 post-1st thinning; (3) immediately prior to the 2nd thinning; and (4) year 1 post-2nd thinning. The majority of wood volume was in late stages of decay, most likely biological legacies from the previous forest stand, and distributed along the streambank. Surprisingly, wood volume in early stages of decay was higher in stream reaches with a narrow 6-m buffer than in stream reaches with larger 15- and 70-m buffers and the unthinned reference units. Additionally, wood volume increased with drainage basin area. Only 45% of wood in late stages of decay could be associated with a particular source. Yet, 82% and 85% of sourced wood in early and late stages of decay, respectively, originated from within 15 m of streams. Expected continue low rates will likely result in declining volumes of wood in late stages of decay. Thinning and directional felling of logs into to streams could be used to augment wood volumes in the near term, and accelerate the development of large-diameter logs for future inputs. However, the relationship between instream wood loading and basin area suggests that instream wood loading depends on management across the entire watershed.

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1. Introduction

In the mountainous forested landscapes of the US Pacific Northwest, headwater streams encompass as much as 80% of the length of stream networks (Gomi et al., 2002; Schumm, 1956; Shreve, 1969). The majority of forests in these watersheds are managed, often for timber production on private land and multiple values on public land. Over time, forest regulations have strengthened the requirement that management plans consider the cumulative effects of management activities on the conservation of aquatic ecosystems (e.g., USDA and USDI, 1994), including headwater streams. This has raised concerns about the effects of forest management practices on stream wood dynamics in forested headwaters (Benda et al., 2015; Czarnomski et al., 2008; Harmon et al., 1986; Montgomery et al., 1996; Pollock and Beechie, 2014).

Large wood is a functionally important component of forested streams, as it moderates streamflow and influences channel morphology, sediment and organic matter transport and storage (Bilby and Bisson, 1998; Bilby and Ward, 1991; Keller and Swanson, 1979; Montgomery et al., 1995, 1996). It is generally

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more abundant in small headwater streams than larger streams as a result of lower current forces and smaller channel areas to distribute debris downstream (Bilby and Ward, 1989; Keller and Swanson, 1979; Wohl and Jaeger, 2009). Here, wood plays a disproportionate role in structuring the channel morphology because any given volume of wood will cover a greater proportion of the channel (Swanson and Lienkaemper, 1978; Triska et al., 1982). Additionally, wood contributes to forest biodiversity by providing habitat for numerous plant, fungi, and animal species (e.g., Harmon et al., 1986; Wondzell and Bisson, 2003) including macroinvertebrates, fish (e.g., Bilby and Bisson, 1998; Bisson et al., 1987) and amphibians (Olson and Burton, 2014; Olson and Weaver, 2007).

A diversity of wood recruitment, decomposition, and redistribution processes interact with geomorphic conditions to control the spatial and temporal variability of wood in streams (Fig. 1). Hillslope processes, or mass wasting events, such as landslides, debris flows and forest disturbances can introduce large quantities of wood to streams (Keller and Swanson, 1979; May, 2002; Reeves et al., 2003). Between these infrequent events, smaller volumes of wood are recruited chronically from local tree falls, with the probability of a tree landing in a stream being a function of slope distance (i.e., the distance from the stream along the riparian hillslope) from the stream in relation to tree height (McDade et al., 1990; USDA and USDI, 1993; Van Sickle and Gregory, 1990). Large wood also can be recruited gradually with streambank erosion and undercutting streamside trees, and hillslope creep (e.g., Bisson et al., 1987; Hassan et al., 2005). Once recruited, wood redistribution in headwater streams generally proceeds slowly as wood decays (Nakamura and Swanson, 1993), although floods can periodically redistribute larger quantities of wood downstream. Headwater streams may serve as important sources of large wood sources, with extreme flood events and periodic slope failures delivering large wood volumes downstream. Wood redistribution downstream is especially important for the maintenance and restoration of habitat conditions for different assemblages of wood-associated species in larger streams, including several sensitive salmonid species (e.g., Naiman et al., 1992).

Wood recruitment and redistribution processes can vary spatially with geomorphic conditions (Czarnomski et al., 2008; Spies et al., 1988; Wohl and Cadol, 2011). For example, unstable, steep slopes that constrain streams may increase recruitment of large wood to narrow colluvial stream channels resulting from a higher density of trees within the fall zone (i.e., one tree-height distance) of the stream, compared to larger alluvial channels (May and Gresswell, 2003). In narrow, highly constrained streams, fallen logs can be suspended above the channel and eventually fall into the

wet and dry zones of the bankfull channel or be redistributed downstream with breakage and decomposition (Nakamura and Swanson, 1993; Robison and Beschta, 1990; Wohl and Goode, 2008). Fluvial redistribution of wood depends not only on the size of the wood relative to the stream but is also influenced by morphological characteristics such as stream width relative to depth, and gradient (e.g., Bilby and Ward, 1989; Lienkaemper and Swanson, 1987; Wohl and Goode, 2008). Thus, efforts to understand and predict effects of forest management practices on wood in streams (e.g., Bragg, 2000; Czarnomski et al., 2008; Davidson and Eaton, 2015; Martin and Benda, 2001; Meleason et al., 2002; Pollock and Beechie, 2014; Van Sickle and Gregory, 1990; NetMap Riparian Management: http://www.terrainworks.com/riparian-management, accessed 22 April 2015) may be improved by accounting for basin characteristics and reach-scale geomorphology (Fig. 1).

Large wood dynamics relative to stand development have been documented in upland forests (Duvall and Grigal, 1999; Spies et al., 1988) and similar trends apply to forested riparian areas (Keeton et al., 2007; May, 2002). During early developmental stages of forest stands, recruitment of wood is limited to small trees undergoing density-dependent mortality. High volumes of large wood, or "legacy wood", reflect the previous rather than the current stand and the associated history of disturbance or harvesting (Duvall and Grigal, 1999; May, 2002; Spies et al., 1988). As trees grow and legacy wood decays, wood volumes are predicted to decline during the stem-exclusion phase (i.e., stage of stand development characterized by high levels of density-dependent mortality as trees compete for resources, grow in height and stratify their canopies into exposed and suppressed crown classes; Oliver and Larson, 1996). Increased inputs of larger trees in later stages of stand development result a U-shaped distribution of large wood volume over time (Duvall and Grigal, 1999; Harmon et al., 1986; Spies et al., 1988).

