Dynamics of Coarse Woody Debris Placed in Three Oregon Streams

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ABSTRACT. Many streams of the North American west coast are deficient in coarse woody debris (CWD) and have been subjected to aquatic habitat restoration by adding CWD. The ready availability of alder (Alnus rubra Bong.) CWD makes it attractive for such uses, but the dynamics of this relatively small debris are poorly understood. We placed CWD in three third-order streams in western Oregon either as large, key pieces (pulled-over streamside alders or bucked conifer logs) or as smaller logging debris (mostly alder). This treatment immediately increased CWD in the streams by 86% to 155%. We used chronosequences of surveys to evaluate whether the increased loadings of CWD persisted for more than a year, and whether the key pieces trapped smaller debris to create accumulations. Although there was more CWD in all three streams during the 3 yr after treatment than there had been before treatment, rates of movement were high. Aggregation of CWD increased in all three streams for at least 1 yr, and accumulations of CWD associated with key pieces were larger after 3 yr than immediately after treatment. Pulled-over alders were more stable and more effective in forming accumulations than bucked conifers but were subject to rapid decay. For. Sci. 46(1): 13–22.

Additional Key Words: Large woody debris, aquatic habitat restoration, logging debris.

Concern about degraded freshwater habitat for salmonids on the west coast of North America has led managers of fisheries and forests to examine causes and explore strategies for mitigation. One widespread problem is that past management of streams and riparian forests has reduced the interaction of coarse woody debris (CWD) with streams (e.g., Harmon et al. 1986, Maser and Sedell 1994), simplifying and thus degrading aquatic habitat for threatened populations of anadromous salmonids (Nehlsen et al. 1991). While long-term solutions are being sought, many managers are manipulating stream channels to solve some of the most obvious problems (Reeves et al. 1991, Hayes et al. 1996). Efforts to restore aquatic habitat in the Coast Range mountains of Oregon have focused on second- and third-order streams where these fish, especially coho salmon (Oncorhynchus kisutch Walbaum), spawn and rear their young. Because of the lack of CWD in many streams, addition of CWD has been a common component of these restoration projects; however, much work remains to be done to quantify the effects of these treatments on streams.

The effects of CWD on streams and aquatic habitat have been well described: CWD influences the morphology of stream channels both locally (Beschta 1979, Bilby 1984, Smith et al. 1993a) and at the reach scale (Montgomery and Buffington 1997) by dissipating the hydraulic power of the stream (Beschta and Platts 1987) and consequently slowing transport of bedload and storing sediment (Bilby and Ward 1989, Smith et al. 1993b). Streams with different loadings of CWD differ distinctly in longitudinal profile (Montgomery et al. 1996), sinuosity (Beschta and Platts 1987), hydraulic radius (Ralph et al. 1994, Wood-Smith and Buffington 1996), complexity (Robison and Beschta 1990a), and roughness...
Coarse woody debris contributes to aquatic habitat by creating pools (Stack and Beschta 1989, Hicks et al. 1991, Montgomery et al. 1995), serving as cover (Bustard and Narver 1975, Grette 1985, Heifetz et al. 1986), and providing low-velocity refuges in winter (Tschaplinski and Hartman 1983, McMahon and Hartman 1989, Quinn and Peterson 1996). Also, CWD traps gravel used by salmonids for spawning (House and Boehne 1986), traps fine organic debris and retains nutrients in the stream (Harmon et al. 1986), and is itself a source of food for aquatic invertebrates (Anderson et al. 1978, Ward and Aumen 1986).

Accumulations of CWD are more effective than isolated pieces in affecting reach-scale channel morphology (Kaufman 1987). Accumulations, which are generally the result of large, stable pieces (“key” pieces) trapping smaller, mobile ones (Lienkaemper and Swanson 1987), can influence the morphology of entire reaches by trapping enough sediment to alter the slope of channels and reduce the power of streams to transport sediment (Nakamura and Swanson 1993). Montgomery et al. (1996) observed that accumulations of CWD sometimes trap enough sediment for alluvial substrate to exist in reaches that would otherwise have enough stream power to scour bedrock.

