Living trees provide stable large wood in streams

Jeff J. Opperman1,2* and Adina M. Merenlender3
1 Center for Watershed Sciences, University of California, Davis, Davis, CA, USA
2 The Nature Conservancy, Chagrin Falls, OH, USA
3 Department of Environmental Science, Policy, and Management, University of California, Berkeley, Berkeley, CA, USA

Abstract

Large wood exerts strong influences on stream channel morphology and aquatic ecosystems. Previously, in-stream large wood has generally been equated with dead wood. However, in streams in Northern California we found that living wood – trees that entered the channel but remained rooted and living – represented a major portion of the functional in-stream large wood. We hypothesized that living wood will tend to be more stable, due to an attached root wad, and more persistent, due to lack of decay, than similarly sized dead wood. Living wood may provide important in-stream structure in streams with riparian corridors that lack large conifers. We surveyed 20 stream reaches in Northern California with riparian corridors dominated by broadleaved trees and found that a high proportion of wood jams had key pieces that were still living. Living wood was capable of serving as a key piece for a wood jam at a smaller size than dead wood and had a greater influence on channel morphology. We found that only 74% of the jams without living wood persisted over 1–2 years while 98% of those with living key pieces remained in place. Due to living wood, the range of tree species and sizes that provide stable and functional in-stream large wood may be broader than previously described. Copyright © 2007 John Wiley & Sons, Ltd.

Keywords: large wood; channel morphology; riparian vegetation; steelhead

Introduction

Large wood – including trees, logs, branches and rootwads – exerts significant influence on stream-channel morphology and aquatic ecosystems. In-stream large wood provides habitat for a broad range of aquatic biota and can strongly affect basic geomorphic and ecological processes such as sediment transport and nutrient retention and cycling (Gregory et al., 2003). Wood in streams and rivers provides critical habitat features for fish through a variety of mechanisms including pool formation (Montgomery et al., 1995), cover from predators (Shirvell, 1990), refuge during high flows (Tscharplinkski and Hartman, 1983), substrate for invertebrate prey (Benke and Wallace, 2003), promotion of riparian regeneration (Abbe and Montgomery, 1996) and deposition and storage of spawning gravels (Crispin et al., 1993) and organic matter (Bilby and Likens, 1980). Consequently, researchers consistently characterize large wood as one of the most important habitat components for anadromous salmonids (National Research Council, 1996).

Previously, large wood has generally been equated with dead wood (see, e.g., Krajick, 2001), with a notable exception provided by researchers working on the Tagliamento River, a large, braided river draining the Italian Alps, who describe the contribution of living large wood to island formation (Gurnell et al., 2005). The bias toward dead wood in other systems is likely because much of the initial research on large wood was conducted in the United States’ Pacific Northwest, where conifer-dominated riparian forests produce massive dead logs. The current body of knowledge of and sampling techniques for large wood draw heavily from this region.

However, we found that in northern California living wood provided much of the functional in-stream large wood (Opperman, 2005; Figure 1). In particular, living wood contributed to the formation of wood jams, which are a primary mechanism by which wood influences channel morphology.

Here, we explore how this living wood functions and influences channel morphology. We define living in-stream large wood (or, more simply, ‘living wood’) as trees, or portions of trees, that have entered the stream channel, generally through bank erosion, that remain rooted and alive. After falling and entering the stream, these trees often sprout new branches and/or reorient existing major branches to grow vertically and assume the primary photosynthetic
activity for the tree (Figure 1). We hypothesize that, because these woody elements are still living, they will have greater stability and persistence than dead wood of similar dimensions. Stability should be enhanced due to the living root system anchoring the piece to the bank. Persistence should be increased because the piece remains alive – rooted and photosynthesizing – and thus will not decay.