In managed forest landscapes, stands are typically harvested before they reach later stages of development, resulting in a landscape that is dominated by early stages of stand development (e.g., Nyland, 2002) where large wood recruitment is limited in amount (e.g., volume or biomass) and piece size. For example, industrial management practices in western Washington and Oregon typically result in clearcut-harvest rotation ages of around 50 years (Briggs and Trobaugh, 2001). Thus, forests in this region contain a greater proportion of young to middle-aged stands in the "stem-exclusion phase" (~71%) than were present historically (Ohmann et al., 2007; Wimberly and Ohmann, 2004). Landowners who plan for longer rotation ages typically implement thinning operations to bring merchantable timber to markets and increase
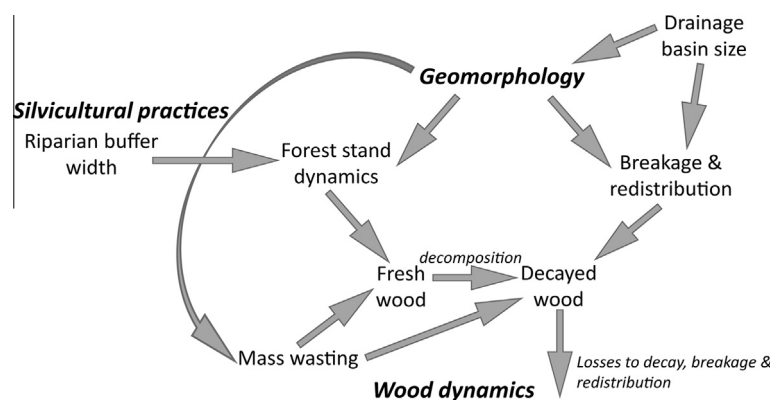

Fig. 1. Conceptual model placing streamside riparian buffers with upland forest thinning into a general ecological context for wood dynamics in headwater streams.

the growth and vigor of the residual trees (Nyland, 2002). Thinning to lower and more variable residual tree densities also is used as a method of restoring heterogeneity in even-aged stands (Dodson et al., 2012; Franklin and Johnson, 2012). Currently, nearly all wood volume harvested from federal land in the Pacific Northwest (i.e., forested lands managed by the US Forest Service and Bureau of Land Management) is from thinning (e.g., Thomas et al., 2006). Removing trees that can provide potential large wood during the stem-exclusion phase, when large wood values are "naturally" low, however, has received intense scrutiny (Harmon et al., 1986; Montgomery et al., 1996; Pollock and Beechie, 2014).

To address these and other concerns, streamside no-harvest riparian buffers are implemented on public and to a lesser extent on private lands (Olson et al., 2007). They are promoted as a 'Best Management Practice' and an aquatic conservation tool that can retain water resources and stream-riparian habitat conditions for sensitive species, and often include consideration of wood inputs to streams (e.g., Blinn and Kilgore, 2001; USDA and USDI, 1994). Attempts at determining an appropriate width of riparian buffers in Pacific Northwest forests for aquatic conservation have been based in-part on findings that most stream wood is recruited from within a distance of one site-potential tree-height (defined as the maximum height of dominant trees for a given site) from streams (USDA and USDI, 1993). This, in addition to analyses of other stream conditions influenced by riparian tree canopies (e.g., litter fall, microclimate), led to the development of US federal interim riparian reserves with widths of two and one site-potential tree heights for fish-bearing and non-fish-bearing headwater streams, respectively (USDA and USDI, 1994). However, the scientific basis underlying these buffer widths was limited. For instance, the microclimate analysis was mostly based on two sites that evaluated microclimatic conditions in old-growth forest adjacent to clearcuts on fairly level ground (Chen et al., 1993, 1995). Accordingly, these buffer sizes were considered interim (USDA and USDI, 1994). The intent was that buffer sizes could be refined and adjusted as part of a larger program of adaptive management as watershed analysis or research results provided new information. With two decades-worth of new information brought to bear on the issue, it is timely to assess how effective alternative buffer widths have been in achieving the various management goals for which they were designed in the context of contemporary riparian-and-upland forest management practices (e.g., the shift from clearcut harvest to thinning as the dominant silvicultural practice on federal land), associated stand structures, and local geomorphic and stream channel conditions.

We examined the relationships between instream wood loading and riparian buffer width in thinned forests, in conjunction with a variety of stream-, stand-, and site-level variables. We report wood patterns at 34 headwater stream reaches on six sites over a 14-year timeline, which included two separate thinning entries of the upland forests. First, we characterized stream wood patterns over time by decay stage and position in the stream prism (stream "influence zones", *sensu* Robison and Beschta, 1990): in the wetted stream, along banks, and suspended over the stream channel. Second, we examined wood volume patterns over time relative to riparian buffer width, testing the hypothesis that wider riparian buffers result in increased wood volume in early stages of decay. Third, we assessed the role of the geomorphic and spatial context—variation among reaches in width:depth ratio, drainage basin area, and gradient. We examined whether wood volume was greater in narrower, more constrained reaches, in larger drainage basins, and along steeper gradients (Fig. 1). Lastly, we examined how far away from streams the instream wood originated, to test the hypothesis that most sources occur within a one site-potential tree height slope distance of streams.

2. Methods

2.1. Study area

Our experimental riparian buffer study is part of a larger density management study that was replicated at six forested sites along the Coast and Cascade Ranges in western Oregon, USA (Fig. 2). Sites were selected to be representative of the forest lands managed by the BLM in western Oregon on the basis of age (30–70 year old Douglas-fir), minimum area (~80 ha), homogeneity, and the absence of wind disturbance and root disease (Cissel et al., 2006). Located primarily in the western hemlock (*Tsuga heterophylla*) zone, the climate is characterized as Mediterranean with mild, wet winters and warm, dry summers (Franklin and Dyrness, 1988) and an associated high variability of seasonal streamflow patterns (e.g., high frequency of ephemeral and spatially discontinuous reaches, Olson and Weaver, 2007). Soils consist primarily of as well- to poorly-drained Ultisols and Inceptisols (Cissel et al., 2006; NRCS, 2016). Forests were initially dominated by dense second-growth 30- to 70-year-old Douglas-fir (*Pseudotsuga menziesii*) trees with varying abundances of
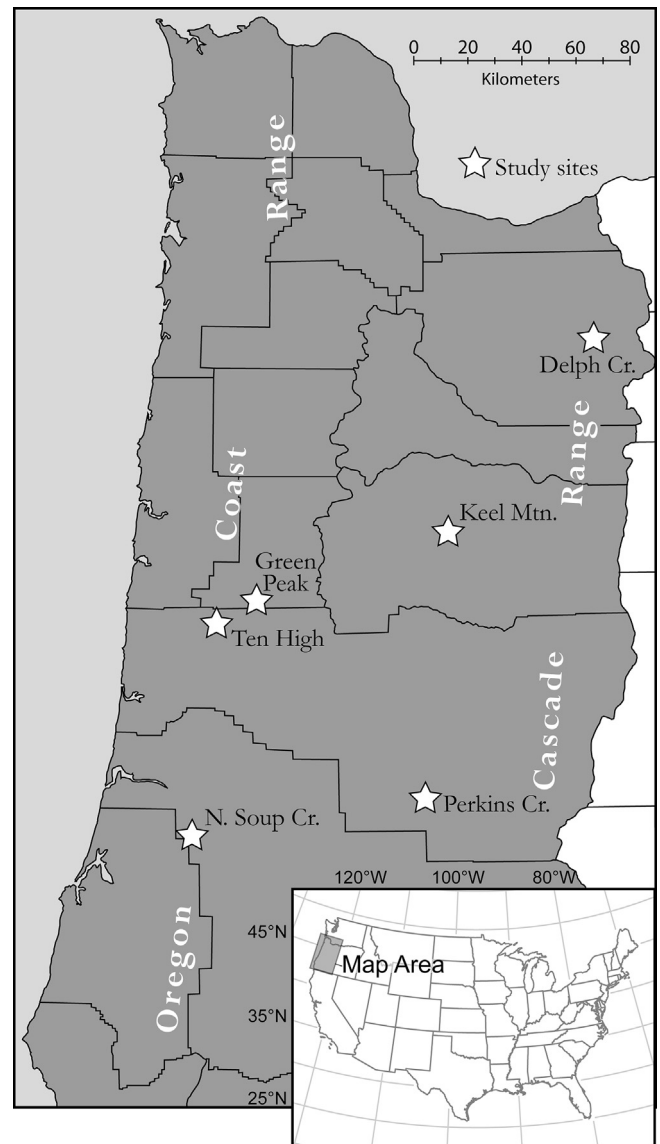