Because CWD from red alder (Alnus rubra Bong.) is generally smaller and less resistant to rot than CWD from conifers such as Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco) or western redcedar (Thuja plicata Donn.) (Anderson et al. 1978), it has been thought to be less functional in affecting channel morphology (Grette 1985, Long 1987, Hicks 1989, Bilby and Ward 1991, Ralph et al. 1994). Therefore, aquatic habitat restoration projects that add CWD have most frequently used large, conifer debris, even though some researchers have reported that debris from alder can form pools in small streams (Andrus et al. 1988, Beechie and Sibley 1997) and provide desirable habitat for coho fry (Scriven and Andersen 1984). The effects of CWD from alder on channel morphology have not been well described but deserve greater attention, given that many riparian stands in the northwestern United States are dominated by alder (Hibbs and Giordano 1996) and have too few conifers to consistently supply large, conifer CWD (Andrus et al. 1988, Heimann 1988, Van Sickle and Gregory 1990, Bilby and Ward 1991).

Modification of stream channels to enhance habitat, which can include engineering structures of CWD (Reeves et al. 1991 reviewed some methods), is often expensive (e.g., Cederholm et al. 1997) because even simple placement of CWD in channels without further engineering usually requires heavy equipment. Alternative methods for placing CWD, such as use of cable systems or teams of horses, have not been well examined, and the differences in the effects of CWD placed by various methods are largely unknown.

As part of a project investigating alternative management of riparian zones and streams, we used cable-logging equipment in place near the site for logging up slope to place CWD in streams. The CWD was placed within small riparian clearcuts that had been made to convert stands from alder to conifer. Kellogg et al. (1993) and Pilkerton and Kellogg (1999) described the costs, mechanics, and context of the operation.

This paper describes the fate of the CWD placed in the stream. Our specific hypotheses were that (1) logging slash CWD added to a stream during logging can increase loadings and accumulations of CWD for more than 1 yr of high flows, and (2) large, key pieces of CWD can effectively trap smaller debris and create accumulations large enough and stable enough to potentially affect the morphology of the channel.

Methods

Site Description

Reaches of three third-order streams (from maps 1:24000) in the Oregon Coast Range (Bark Creek, Buttermilk Creek, and Hudson Creek) were selected based on (1) scarcity of CWD; (2) potential for additional CWD to affect the channel, based on morphology (Montgomery and Buffington 1997); (3) dominance of alder in the riparian zones; and (4) cooperation of landowners (Figure 1, Table 1). All three reaches lie within the Tyee formation of incompetent sandstone of marine origin, which is the most common geology of the central Coast Range (Wells and Peck 1961). All three watersheds are in the Tsuga heterophylla zone of Franklin and Dyrness (1973), on industrial forestland that has been extensively logged. All three watersheds receive 100 to 200 cm of precipitation annually, mostly in the form of rain from October to June. Streams of this region are characterized by high base flows during the rainy winters and low base flows during the dry summers. Frontal storms in the winter result in frequent high flows, but summer storms are rare.
Table 1. Characteristics of three stream reaches in the Oregon Coast Range.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Watershed above reach (km²)</th>
<th>Active channel width (m)</th>
<th>Gradient (m/m)</th>
<th>Length of reach (m)</th>
<th>Morphology*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bark</td>
<td>15.5</td>
<td>7</td>
<td>0.0004</td>
<td>450</td>
<td>C6, pool-riffle</td>
</tr>
<tr>
<td>Buttermilk</td>
<td>7.0</td>
<td>6</td>
<td>0.0060</td>
<td>575</td>
<td>C4, pool-riffle</td>
</tr>
<tr>
<td>Hudson</td>
<td>7.6</td>
<td>7</td>
<td>0.011</td>
<td>700</td>
<td>C1/C4, bedrock/forced pool-riffle</td>
</tr>
</tbody>
</table>

* Values are approximate means over the length of each experimental reach.

** Classifications according to Rosgen (1994) and Montgomery and Buffington (1997).

The experimental reach of Bark Creek is low in gradient (Table 1), somewhat incised into alluvial terraces, and characterized by bed and banks of fine sediment. The experimental reach of Buttermilk Creek is moderate in gradient and has a predominantly gravel bed with some sand and bedrock; its streamflow is laterally constrained in places by hillslopes, but there are small floodplains and terraces in others. The experimental reach of Hudson Creek is higher in gradient than the other two streams. Although this reach is dominated by bedrock, this study was conducted on two subareas bounded by debris-flow outwash fans (Benda 1990), where large accumulations of CWD have trapped sediments to create substrates of sand and gravel for approximately 100 m upstream [this phenomenon was described by Swanson (1991) and Montgomery et al. (1996)]. Streamflow in Hudson Creek is laterally constrained by a combination of hillslopes, low terraces, and road fills.