These proposed characteristics of living wood lead to the following specific hypotheses. (1) Due to the presence of a living and attached root mass, living wood will have greater stability in high flows. Thus living wood will be geomorphically effective (e.g. able to form a pool or serve as a key piece for a wood jam) at smaller dimensions than
dead wood. (2) Because living wood is more stable and, due to the lack of decay, more persistent than dead wood, wood jams that include living wood will be more stable and persistent through time and have a greater influence on channel morphology – forming pools and altering channel profile – than wood jams composed of only dead wood. (3) Because living wood will not decay and break apart, living wood pieces are more likely to have major branches than dead large wood. The presence of major branches will allow wood jams to more effectively trap wood in transport and thus form larger wood jams than dead wood. (4) Because wood jams with living key pieces may branch and leaf out (Figure 1), pools formed by these jams will have greater cover values than pools formed by jams without a living key piece.

These hypothesized characteristics may strongly influence the nature and extent of interactions between wood and channels, particularly in streams within forests lacking large conifers. Broadleaved riparian trees have commonly been characterized as producing wood that is smaller with faster decay rates than conifer wood (Cederholm et al., 1997; Hyatt and Naiman, 2001) and, therefore, less capable of influencing channel morphology (Roni et al., 2002; Swanson and Lienkamper, 1978). Living wood may partially offset these limitations and, thus, the range of tree species and sizes that provide stable and functional large wood may be broader than previously described. Understanding living wood may therefore inform the management of streams in systems that lack large conifers, either naturally or due to previous timber harvest. For example, many streams in northern California that support runs of steelhead trout (*Oncorhynchus mykiss*) are within watersheds dominated by broadleaved trees (Opperman, 2005). Examining living wood may provide important insight about the interaction of wood and channels in these and other systems that lack large riparian trees.

### Methods

We surveyed large wood, wood jams and pools in 20 stream reaches within 16 watersheds in the San Francisco Bay Area and the Russian River basin (Figure 2). These watersheds have Mediterranean-type climates (cool, wet winters and dry, hot summers) and are dominated by oak woodlands. The riparian corridors are composed of broadleaved species such as California bay laurel (*Umbellularia californica*), white alder (*Alnus rhombifolia*), big-leaf maple (*Acer macrophyllum*), willows (*Salix spp.*) and oaks such as Canyon live oak (*Quercus chrysolepis*) and California black oak (*Quercus kelloggii*). All of the study streams have been historically utilized by anadromous salmonids, primarily steelhead trout, with some streams also supporting coho salmon (*O. kisutch*). Most of the streams continue to support at least remnant populations of anadromous fish, while six of the streams are blocked by dams or other impassable barriers and only support resident rainbow trout (*O. mykiss*).

Single streams were broken into more than one reach if the reaches were separated by a dam or other major obstruction to wood transport or if major tributaries entered the stream and increased considerably the drainage area of the reach. For each reach we measured the bankfull width (BFW) and determined the drainage area using a global positioning system and a 10 m digital elevation model within a geographic information system.

We defined large wood as any piece of wood at least 1 m length and at least 10 cm diameter within the bankfull dimensions of the channel (these are common criteria; see, e.g., Dolloff and Warren, 2003). For each piece of wood we measured the diameter and length, identified the species, determined whether it was living or dead, and noted whether the piece contributed to pool formation. A living tree was only categorized as large wood if it, or one of its major branches, had actually entered the channel – generally through undercutting, bank erosion or hillslope failure – with the primary trunk, or branch, oriented parallel to the plane of the channel bed and within the bankfull dimensions of the channel. Thus the trunks and roots of living, standing trees rooted on the channel margin or within the channel, with trunks perpendicular to the plane of the bed, were not categorized as large wood and their contributions to channel form or wood jam stability were noted separately.

We defined a wood jam as an aggregation of at least three pieces of large wood, although most wood jams were larger (mean = 12.0 ± 0.6; median = nine pieces, interquartile range = 6–15). We assessed whether a jam had a key piece or pieces and, if so, measured its dimensions and recorded whether it was living or dead. We defined the key as the piece or pieces primarily responsible for trapping the other wood and providing the greatest stability to the jam. We recorded whether or not the key piece had major branching, defined as the primary piece having any branch that met the dimensional criteria for large wood.