Fig. 2. Distribution of study sites in western Oregon.

Table 1
Overstory characteristics in unthinned controls, and timing of sampling relative to thinning treatments and stand age at each study site.

Site	Thinning years (first, second)	Initial age[a] (years)	Control density (trees ha^{-1})[b]	Control diameter[c] (cm)	Year sampled per measurement[d]			
					1	2	3	4
Delph Creek	2000, 2011	53	510	42	1998	2005	2010	2012
Green Peak	2000, 2011	56	438	44	1998	2004	2010	2012
Keel Mt.	1998, 2011	44	556	42	1997	2003	2011	2012
Perkins Creek	2000, 2011	70[e]	~250	–	1997	2004	2008	2012
N. Soup Creek	1998, 2011	48	384	43	1997	2003	2009	2012
Ten High	1999, 2011	44	666	37	1997	2005	2009	2012

[a] At first thinning.
[b] Live trees only, measured 11 years following the first thinning (from Dodson et al., 2012).
[c] Measured as the quadratic mean diameter (from Dodson et al., 2012).
[d] Measurements relate to thinning treatments as follows: (1) preceding 1st thinning treatment; (2) year 5 following 1st thinning; (3) year 9–13 following 1st thinning, immediately preceding 2nd thinning treatment; (4) year 1 following 2nd thinning.
[e] Perkins Creek was thinned 20 yrs before our study began at age 50 yrs to 250 tph, the density within our control unit; the site was rethinned during our study at age 70 yrs, and thinned during a third entry at ~80 yrs. Control diameter unavailable.

western hemlock. Other conifer species, such as western redcedar (*Thuja plicata*), and hardwood species including bigleaf maple (*Acer macrophyllum*), red alder (*Alnus rubra*), Pacific dogwood (*Cornus nutalli*), Pacific madrone (*Arbutus menziesii*), and golden chinquapin (*Chrysolepis chrysophylla*) were minor components of the overstory. Forests regenerated naturally following clearcut and seed tree harvests lacking riparian buffers, with the exception of portions of two sites (Keel Mountain and OM Hubbard), at which Douglas-fir seedlings were planted in some locations, and portions of three sites that were pre-commercially thinned (Cissel et al., 2006). More detail about the tree and understory vegetation response to these thinning treatments can be found in Ares et al. (2010), Dodson et al. (2012, 2014) and Burton et al. (2013, 2014).

2.2. Experimental design

Thinning treatments were applied to a portion of each site at an operational scale (i.e., 14–69 ha stands), while another portion was designated as an unthinned control (16–24 ha stands). In treatment units, upland forests underwent two consecutive forest thinning treatments, and stream reaches were treated with one of three no-harvest riparian buffer treatments that were applied to both sides of the stream: a ~70-m buffer (one site-potential tree-height buffer); a ~15-m minimum-width buffer that reflected the extent of riparian vegetation or a topographic break in riparian zones; a 6-m minimum buffer that reflected retention of only those trees immediately adjacent to the stream. With the exception of Perkins Creek, which had also been thinned 20 years earlier to 250 tph, the thinning treatment in the upland areas, implemented between 1997 and 2000, reduced overstory tree densities to ~200 tph. Additionally, 10% of the treatment unit was harvested as 0.04-, 0.08-, and 0.16-ha canopy openings and leave islands each (20% total). At the time of the first thinning for five of the six sites, Perkins Creek was thinned to 100–150 tph in its second entry. The second thinning (third for Perkins Creek) occurred between 2009 and 2011, and further reduced upland overstory tree densities to ~85 tph. Thinning treatments were designed to assess alternative silvicultural practices for accelerating development of old-growth forest conditions within in 30- to 70-year-old managed stands originating from clearcuts (Cissel et al., 2006), a regional priority due to designation of federal late-successional reserve land allocations in 1994 to address forest landscape ecological integrity (USDA and USDI, 1994). With the exception of Perkins Creek, control reaches were in unthinned second-growth stands, with overstory tree densities ~400–600 trees per hectare (tph).

Within sites, stream reaches in controls and treatments had random selection elements when possible, and criteria for their layout. When operational constraints permitted (e.g., location of

existing roads for site access during harvest operations at treatment units), a coin flip determined which unit would be the control and which would be thinned. Our study design criteria aimed for ~60 m slope distance of thinned upland between the buffer edge and a ridgeline, on both sides of a buffered stream reach. In our small drainages, this constrained implementation of the 70-m buffer, in particular, which consequently was included at a site in the thinned treatment whenever it fit along a stream reach (e.g., 70 m + 60 m = 130 m from stream to ridgeline needed). The other two buffer widths, 6-m and 15-m minimum, were randomly assigned to stream reaches within the thinned upland whenever such logistical constraints did not arise. This 60-m criterion for upslope distance between buffer edge and ridgeline reduces the chance for a treefall to enter a stream in an adjacent subdrainage; it is unlikely to fall over the ridge and into the neighboring stream. Another criterion was that we aimed for stream reaches to have a minimum length equivalent to 2.5 times a site-potential tree height of 70 m. The beginning and ending of selected reaches were located permanently with PVC pipes and georeferenced using GPS. Most reaches were independent, i.e., not connected as part of the same stream, and separated by ridges; however, there were two sites in which two reaches were connected as part of the same stream (Keel Mt.: 6-m reach flowed into the 15-m min., and 70-m reach flowed into 15-m min; Perkins Creek: control reach flowed into 70-m reach). In total, 34 stream reaches were included in the study (Tables 1 and 2).