During the study, the streams were not all subject to the same high flows. The approximate return intervals of peak flows in Bark and Buttermilk creeks, based on the nearest USGS gaging stations (14190500 Luckiamute R., 14305500 Siletz R., and 14306500 Alsea R.) and calculated from Wellman et al. (1993), were 1–2 yr in the first and second years of the study and 25 yr in the third year; in Hudson Creek (14311500 Lookingglass Cr. and 14325000 S. Fk. Coquille R.) return intervals of peak flows were 5 yr in the first year, 2 yr in the second year, and 50 yr in the third year. The biggest flows during the study period were during storms that caused extensive changes in streams throughout the Oregon Coast Range (Bush et al. 1997; Laenen and Ruff 1997).

Two small clearcuts were made along each experimental reach in conjunction with upslope logging (Figure 2). These paired clearcuts were 90 m long along the stream, separated by uncut buffers of 140 m at Bark Creek, 190 m at Buttermilk Creek, and 290 m at Hudson Creek. The buffers varied in width, both within and among streams, from 8 m to more than 25 m on each side of the stream.

Establishing a Baseline

Before treatment, we made a topographic survey of every stream with a total station theodolite (Keim et al. 1999). In each stream, the survey included the channel in both 90 m riparian clearcuts, the intervening buffer, and 30–50 m into the buffers above and below the clearcuts (Figure 2). The total surveyed lengths were 450 m in Bark Creek, 575 m in Buttermilk Creek, and 700 m in Hudson Creek.

The surveys recorded every piece of CWD that was at least 2 m long and 10 cm diameter that was between the banks and below the top of the bank, corresponding to “influence zones” 1 and 2 described by Robison and Beschta (1990b). We measured the lengths of pieces in their entirety to a minimum 10-cm-diameter end, even if they extended out of zones 1 and 2, and measured or estimated diameter at the midpoint. We classified CWD from hardwoods, which included red alder, bigleaf maple (Acer macrophyllum Pursh), and, at Hudson Creek only, Oregon myrtle (Umbellularia californica [Hook. & Arn.] Nutt.), into diameter classes of 5 cm (smallest class 10 cm). Because of its larger range of sizes, we classified CWD from conifers, which included Douglas-fir, western redcedar, and western hemlock (Tsuga heterophylla [Raf.] Sarg.), into diameter classes of 12.75 cm (smallest class 25 cm). In addition, we assigned each piece to a category of stability, either “fixed” (embedded in the bank or substrate) or “floating” (unembedded and free to move during high flow), and noted whether it had attached roots. We assumed that pieces with attached roots would be more stable than pieces without attached roots, but less stable than pieces embedded in the banks or streambed. To quantify loadings of CWD, we calculated the total number of pieces, total volume of all pieces [each treated as a cylinder, as in Bilby and Ward (1989)], and total length (sum of all lengths) of all CWD for each stream.

In all three streams, there were old, large pieces of CWD that were strongly embedded in the banks or bed of the channel, and even minor movements of sediment were capable of partially exhuming or burying these pieces. Compared to the relatively small, predominantly alder CWD that was of interest in this study, these embedded pieces of CWD had a disproportionate influence on reach-level measurements of volume of CWD. Because of this, we did not use volume as the most important measure of CWD loadings.

Figure 2. Schematic of active riparian area management in streams of the Oregon Coast Range (not to scale). White areas represent logged forest, and shaded areas represent standing forest. The heavy line represents the stream. Coarse woody debris was placed in the stream within the pair of 90 m riparian clearcuts, and the entire length of stream within the diagram was monitored.
Instead, we chose the number of pieces of CWD or the total length of all pieces of CWD as metrics that would be most sensitive to changes in the smaller component of CWD that we affected by the treatment. In addition, these metrics are less prone to errors in measurement than is volume, because they did not include an estimated diameter.