Jams were further categorized according to channel position: (1) bank jams were confined to the channel margins, (2) partially spanning jams extended into the active channel and (3) spanning jams extended across the entire wetted channel with pieces touching both banks. We collectively labeled the latter two categories channel jams. Several of our analyses focused on channel-spanning jams (or the key pieces that formed them) because we had found that channel-spanning jams had the largest influence on channel morphology and stored the most wood in these streams (Opperman, 2005). We investigated persistence of wood jams by resurveying four reaches after one or two winters (the period of high flow; Table 1).
Additionally, we recorded whether or not the jam created a step in the channel profile and/or a pool. Because jams were frequently formed behind (i.e. upstream of) standing trees rooted at the channel margin, which may influence jam stability (Opperman and Merenlender, 2004), we also recorded whether or not the jam was stabilized by standing trees. If the wood jam created a pool, we measured the pool’s dimensions and recorded its cover value by estimating the proportion of the pool surface area influenced by cover elements such as wood, boulders or vegetation.

**Statistical Analyses**

To examine the factors that influenced the size of key pieces, we used multiple linear regression models with response variables for wood dimension (diameter or volume) and model terms for bankfull width (BfW), decay class (living or dead) and whether the wood jam behind the key was also stabilized by standing trees. To compare the average dimensions of living and dead key pieces, we then examined the partial regression leverage plots for decay class. We also used a multiple linear regression model to examine the factors that influenced jam size with a response variable


### Table I. Characteristics of stream reaches surveyed for large wood. Among ‘all other streams,’ spanning jams were found in channels with a bankfull width up to 10 m and drainage area of 2500 ha

<table>
<thead>
<tr>
<th>Stream reach</th>
<th>Date of survey(s)</th>
<th>Drainage area (ha)</th>
<th>BfW (m)</th>
<th>Survey distance (m)</th>
<th>No. of spanning jams</th>
<th>No. of spanning jams with living key piece (proportion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grape</td>
<td>Summer 2001</td>
<td>340</td>
<td>3·5</td>
<td>200</td>
<td>8</td>
<td>5 (0·63)</td>
</tr>
<tr>
<td>Redwood</td>
<td>Fall 2000; Fall 2002</td>
<td>461</td>
<td>3·5</td>
<td>700</td>
<td>13</td>
<td>7 (0·54)</td>
</tr>
<tr>
<td>Upper Wildcat</td>
<td>Fall 2000; Fall 2002</td>
<td>493</td>
<td>4·2</td>
<td>1500</td>
<td>13</td>
<td>7 (0·54)</td>
</tr>
<tr>
<td>San Leandro</td>
<td>Summer 2001</td>
<td>703</td>
<td>4·4</td>
<td>900</td>
<td>9</td>
<td>6 (0·67)</td>
</tr>
<tr>
<td>Middle Wildcat</td>
<td>Summer 2001; Summer 2002</td>
<td>800</td>
<td>4·6</td>
<td>3300</td>
<td>29</td>
<td>14 (0·48)</td>
</tr>
<tr>
<td>Lower Wildcat</td>
<td>Summer 2001; Summer 2002</td>
<td>1780</td>
<td>5·7</td>
<td>3350</td>
<td>27</td>
<td>7 (0·26)</td>
</tr>
<tr>
<td>Upper Olema</td>
<td>Summer 2001</td>
<td>2500</td>
<td>7·6</td>
<td>2800</td>
<td>23</td>
<td>9 (0·39)</td>
</tr>
<tr>
<td>Lower Olema</td>
<td>Summer 2001</td>
<td>4200</td>
<td>9·3</td>
<td>1200</td>
<td>6</td>
<td>3 (0·50)</td>
</tr>
<tr>
<td>All other streams</td>
<td>Summer 2001</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
<td>5 (0·31)</td>
</tr>
</tbody>
</table>

of the volume of wood stored behind the key piece and model terms for key decay class, drainage area and channel location (bank, partially spanning, spanning). In the multiple regression models, dummy variables were used for binary variables (e.g. key decay class: living or dead).