2.3. Field sampling

Wood surveys were conducted four times: (1) prior to the first thinning; (2) five years after the first thinning; and (3) nine to 13 years after the first thinning treatment and just prior to the second thinning; and (4) one year after the second thinning, which was 12–14 years after the first thinning (Table 1). Each time, wood was sampled along the entire lengths of 34 stream reaches at six sites (Table 2). The diameter and length of all pieces ⩾10 cm in diameter and ⩾1 m in length were visually estimated. Diameter was estimated at 1/3 distance from the larger end. To calibrate estimates and account for observer error, diameter and length were measured during each survey on a subsample of pieces at each reach, accounting for 18% of the number of pieces recorded. Size estimates were strongly correlated with measurements on those pieces ($r = 0.96$ and 0.97 for length and diameter, respectively), suggesting visual estimates are very accurate and precise. Each piece was classified into one of five decay classes: class 1 – freshly fallen; class 2 – round, bark and wood intact; class 3 – sapwood partially decayed, bark sloughs, heartwood structurally sound; class 4 – heartwood rotten, logs soft and blocky; class 5 –

Table 2

Number of replicate reaches for each thinning buffer treatment and untreated control, and geomorphology of reaches sampled. Minimum and maximum values show the ranges sampled among reaches within each site.

Site	Buffer width (m)			Unthinned control	Area[b] (ha)	Gradient (%)	Length (m)	Width (m)	Depth (m)	W:D[c]
	6	15[a]	70							
Delph Creek	1	1	0	1	15–52	9–14	208–588	0.1–1.3	0.01–0.10	9.6–30.9
Green Peak	1	1	1	2	5–16	17–30	198–518	0.3–1.0	0.01–0.11	5.6–36.0
Keel Mt.	1	1	1	2	5–176	5–15	162–510	0.3–3.4	0.03–0.28	6.4–16.9
Perkins Creek	2	2	0	4	4–132	12–30	330–869	0.1–2.1	0.02–0.22	3.5-14.7
N. Soup Creek	1	1	1	2	5–29	20–27	242–463	0.4–1.4	0.04–0.15	4.0–9.6
Ten High	2	3	1	2	2–59	24–40	148–680	0.2–2.5	0.01–0.25	3.5–24.9

[a] Variable-width buffer with a 15-m minimum width.
[b] Area refers to the size of the basin draining into a reach.
[c] W:D refers to the ratio of the width (m) to the average depth (m) of the wetted stream channel.

highly decayed, no remaining structural integrity (e.g., Sollins et al., 1987). For all wood pieces, we visually estimated the percentage of volume present in three stream influence zones (modified from Robison and Beschta, 1990): zone 1—the wetted channel; zone 2—outside the wetted channel and within 2-m of streambank slope distance to the wetted channel (surrogate for bank-full stages of high water flow which are difficult to ascertain for headwater streams); and zone 3—suspended above the stream prism defined by zone 2. During the surveys immediately prior to and following the 2nd thinning, the source distance, the slope distance from stream edge (m) to the location where the tree stood prior to falling, was determined for large wood pieces when possible. It was noted when individual pieces were part of a log jam.

We characterized the spatial and geomorphological context of reaches using field measurements and geospatial data. Reach lengths were measured, as well as wetted widths and depths for fast-water and slow-water units (riffles and pools) within reaches. These widths and depths were used to calculate the reach-scale width:depth ratio, a unitless indicator of channel morphology (e.g., Beschta and Platts, 1986). Bankfull widths and depths are typically used to calculate width:depth, however, a large proportion of the lengths of these headwater streams lack conspicuous banks. Thus, these surveys were conducted during periods of high flow between February and June each year. This allowed measurement of the actual bank full width and characterization of the potential for downstream wood transport. Additionally, we estimated reach gradient based on reach end coordinates determined with a Global Positioning System (Garmin GPSmap 60CSx). Gradient was calculated as the elevation difference between reach end-points determined from digital elevation models divided by the straight-line distance between those points (i.e., rise/run). The estimated drainage (basin) area of reaches was determined by overlaying the stream in a Geographic Information System with a 10-m digital elevation model, and calculating the area encompassed from the downstream end-point within estimated ridgeline boundaries.

2.4. Statistical analysis

We calculated wood volume per reach, zone, and decay stage (m^3 100 m^{-1}) assuming no taper (cylindrical geometry). To examine relationships between large wood volume in headwater streams over time and instream wood character (decay class, zone), buffer width (6-, 15- or 70-m buffer vs. unthinned control), and reach and stream basin-level variables, we developed hierarchical linear mixed models with repeated measures using a multi-step process (Table 3) (Burton et al., 2014). Because of their similarity in function (stream structure and habitat), decay classes 1 and 2 were combined as "early" stages of decay, and classes 3, 4, and 5 were combined to represent "late" stages of decay for the analysis. In step one, we compared three models with main effects

Table 3

Multi-step modeling process used to examine processes controlling the distribution of wood volume within (steps 1 and 2) and among (step 3) headwater stream reaches.

Step	Process	Independent variables
1	Distribution within streams	Decay stage, zone
2	Experimental treatment structure	Buffer width, time since thinning (time)
3	Geomorphology	Drainage basin area, width:depth ratio, gradient

and interactions among decay stage, zone, and a decay stage/zone interaction. The model best supported by the data (having the lowest AIC$_c$) was selected and carried forward to step two. In step two, we added the effects of buffer width and measurement time (1, pre-treatment; 2, year 5 post-thinning; 3, year 9–13 post-thinning; 4, year 1 post-2nd thinning), and interactions thereof to the model selected in step one. At this stage, we developed and compared alternative models containing various combinations of main effects and appropriate interactions among the treatment structure and decay stage and zone. In step three, using the same approach as in step two, we added variables characterizing the geomorphic setting of each reach (basin area, reach gradient, reach width:depth ratio) to the best-performing model selected from step two (Table 3). Models were assessed using the mixed procedure with degrees of freedom estimated using the Kenward and Roger (1997) approximation in SAS (SAS version 9.4). Random effects for site, stream (nested in site) and reach (nested in site and stream), and repeated measurements of zones were included in all models (first-order autoregressive covariance). Volume was log-transformed prior to analysis. Prior to transformation, we added a constant equal to the square of the first quartile divided by the third quartile to account for observations of zero volume (Stahel, 2002). Large differences in volume between pre- and year 5 post-treatment surveys that were not related to thinning or buffer treatment suggested a potential bias against smaller pieces of wood as well as stumps in the first measurement. Therefore, all stumps were excluded from the analysis. Additionally, we developed models for pre- and all post-thinning surveys separately; data from the pre-treatment surveys was examined to confirm a lack of initial differences among buffer treatments.