**Treatment**

After completion of the baseline surveys, CWD was placed in Bark Creek in April 1993, in Buttermilk Creek during August 1993, and in Hudson Creek from August to October 1994. Placement was done in conjunction with upslope logging; loggers placed bucked, delimbed conifer logs into the stream and pulled over standing alders into the stream within each 90 m clearcut to act as key pieces (Table 2). The conifer logs were selected from those cut during logging to be large enough that we expected them to be stable when placed in the channel. The logs averaged 2.54 m³, and ranged in length from 0.9 to 1.7 times the width of the active channel. The pulled-over alders were growing on banks, so that pulling them into the stream left them with roots in the bank. We expected the intact roots to lend stability to the pieces (Swanson 1991), making them better able to trap debris (Lienkaemper and Swanson 1987) and create pools (Kaufmann 1987). Also, CWD with intact roots mimics natural inputs (Kaufman et al. 1997) and increases the hydraulic complexity of the channel (Beschta and Platts 1987). The pulled-over alders averaged only 1.25 m³, but were longer than the conifer logs (1.1 to 4.2 times the width of the active channel). We marked each key piece with a single aluminum tag with a unique number so we could track its fate.

All key pieces were placed perpendicular to flow, which is the most common orientation for naturally stable pieces of CWD (Bilby and Ward 1989). Although this orientation exposes CWD to greater force from the stream and increases its likelihood of being displaced, we assumed that it would also be the orientation most likely to cause accumulation of debris.

The methods of placing debris differed at each stream, as did the number of pieces (Table 2). At Bark and Hudson Creeks, loggers used cable-logging equipment to pull alders over into the stream and to yard conifer logs from the hillslope into the channel. At Buttermilk Creek, a hydraulic excavator placed the key pieces in the stream after upslope logging was complete. For a description of the process of placing the key pieces, see Kellogg et al. (1993).

In addition to the key pieces, logging crews placed debris in all three streams in an effort to seed accumulations. At Bark and Hudson Creeks, this debris was slash that was incidental to logging, strewn haphazardly along the length of the clearcuts. At Buttermilk Creek, a tree faller and excavator placed debris by felling trees directly into the stream or by pulling felled trees into the channel. Much less of this simulated slash was placed in Buttermilk Creek than the amount of true slash placed in the other two streams. All logging slash added to the Bark and Hudson Creeks was alder, because upslope logging was primarily of alders. In Buttermilk Creek, however, 22% of the simulated slash was conifer. All slash was initially in the “floating” class of stability.

**Monitoring and Analyses**

After logging, we made another topographic survey of each stream, recording all added and pre-existing CWD. The

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**Table 2. Fate and effectiveness at trapping other coarse woody debris for key pieces of CWD placed in three streams in the Oregon Coast Range.**

<table>
<thead>
<tr>
<th>Stream</th>
<th>Species</th>
<th>Length (m)</th>
<th>Diam (m)</th>
<th>Cumulative downstream movement (m)</th>
<th>Number of associated pieces of CWD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Immediate post-treatment</td>
<td>Year 1</td>
</tr>
<tr>
<td>Bark</td>
<td>Conifer</td>
<td>11.9</td>
<td>0.53</td>
<td>48</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.2</td>
<td>0.53</td>
<td>24</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Alder</td>
<td>22.9</td>
<td>0.30</td>
<td>0^†</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.8</td>
<td>0.30</td>
<td>17</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.6</td>
<td>0.30</td>
<td>0^†</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.7</td>
<td>0.15</td>
<td>92</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Buttermilk</td>
<td>7.9</td>
<td>0.61</td>
<td>0^†</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.9</td>
<td>0.43</td>
<td>0^†</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Alder</td>
<td>5.5</td>
<td>0.23</td>
<td>—</td>
<td>4</td>
</tr>
<tr>
<td>Hudson</td>
<td>Conifer</td>
<td>25.0</td>
<td>0.30</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.0</td>
<td>0.81</td>
<td>—</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Alder</td>
<td>10.0</td>
<td>0.58</td>
<td>67</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.2</td>
<td>0.81</td>
<td>79</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.8</td>
<td>0.32</td>
<td>—</td>
<td>8</td>
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<tr>
<td></td>
<td></td>
<td>24.0</td>
<td>0.40</td>
<td>0^†</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25.0</td>
<td>0.28</td>
<td>0</td>
<td>7</td>
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<tr>
<td></td>
<td></td>
<td>17.6</td>
<td>0.20</td>
<td>0^†</td>
<td>1</td>
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<td></td>
<td></td>
<td>17.4</td>
<td>0.30</td>
<td>0^†</td>
<td>9</td>
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<tr>
<td></td>
<td></td>
<td>19.2</td>
<td>0.30</td>
<td>0</td>
<td>2</td>
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<tr>
<td></td>
<td></td>
<td>23.8</td>
<td>0.28</td>
<td>0</td>
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<td></td>
<td></td>
<td>21.3</td>
<td>0.23</td>
<td>0</td>
<td>5</td>
</tr>
</tbody>
</table>

* Letters indicate movement of key pieces during the previous winter: R = piece rotated in place; M = piece moved downstream; B = piece broke.
† No downstream movement, but piece broke or rotated in place.
†† = piece moved out of the surveyed reach.