To test the hypothesis that individual pieces of living wood were more likely than similarly sized dead pieces to form a pool or act as a key piece (binary response variables) we used multiple logistic regression with model terms for decay class of the piece and ratios of piece size to channel dimension (e.g. diameter:BfW). For the analysis of pool formation we considered only individual pieces (i.e. not key pieces or pieces otherwise contained within a wood jam). For this logistic regression test we report the odds ratio, which is the probability of a binary response variable being a ‘yes’ (e.g. formed a pool) divided by the probability of that variable being a ‘no’ (Agresti and Finley, 1997). We also used multiple logistic regression to test the hypothesis that wood jams with living wood were more persistent than jams composed of only dead wood. For this analysis, the response variable was whether or not the jam was relocated in the second survey with model terms including the presence of a live key, presence of a dead key and whether the jam was stabilized by standing trees.

We used ANCOVA to compare the depths of pools formed by jams with living and dead key pieces with drainage area as the covariate (because pool depths generally increase with increasing drainage area). We also used ANCOVA to examine the cover values of pools formed by wood jams with living and dead keys, with pool surface area as a covariate. Statistical analyses were conducted with the software JMPIN 4.0.4 (2001, SAS).

### Results

Overall, 10% of all in-stream large wood pieces were living, representing 11% of the total wood volume. Approximately one-third of wood jams had a living key piece. The proportion of wood jams with a key piece and the proportion with a living key piece increased from bank jams to channel-spanning jams; 44% of all channel-spanning jams had a living key piece (Figure 3). Within individual streams, the proportion of channel-spanning jams with living keys averaged $42 \pm 8\%$ (mean \pm standard error) and the proportion of partially spanning jams with living keys averaged $22 \pm 9\%$. However, these results include 12 reaches that had fewer than three channel jams (channel jams were rare on many streams; see Opperman, 2005). Eight of the reaches had 10 or more channel jams, with at least six channel-spanning jams. For these eight reaches the proportion of channel-spanning jams with live keys averaged $50 \pm 5\%$ (Table I).

Willows, primarily red willow (*Salix laevigata*), were the most common species providing living key pieces (47% of all live keys), followed by California Bay (27%) and white alder (20%). Other species providing living keys included coastal live oak (*Quercus agrifolia*), Oregon ash (*Fraxinus latifolia*) and big-leaf maple.

Living wood was geomorphically functional at smaller dimensions than dead wood. Among the eight reaches with at least six channel-spanning jams, the minimum diameter for a live key piece (17 ± 2 cm) was smaller than the
Figure 3. The proportion of all wood jams with a live key piece (shaded), dead key piece (white) or no key piece (black), based on channel position of the wood jam.

Figure 4. Based on logistic regression, the probability that living and dead individual pieces of large wood act as a key piece with increasing piece size (diameter) relative to channel dimension (bankfull width (BfW)).

minimum diameter for a dead key piece (27 ± 3 cm; paired $t = 2.5, p = 0.04$). The minimum volume for a dead key piece (0.24 ± 0.04 m$^3$ of wood) was nearly twice that of a live key piece (0.13 ± 0.04 m$^3$; paired $t = 2.5, p = 0.04$).

Decay status (living, dead) and ratios of piece size to channel dimension were highly significant predictors of whether an individual piece of wood formed a pool or acted as a key piece. Based on the odds ratio from logistic regression, individual living wood elements were more likely by a factor of three than similarly sized dead wood elements to serve as a key piece (Wald $X^2 = 91.1; p < 0.0001$; Figure 4) and more likely by a factor of 1.4 to form a pool (Wald $X^2 = 7.2; p = 0.007$).
Controlling for bankfull width, wood jams stabilized by standing trees had key pieces with smaller average volume and diameter than the key pieces of jams that were not stabilized by standing trees (Figure 5). The average diameter of live keys for channel-spanning jams (26·5 ± 3·8 cm) was significantly smaller than that for dead keys (38·1 ± 3·6 cm; \(F_{3, 62} = 3·5; p = 0·02\)), controlling for bankfull width and whether or not the jam was stabilized by standing trees. Similarly, the average volume of a living key piece for a channel-spanning jam (0·5 ± 0·2 m³ of wood) was smaller than the average volume of a dead key piece (0·9 ± 0·2 m³), although this difference was not statistically significant (\(F_{3, 62} = 3·2, p = 0·22\)). Dimensions of key pieces for bank jams and partially spanning jams were not statistically different between live and dead keys.