The performance of alternative models was compared within and among steps one through three using AIC$_c$, a bias-corrected version of the Akaike Information Criterion (AIC) for small sample sizes (Burnham and Anderson, 2002). To assess the contribution of each additional process to improving model performance, we calculated AIC weights (w) and weight ratios, the ratio of the weight for the best performing model with the lowest AIC$_c$ to the weight of the model under consideration. Support for alternative models decreases with weight ratio: when weight ratios are <3, model

performance is not much different from the best model (Burnham and Anderson, 2002). To assess the variability explained by the selected models from each step, we calculated a "pseudo" R^2 for mixed models to quantify the marginal contributions of fixed effects (R_m^2) in explaining observed variation by dividing the variance in the predicted values by the sum of all variance components (Nakagawa and Schielzeth, 2013). Differences among decay stages, zones, measurement times, and interactions thereof in final models were assessed post-hoc using Fisher's F-protected least significant difference method to control comparison-wise error rate.

Finally, we used a mixed modeling approach to test whether volume of inputs declined with the distance of the source from stream at a resolution of 1 m, and to test the assumptions of the one tree-height buffer width. We related the logarithm of volume to distance, decay (early vs. late) and measurement (pre- vs. post-treatment). The log transformation was supported by visual assessment diagnostic plots of residuals. Streams-nested-within-sites was modeled as a random effect. The random effect for reach (nested in stream and site) was estimated to be zero, and there was no evidence that it led to improvements in the model after accounting for stream ($\Delta AIC_c < 1$), so it was excluded. The volume of wood that could not be associated with a particular source, and thus had no distance measurement associated with it, was not included in this analysis.

3. Results

3.1. Model selection

Our step-one model characterized wood volume patterns with decay class and influence zone: for all post thinning data, the best model from step one included main effects and interactions of decay class (early vs. late) and zone (1, 2, 3; Table 3). This model performed substantially better than models with only effects for decay class (did not converge), or zone ($\Delta AIC_c = 389$), and a model lacking an interaction term ($\Delta AIC_c = 57$). To address the role of riparian buffer width in explaining instream wood volumes, the best step-two model suggested a time trend—the model with the lowest AIC_c included additional main effects of time since thinning (3 time periods after thinning), buffer width (6-, 15-, and 70-m, and unthinned control), two-way interaction between decay stage and zone, and a three-way interaction among time since thinning, buffer width, and decay class ($w = 0.70$). Including effects of geomorphic conditions, the best step-three model included an additional main effect of drainage basin area ($w = 0.36$). The evidence in support of this top-ranking model relative to the second- and third-ranking alternatives with additional effects of width:depth ratio and gradient, respectively, was equivocal ($\Delta AIC_c = 1.0$ and 2.0, respectively; weight ratios <3; Table A.1 in supplementary material). Support for the final model selected in step three was, however, unequivocal ($w = 0.98$) relative to the final model selected in step two lacking an effect of drainage basin area. Yet, additional terms added in steps two and three did not substantially increase the proportion of the variance explained (sensu Nakagawa and Schielzeth, 2013) (Table 4). Our separate analysis of our pre-treatment data set revealed no evidence for differences in wood volume among treatments (Tables A.2 and A.4 in supplementary material).

3.2. Distribution of wood volume among decay classes and zones

Wood volume was 248 (95%CI = 174–355), 61 (95%CI = 42–86) and 36 (95%CI = 24–52) times greater in late than early stages of decay in zone 1, 2 and 3, respectively. Wood volume in early stages of decay was estimated to be 17.7 times greater in zone 2 (the dry portion of the bankfull channel) than in zone 1 (0.024 m^3 100 m^{-1} stream length, 95% CI = 0.016–0.035 compared to 0.485 m^3 100 m^{-1} 95% CI = 0.343–0.682, $t = -20.09$, $p < 0.0001$) on average and $\sim$2 times greater than in zone 3 (0.245 m^3 100 m^{-1}, 95% CI = 0.173–0.346, $t = 4.71$, $p < 0.0001$). Wood volume in late stages of decay was also 4.3 times greater in zone 2 (29.5 m^3 100 m^{-1}, 95% CI = 21.0–41.7) than zone 1 (6.85 m^3 100 m^{-1}; $t = -10.22$, $p < 0.001$), and 3.3 times greater than in zone 3 (9.06 m^3 100 m^{-1}; $t = 8.26$, $p < 0.001$). Wood volume in early stages of decay in zone 3 was 9.0 times greater than in zone 1 ($t = -13.63$, $p < 0.0001$), whereas there was only weak evidence that volume differed between zones 1 and 3 for wood in late stages of decay ($t = -1.74$, $p = 0.084$).

3.3. Effects of buffer width on wood volume over time

Wood in early stages of decay appeared to be influenced by thinning treatments in the short term. This wood volume was greater in reaches with the narrowest buffer width (6 m) than the other buffer treatments (15 and 70 m) and unthinned control (Fig. 3). This increase was sustained from year 5 following the 1st thinning through year 1 post-2nd thinning, but the 2nd thinning did not cause a similar increase. Additionally, volume in late stages of decay in the 15-m buffer was lower in year 5 and in years 9–13 than in the 6-m buffer in year 1 following the 2nd thinning (year 10–14 post-1st thinning; $p < 0.05$).

3.4. Relationship of wood volume to basin area

Wood volume increased exponentially with drainage basin area (Fig. 4). For every 1-ha increase in area, wood volume increased by 0.63% (95% CI = 0.03–1.2%). Because of differences in volume between early and late stages of decay, the magnitude of the increase differed between the low volume of wood in early- and relatively high volume in late stages of decay. For example, for wood in early stages of decay, volume increased from 0.07 (95% CI = 0.04–0.12) to 0.41 m^3 100 m^{-1} stream length (95% CI = 0.14–1.14) across the range of basin areas in controls in year one following the second thinning. In contrast, across this same range of basin areas, volume increased from 9.60 (95% CI = 5.70–16.18) to 54.22 m^3 100 m^{-1} (95% CI = 19.51–150.70) for wood in late stages of decay (also in controls in year one following the second thinning).

3.5. Relationship of wood volume to source distance

Wood volume for which sources could be identified in the field accounted for over 90% of the total on average for wood in early stages of decay. In contrast, sources could be identified for only 45% of the total volume of wood in late stages of decay (Fig. 5). The relationship between volume and distance to source differed between wood in early and late stages of decay ($F = 30.9$, $DF_n = 1$, $DF_d = 953$, $p < 0.001$; Fig. 5). As source distance increased, the volume of wood in late stages of decay decreased by 11.6% per meter (slope on a log scale = -0.11, SE = 0.02, $T = 1.93$, DF = 965, $p < 0.001$). In contrast, the evidence for a negative relationship

Table 4
Fixed effects for models of wood volume (log-transformed) selected at each step, and comparisons of AIC_c and variance explained (marginal effects) among steps.