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time between logging and the resurveys varied from less than 1 day to several weeks; in no case had any of the CWD added by logging been redistributed by high flows before the resurveys. For 3 yr following the placement of debris, we made annual topographic surveys of all three streams during the summer low-flow period, recording all CWD in each survey.

To quantify the effects of treatments on accumulations of CWD, we used two measures of how CWD was distributed in the stream. First, we used geostatistical analysis to assess spatial distribution of CWD (see Wing et al. 1999 for a detailed description) by calculating the empirical distribution function (EDF) of point-to-point nearest-neighbor distances (Mathsoft 1996). An EDF is represented by a cumulative plot of \( G \), the proportional frequency of distances between nearest pairs of pieces of CWD over a range of lags (distances). The more rapidly \( G \) approaches 1.0, the more spatially aggregated are the elements described by that EDF. Comparing EDFs among years for each stream identifies changes in the spatial distribution of CWD in the channel. The use of \( G \) allowed integrated description of all potential processes that aggregate CWD.

Our second measure of how CWD was distributed within the stream was a count of pieces of CWD within 2 m of each key piece, to determine the size of any accumulation associated with that key piece. Field observation revealed that pieces of CWD more than 2 m apart never directly physically interacted with each other, so we assumed that no pieces actually detained solely by a key piece would lie outside this zone. Although this measure indicates whether key pieces and accumulations were associated with each other, it does not necessarily reflect the effectiveness of key pieces in detaining CWD and creating accumulations, because other mechanisms may also detain CWD in the same space. For example, a key piece may move and become part of an accumulation caused by another obstruction. In such cases, pieces of debris within 2 m in that accumulation would be associated with the key piece, even though it played no role in detaining them. Also, because two key pieces were sometimes close enough that their 2 m zones overlapped, some pieces of CWD were associated with more than one key piece and were counted twice.

Our use of the word “treatment” in this article does not imply a traditional study design that includes both treatment and control. We originally intended the unlogged buffers between treatments to serve as controls, defining short sections of stream as experimental units. However, we were unable to use the buffers as controls because CWD moved between sections, making dynamics of CWD within each section dependent on other sections. Lacking these controls, we considered entire reaches as experimental units and relied on the replication among streams as experiment-wise control. Difficulty with experimental control is common in research in natural streams; because streams vary longitudinally in subtle and unforeseeably important ways, reaches designated as controls are rarely true replicates, and inferences based on such control reaches are likely to be specious. We therefore limited inferences and conclusions to phenomena that were either repeated at all three study streams or obviously related to the differences among them. The lack of control precluded any inferences regarding the processes that resulted in changes in the streams, and we have been conservative in making conclusions as a result.

**Results**

**Total Loadings of CWD**

The treatment immediately increased the total number of pieces of CWD in the three streams by 86% to 155% (Figure 3). Because no true slash was added to Buttermilk Creek, less CWD was added there than to Bark or Hudson creeks. Although the number of pieces of CWD added to all streams was large (124, 45, and 84 pieces in Bark, Buttermilk, and Hudson Creeks, respectively), the small size of the debris meant that volume increased by just 25% and 24% in Bark and Hudson Creeks, respectively; in Buttermilk Creek, the low initial loading of CWD and the larger size of the added debris resulted in a 115% increase in volume. The mean length of alder added to Bark and Hudson creeks was similar to what already existed in the stream, but the CWD added to Buttermilk Creek substantially increased the mean length of alder debris (Figure 4).

![Figure 3. Loading of coarse woody debris in three streams in the Oregon Coast Range. ‘Pre’ and ‘Post’ refer to measurements made before and after treatment of additional debris. Differences in loading before and after treatment are due to logging and intentional placement of debris. Differences among other years are due to natural movement during winter high flows.](image-url)
The CWD added to each stream responded differently to high flows during the study. The differences appeared to be due to the interaction of stream gradient, the magnitude of high flows, differences in the added CWD (Table 2, Figure 4), and the size of CWD available for recruitment. Although we will suggest some explanations for the results, we could not quantify the complex processes acting on the CWD.