In all four reaches that were resurveyed, a higher proportion of channel jams with living keys remained compared with jams composed of only dead wood (Figure 6). Using logistic regression, only the presence of a live key (Wald’s \(X^2 = 6·6, p = 0·01\)) was a significant predictor of wood-jam persistence. Overall, 43 out of 44 (98%) channel jams with a living key that had persisted, while 48 out of 65 (74%) jams composed of dead wood were still present after one year (lower and middle Wildcat) or two years (upper Wildcat and Redwood).

Jams with a live key were more likely to form a pool (65% formed a pool) than were jams with a dead key (47%) or lacking a key piece (32%; \(X^2_{2, 306} = 24·5, p < 0·0001\)). Channel-spanning jams with a live key were more likely to form a pool (76%) than those with a dead key (61%) or lacking a key piece (57%; \(X^2_{2, 141} = 5·8, p = 0·05\)). Pools formed by wood jams with living key pieces had greater average depth (36 ± 3 cm) than pools formed by wood jams with a dead key piece (31 ± 2 cm), although this difference was marginally statistically significant (\(p = 0·13\)). Wood jams with live and dead keys were equally likely to cause a step in the channel profile.

Living key pieces were nearly twice as likely to have major branching (55%) as dead key pieces (29%; \(X^2_{1, 158} = 10·9, p = 0·001\)). However, wood jams with a living key piece (stored volume = 1·6 ± 0·2 m³ wood) were not
Living trees are an important component of the in-stream large wood in the northern California streams we surveyed. This living wood contributes to fish habitat by creating and maintaining wood jams, forming pools and providing cover. Living wood was significantly more stable, persistent and geomorphically effective than similarly sized dead wood. Living wood may be particularly important in systems where riparian trees produce relatively small pieces of dead wood that have reduced stability and persistence. For example, in northern California and the US Pacific Northwest, broadleaved trees have often been characterized as providing wood that is too small to be geomorphically effective in streams (Roni et al., 2002).

The ability of a piece of dead wood to remain stable in a channel and influence channel morphology is based on its ability to resist transport and decay. Resistance to transport has generally been modeled as a function of piece length (Nakamura and Swanson, 1994) or diameter (Braudrick and Grant, 2000) relative to channel dimensions, along with piece orientation (e.g. parallel or perpendicular to flow), the presence of a rootwad (Braudrick and Grant, 2000) and whether the piece is partially buried in the bed or bank (Young, 1994). Piece size relative to channel width also has been correlated with pool formation (Beechie and Sibley, 1997).

Broadleaved riparian tree species along the Pacific coast are generally much smaller than conifers at maturity (Hickman, 1993) and thus produce smaller pieces of wood. The proportion of heartwood increases and the surface-area-to-volume ratio decreases with increasing piece diameter. Thus, simply by having greater diameters, conifer wood will decay more slowly than broadleaved wood (Harmon et al., 1986). Further, the heartwoods of many riparian broadleaved trees contain lower concentrations of decay-resistant chemicals than do conifers (Scheffer and Cowling, 1966), and several studies have reported that wood from riparian broadleaved trees decays faster than conifer wood (Cederholm et al., 1997; Swanson and Lienkamper, 1978).