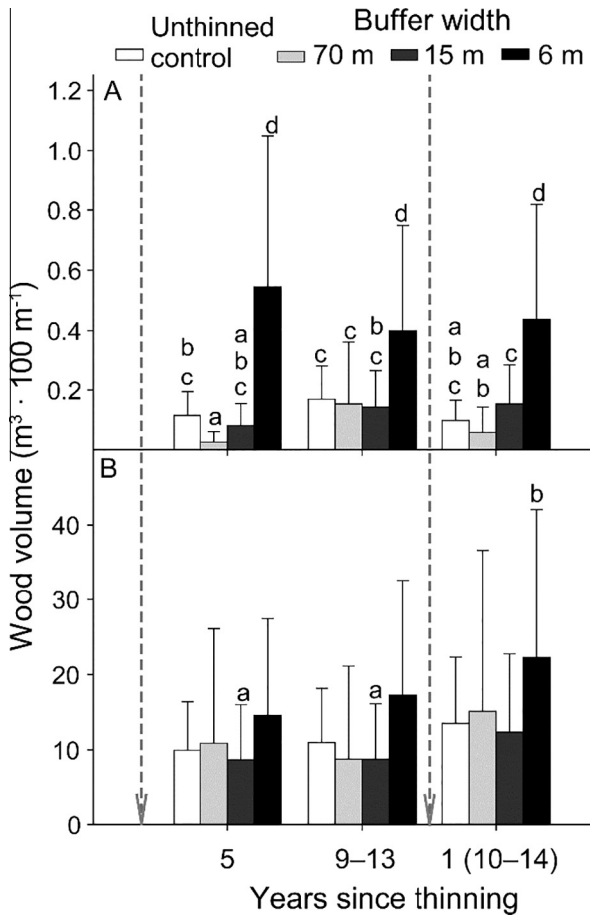| Step	Fixed effects	ΔAIC_c	w	R_m^2
1	Decay + zone + decay∗zone	33.7	0.00	0.67
2	Decay + zone + decay∗zone + treatment + time + decay∗time + decay∗time∗treatment	7.7	0.02	0.70
3	Decay + zone + decay∗zone + treatment + time + decay∗time + decay∗time∗treatment + basin area	0.0	0.98	0.71

Fig. 3. Effects of interactions between treatment, decay stage (A: early; B: late) and time since thinning on the volume of instream large wood (note differences in scale). Shared letters denote a lack of significant differences between groups ($p > 0.05$). Vertical lines and arrows mark timing of first and second thinning treatments relative to the measurement. Values are model estimates, bars show 95% confidence intervals. 15-m buffer indicates a variable-width buffer with a 15-m minimum width. Note scale differs between graphs.
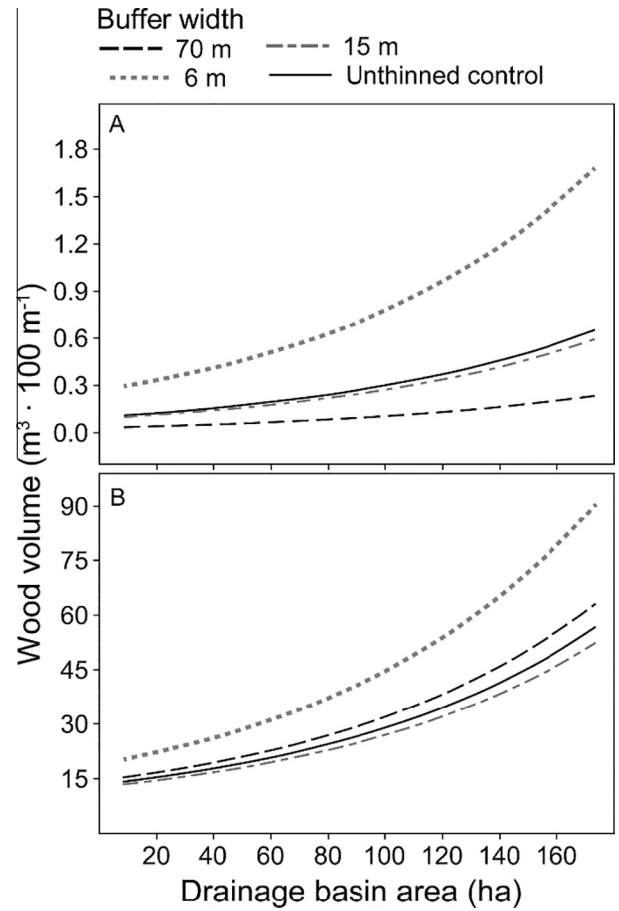

Fig. 4. Relationship between wood volume in headwater streams and drainage basin area. Values are model estimates of volume in early (A) and late (B) stages of decay (note differences in scale). Examples are from all buffer treatments and unthinned controls during the first year after the second thinning treatment (year 10–14 following the first thinning treatment). Other years are not shown. 15-m buffer indicates a variable-width buffer with a 15-m minimum width.
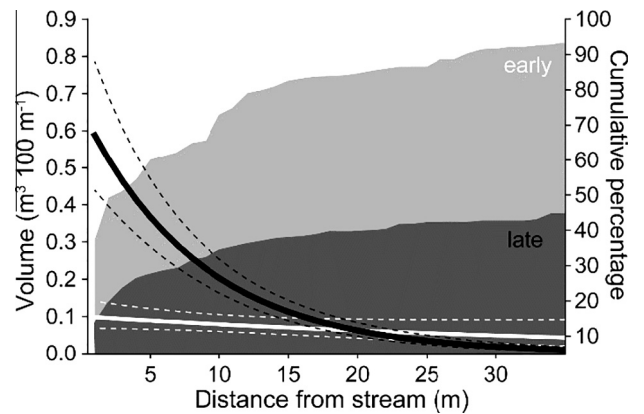
between source distance and volume of wood inputs (3.3% per meter) was weak for wood in early stages of decay (slope on a log scale = -0.03, SE = 0.01, $T = -10.8$, DF = 952, $p = 0.054$). There was no evidence that these effects varied over time (i.e., pre- and post-2nd thinning) (Table 5). Of the volume for which sources could be identified, 82% (early stages of decay) and 85% (late stages of decay) was recruited from within 15 m of the stream.

4. Discussion

Our results suggest that thinning within a site-potential tree-height of non-fish-bearing headwater streams can result in the augmentation of instream wood volume. In the short term, thinning 40- to 80-year-old stands led to slightly higher volumes of wood in headwater streams within a narrow 6-m riparian buffer treatment, compared to 15-m and 70-m riparian buffer treatments. Extending upland thinning treatments closer to streams may result in more harvesting residues or trees and snags falling into streams as a direct result of damage during harvesting operations (Vanderwel et al., 2006), windthrow (Chan et al., 2006; Drake, 2008; Roberts et al., 2007). Relative to the total volume of instream wood, these differences were small, amounting to 0.35 m³ 100 m⁻¹ stream length, but not inconsequential (43.75 pieces of our minimum threshold size of 0.008 m³, or ~13% of a single 22-m average-sized tree at a dbh of 40 cm, assuming a similar cylindrical

Fig. 5. Relationship between instream wood volume and source distance for wood in early (white) and late (dark) stages of decay. Solid line shows model estimates, dotted lines show 95% confidence intervals. Shaded area plots show cumulative distribution of the total observed wood volumes for which sources could be identified and source distances measured (light = early stages of decay in classes one and two, dark = late stages of decay in classes three, four and five). The source location could not be identified for all pieces; thus cumulative percentages do not add up to 100%.

geometry). The ecological impact of these small pieces is uncertain. For example, these pieces are likely too small to stabilize other debris in logjams or to provide many of the habitat benefits of larger-diameter pieces, but they may have functional significance

Table 5
Type three tests of fixed effects of source distance, measurement (pre- vs. post-2nd thinning) and decay class (early vs. late) on the volume of wood per reach. Wood pieces for which sources could not be identified, and hence source distance data were not available, were not included. Degrees of freedom (DF) subscripts indicate values for the numerator (n) and denominator (d).

Effect	DF_n	DF_d	*F*-Value	Pr > *F*
Distance	1	959	69.3	<0.001
Time	1	963	0.8	0.38
Distance * time	1	951	0.01	0.91
Decay	1	950	77.8	<0.001
Distance * decay	1	953	30.9	<0.001
Decay * time	1	946	0.3	0.58
Distance * decay * time	1	950	1.8	0.18

for smaller organisms. In contrast, the majority of wood volume was composed of legacy pieces in late stages of decay, likely derived prior to the original clearcut harvests.

Tree mortality patterns observed in the thinned uplands (Dodson et al., 2012) are consistent with expectations of lower rates than in unthinned controls (e.g., Marquis and Ernst, 1991; Powers et al., 2010). This results from lower levels of competition-related mortality of smaller-diameter and shorter trees (Reineke, 1933). Over longer time scales (~50+ years), trees growing near (Dyer et al., 2010; Ruzicka et al., 2014) or within thinned portions of riparian forest stands (Davis et al., 2007; Dodson et al., 2012) outside of narrower no-entry buffers can develop large diameters faster, eventually contributing larger volumes of wood to streams (Spies et al., 2013). In contrast, wider buffers may lead to greater cumulative volumes of large wood in streams, but piece sizes would be biased toward smaller-diameter trees (Pollock and Beechie, 2014; Spies et al., 1988).

Our results showing increases in wood volume in the narrowest 6-m buffer contrast with those from a companion study at some of these same sites which found high variability in the percent cover of large wood and no clear buffer effect along gradients extending from riparian areas into the uplands (Anderson and Meleason, 2009). Several differences between these studies may explain the differing results, including: sites examined (only 3 of the same sites were used between studies); sampling design (we sampled entire stream reaches; they sampled along transects perpendicular to streams, with 2 or more transects per buffer treatment); reaches studied (we included more stream reaches, overall; however, they subsampled along buffered reaches to examine differences between thinning and patch cuts); wood metrics analyzed (our study, volume; their study, percent cover). For example, wood volume could vary within a given estimate of percent cover depending on the size and number of pieces. Finally, it is possible that lumping wood across all decay stages (Anderson and Meleason, 2009) could obscure the signal, which was present only in wood in early stages of decay in our study.

The observed positive relationship between wood loading and drainage basin size is consistent with results of Fox and Bolton (2007) from Washington and contrasts with those of Wohl and Cadol (2011) from the Colorado Front Range. Wohl and Cadol (2011) suggested that wood loading declines with basin size as a result increasing transport capacity downstream. Opposite relationships observed in the Pacific Northwest might reflect a greater residence time of wood related to differences in piece size and substrate (Wohl and Goode, 2008; Wohl and Cadol, 2011) and increasing incidence of log jams downstream (Kraft and Warren, 2003; Wohl and Jaeger, 2009). Although the ultimate mechanism driving this pattern was not addressed in our study, others have highlighted the importance of headwaters as a dominant source of wood recruitment for downstream reaches, via episodic debris-flow events (May, 2002; Reeves et al., 2003).

4.1. Relationship of instream wood loading to stream geomorphology

We found that effects of stream gradient and width:depth ratio (e.g., Fig. 1) did not improve our model performance to explain variation in wood volume among reaches. Instead the influence of local topography may be captured in the effect of basin size (i.e., basin size was negatively related to gradient, and there was a u-shaped relationship between width:depth ratio and gradient, $r^2 = 0.2$ in both cases), or could be driven by rare, extreme events with no strong topographic predictor. These results conflict with those of Wohl and Cadol (2011) who observed a greater importance of local valley and channel geometry on wood loading than time since forest disturbance or increasing basin size. Similar to the opposite relationships between wood loading and drainage basin size, these different results could stem from differences in stream gradient (higher in the Colorado Front Range) and underlying substrates (bedrock vs. alluvium) resulting in greater current forces and less wood burial compared to the Pacific Northwest. Other unanalyzed geomorphic features also could contribute to observed variability as we did not address all attributes associated with basin-scale landslide potential, or reach-scale tree-fall directionality (Sobota et al., 2006).

4.2. Source distance

The US Northwest Forest Plan (USDA and USDI, 1994) assumed that large wood sources for streams in managed forests were dominated by treefalls, with the probability of a tree entering a stream being a function of slope distance in relation to tree height and floodplain constraints (McDade et al., 1990; Van Sickle and Gregory, 1990). The general expectation was that the primary source of large wood would be trees growing within their fall zone (one site-potential tree-height) from the stream. Our results showed that the 82–85% wood for which we could determine original sources came from within 15 m of the stream, and the relative contribution of wood declined quickly with increasing distances from streams. Yet over 55% of the total volume of wood in late stages of decay in our study could not be associated with a particular source, indicating this wood originated further from the stream or from sources that were difficult to detect. Linking this result to our other finding of the positive relationship between wood volume and basin area suggests a greater role for other recruitment processes of large wood in small basins, such as downstream transport of wood, creep, landslides, and debris flows (e.g., Hassan et al., 2005; Nakamura and Swanson, 1993; Reeves et al., 2003). This supports the notion that historical wood redistribution processes are important to explain current stream wood loading. This was anticipated in the US Northwest Forest Plan riparian reserve guidelines, in that they included provisions for potentially unstable areas in headwaters (B-13 in USDA and USDI, 1994). Hence, as current managed stands develop and future large wood is managed, recruitment sources in headwater basins from riparian buffer treefalls, basin-wide upland erosion processes and wood redistribution may be key considerations. However, caveats are needed regarding the interpretation of our results: wood in late stages of decay may be have been difficult to trace to a source due to its character of being highly decayed and fragmented, as well as the potential for it to have been redistributed during harvesting operations (Loretta Ellenburg, *personal communication*).