Thus, individual pieces of dead wood produced by broadleaved trees will tend to be less stable, persistent and geomorphically effective than conifer wood. Additionally, total loading of wood is much lower in streams within watersheds and riparian corridors dominated by broadleaved trees (Opperman, 2005) because individual pieces are smaller and because broadleaved trees are shorter, resulting in a narrower wood recruitment zone (Van Sickle and Gregory, 1990). These factors – smaller individual pieces and, in aggregate, lower loading – explain why riparian broadleaved trees have generally been characterized as providing wood that is inferior to conifer wood for fish-habitat functions.

However, living wood may greatly increase the effectiveness of in-stream wood in California’s watersheds that are dominated by broadleaved trees. Living wood provides individual pieces with greater stability and, consequently, greater influence on channel morphology. The increased stability of living wood is demonstrated by several results, including the smaller mean and minimum sizes for key pieces for channel-spanning wood jams. Further, the proportion of wood jams with a living key piece increased from bank jams, which have the least interaction with high flows, to channel-spanning jams, which have the greatest interaction with high flows. This suggests that the presence of a stabilizing living key piece becomes increasingly important as wood jams are exposed to higher energy flows.

The increased stability of living wood contributes to the formation of wood jams. Because spanning wood jams store a large proportion of total wood volume within the study reaches (Opperman, 2002), any process that promotes jam formation will tend to increase total loading by capturing a higher proportion of wood in transport (Montgomery et al., 2003). Further, because living keys likely result in more persistent wood jams they will contribute to larger wood loadings through time and increase a reach’s retention of organic matter. Wood jams, particularly channel jams, are also the primary cause of wood-formed pools in the study streams (Opperman, 2002), and, thus, living wood likely increases the frequency of pools in these streams.

Through these processes, living wood may increase both the geomorphic effectiveness and total loading of wood in stream channels in broadleaved systems beyond that which would be expected from the dimensions of riparian tree
Living trees as in-stream large wood

species and the size of the potential recruitment area. This mechanism should be considered in models predicting large wood characteristics in systems in which riparian corridors produce living in-stream wood. For example, common models for wood stability, loading and potential for pool formation place strong emphasis on piece diameter and length (Beechie et al., 2000; Braudrick and Grant, 2000). Current wood-budget models (see, e.g., Benda et al., 2003) focus on the recruitment of dead material to the stream and utilize as inputs the range of sizes of wood that can be contributed from riparian trees. Equations for transport and decay are then applied to the pool of wood provided to the stream. Because living pieces can function effectively at smaller sizes, and because they can potentially remain in the stream much longer than a decaying dead piece, models that only consider the rate of input, stability, geomorphic effectiveness, and persistence of dead material will underestimate the abundance and influence of wood in streams where living wood plays a major role.

Further, most protocols for measuring and monitoring wood do not consider living material or even specifically stipulate that surveyors not record in-stream living woody material as large wood (Moore et al., 2002; Schuett-Hames et al., 1999). Field protocols as well as methods cited in the literature (e.g. Murphy and Koski, 1989) place all sampled pieces of wood into a decay classification that lacks a category for ‘living’. Because of the potentially important role of living wood, survey protocols should allow for the inclusion of living pieces.

This paper has focused primarily on the geomorphic role of living wood, with some consideration of its ecological importance (e.g. pool formation, cover). The ecological effects of living wood in streams, ranging from the scale of organisms to ecosystems, merit further investigation. The persistence of living wood, and associated wood jams, could be further investigated through dendrochronological techniques that can indicate when the living wood achieved its current position. Dendrochronological techniques have been used to estimate the timing of other geomorphic processes such as mass wasting or gully erosion (Hupp, 1983; Vandekerckhove et al., 2001) and, by coring ‘dependent saplings’, the time period in which a piece of large wood entered its current position (Martin and Benda, 2001).

In summary, living pieces are a dominant feature of the large wood in the streams in this study. By compensating for the factors that reduce the effectiveness of broadleaf large wood relative to conifer large wood – lower stability and faster decay – living wood may greatly increase the overall interaction between wood, channel morphology and fish habitat in broadleaf-dominated streams. The influence of living wood should be explored in other systems and, where living wood plays a major role, it should be included in stream survey methods and incorporated into models predicting large wood abundance and effectiveness.

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