4.3. Distribution among decay classes

Consistent with previous reports (Burton et al., 2013; Duvall and Grigal, 1999; Spies et al., 1988), we documented that wood in stands that are in early stages of stand development was dominated by "legacy wood" in late stages of decay that was likely

deposited prior to the initiation of the current stands (May, 2002). Overall, within our study context, the mortality of small-diameter trees during the stem-exclusion phase appears to contribute relatively little to the overall biomass and volume of wood in streams (Fig. 3). This is consistent with the observed low mortality rates at these sites (Dodson et al., 2012). Recruitment of fresh large wood and subsequent fragmentation and decomposition thus appears to be an extremely slow process during the early stages of stand development (Hassan et al., 2005). However once in the stream, wood loading appears to remain stable for very long periods of time (May, 2002). It is likely that decomposition of legacy wood and continued low inputs to streams over the next few decades of stem exclusion could further depress wood loadings (Duvall and Grigal, 1999; Harmon et al., 1986; McHenry et al., 1998; Spies et al., 1988). Our results therefore highlight the importance of leaving legacy wood during harvest operations, as these larger trees have a long-term influence that can mediate the low input levels to be expected in residual stands. Alternatively, or in combination, management practices such as snag or large wood creation may be necessary and should be planned for if it appears that they are necessary to achieve desired instream wood targets.

4.4. Distribution among influence zones

Our results show that wood distribution within the stream varies with influence zone (Robison and Beschta, 1990) and has been very stable throughout the duration of the study. The much higher volume in zone 2, the dry portion of the bankfull channel relative to zone 1, the wetted zone, is likely partially related to the greater sampling area, as zone 2 extends 2 m from each edge of the stream (4 m total) while wetted widths ranged 0.24–2.50 m (modal width = 0.6 m). This ~seven-fold difference in width, however, would not account for the twenty-fold difference in volume for wood in early stages of decay, suggesting that much of the recently recruited wood is not reaching or retained in the wetted zone of the stream. Pieces of wood often get hung up on stream banks and are aggregated in log jams (Kraft and Warren, 2003; Wohl and Cadol, 2011). However, this pattern might also be related to younger trees being short and not reaching the wetted portion of the active channel if they grow near the upper edge of a site-potential tree height buffer. For example, trees in a 50-year-old stand with a site index of 36 (base age = 50), are projected to be 36-m tall and do not reach a height >60 m until they are over 100 years old (King, 1966). Hence, younger trees in managed stands may fall short of streams, especially if their fall lines are not perpendicular to streams. Tree-fall directionality may be dependent upon location of other standing trees or topographic features (steepness of hillslopes constraining streams), again dropping them short of streams (Sobota et al., 2006). These factors may contribute to larger wood loadings in zone 2 relative to zone 1. On the other hand, wood in late stages of decay was only ~4-fold greater in zone 2 than zone 1, which is more consistent with differences in zone width and tree height (e.g., taller trees that characterized older stands before they were logged would have contributed to this legacy wood). The smaller ~10-fold difference in wood volume in zone 3 than zone 1 suggests that wood in early stages of decay may contribute to increased wood volumes in zones 1 and 2 in the future with decay, breakage and transport during flooding events (Wohl and Goode, 2008). These events are apparently infrequent as the distribution of wood among zones did not vary over the 14-year timeframe of this study.

The ecological role of wood includes providing habitat for a diversity of fauna, and varies across the stream prism. While wood in zones 1 and 2 would affect stream habitat formation at high flows (e.g., roughness, Robison and Beschta, 1990), wood in zone 1 affects instream aquatic species, and zone 2 wood affects bank-associated aquatic species and likely some aquatic taxa at higher flows. In a western Oregon study, instream headwater vertebrate species had strong associations with large wood density, including trout (*Oncorhynchus* spp.), sculpins (*Cottus* spp.), Coastal Giant Salamanders (*Dicamptodon tenebrosus*), and Coastal Tailed Frogs (*Ascaphus truei*) (Olson and Weaver, 2007). Within 2 m of the wetted channel along stream banks, high densities of large wood were associated with abundances of three species: Coastal Giant Salamander, Oregon Slender Salamander (*Batrachoseps wrighti*) and *Ensatina eschscholtzii*. At a subset of those streams after two thinning entries had been conducted upslope, torrent salamanders (*Rhyacotriton* spp.) were associated with large wood volume (Olson and Burton, 2014), along with *Ensatina* along stream banks. For these small-bodied animals, even relatively small pieces of wood in and along headwater streams may be relevant as cover. Wood in zones 2 and 3 also benefits numerous other taxa (Rose et al., 2001) as habitat or dispersal runways; logs in zone 3, suspended over stream channels, may be particularly useful to provide connectivity across streams for those fauna which perceive flowing water as a barrier to dispersal.

5. Management implications

Contrary to our expectation that wood loading in headwater streams would increase with riparian buffer width, thinning closer to streams (i.e., smaller buffers) appears to have increased instream wood loading initially. Deliberate silvicultural considerations and treatments in riparian areas, within a tree-height distance of streams, could therefore be used to recruit wood to streams. For example, directional felling can immediately augment instream volume of wood in early decay stages. If done repeatedly over time, such practices can compensate for lower levels of recruitment of live wood due to thinning (Benda et al., 2015). Simultaneously, thinning will increase the growth of riparian trees, accelerating the production of large-diameter wood and associated stream habitats and functions in the future. Any choice of riparian buffer width and silvicultural treatment benefits from considering the difference between short-term versus long-term effects on wood loading targets and sizes of instream wood.

Although these headwater streams were small, as were the drainages, small streams comprise most of the stream network length in this region, and can be important for understanding larger watershed patterns and dynamics. Continued low tree mortality and wood recruitment predicted by models of forest structural development and stand dynamics, in addition to further decomposition, breakage and redistribution of existing instream wood, may result in future wood deficits in headwater streams in the absence of natural disturbances or human-mediated recruitment. Although drainage areas were sufficiently small that their size was at least partially responsible for the limited instream wood volume, the large amount of wood in late stages of decay that could not be associated with a particular source location also suggested that redistribution of highly fragmented and decayed legacy wood is an important process in these areas over longer time scales. The use of large no-harvest buffer zones may therefore not properly account for the importance of wood sources further away from the stream. In contrast, recruitment of wood near streamside (<15 m) areas appears responsible for the vast majority of sourced wood.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2016.03.053.

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