In Bark Creek, the volume of CWD after 3 yr was similar to the volume before logging, but the pieces were shorter (Figures 3, 4). Apparently either the logging slash was breaking during this time, or longer (apparently unstable) slash was flushed from the reach and replaced by shorter debris recruited from upstream. Decreases in geometric mean length were most conspicuous in the first year of the study (Figure 4). Given that breakup of CWD that is only 1 yr old is unlikely, some combination of recruitment into and loss from the experimental reach is probably responsible for this change. The 25-yr-return-interval flow before Year 3 had little effect on the volume of CWD in Bark Creek but increased both the number of pieces and the total length of CWD. Two large accumulations formed after this storm, and apparently they contributed to net recruitment of small CWD.

The volume of CWD in Buttermilk Creek changed little in the 3 yr following treatment (Figure 3). The total length of CWD fluctuated by as much as 36%, but was consistently 3 to 5 times higher than before; treatment. The steady decline in the geometric mean length of alder after treatment (Figure 4) is likely accounted for by recruitment of CWD; given that the added pieces were much larger than those already in the stream (Figure 4), recruited pieces were probably of a size similar to those in place before the study or smaller. The 25-yr-return-interval flow before Year 3 resulted in increases of the total length, volume, and number of pieces of CWD, but a decrease in the geometric mean length of the alder; small pieces were apparently recruited during this flow.

In Hudson Creek, a 5-yr-return-interval flow during the first year after logging slightly reduced the volume and total length of CWD from post-treatment levels (Figure 3). This change was most likely due to flushing of small pieces of logging slash, as would also be suggested by the increase in mean length of alder (Figure 4). There was an increase in loading of CWD in Year 2, primarily due to the formation of a large accumulation of small pieces that occurred in conjunction with a smaller, 2-yr-return-interval flow. This large accumulation was reduced in size in Year 3, after a 50-yr-return-interval flow. The two highest peak flows during the study period both resulted in increases of the geometric mean length of alder CWD (Figure 4), apparently flushing small pieces more efficiently than the smaller peak flow that occurred before Year 2. Larger pieces, specifically windthrown riparian alders, were also recruited throughout the study period.

In all three streams, the total length of CWD increased at least once during the study (Figure 3), indicating net recruitment of CWD into the experimental reaches. The bulk of the recruitment of CWD was from upstream, as evidenced by the fact that the only CWD that was recruited from within the riparian zones (the windthrown alders) was not enough to account for the increases. This corroborates Hogan's (1986) observation that most CWD in streams of logged watersheds is delivered from upstream rather than recruited from within the adjacent riparian area.

Species and Stability of CWD

Most conifer debris in Bark and Buttermilk creeks predates this study, was larger than any debris we added, and was fixed in place in the bed and banks of the streams. Changes in loading of CWD in Bark and Buttermilk creeks were due almost exclusively to fluctuations in alder debris (Figure 5); few large conifer pieces moved in either stream. There were also many large stable pieces of conifer CWD in Hudson Creek, but there was a higher proportion of conifer in the smaller, more mobile fraction than in the other two streams. The 5-yr peak flow before Year 1 in Hudson Creek, which decreased total volume of CWD while increasing geometric mean length of alder, recruited many pieces of conifer and apparently flushed much of the alder logging slash (Figure 5). Because no conifers were recruited by means of windthrown riparian trees, and because there was a notable increase in conifer CWD before Year 1, it is apparent that conifer debris was recruited from upstream. Both net flushing and net recruitment of conifer CWD occurred in the next 2 yr, but the amount of conifer CWD was consistently higher throughout the study period than it was before or immediately after logging. Apparently much more debris from conifers moves through Hudson Creek than through either Bark or Buttermilk creeks.

Figure 5. Species of coarse woody debris in three streams in the Oregon Coast Range. "Pre" and "Post" refer to measurements before and after placement of additional debris.
Annual fluctuations in loadings of CWD in all three streams were evenly distributed among the classes of stability (differences in the coefficients of variation for annual loadings among stability classes were < 0.06). There are at least two possible reasons for the number of fixed pieces of CWD fluctuating at the same rate as the number of floating pieces. First, some fixed pieces of CWD were so strongly embedded in banks and the substrate that minor fluctuations in morphology of the channel buried and exposed them multiple times during the study; therefore they were not included in the inventory every year. Second, floating pieces of CWD at the edge of the active channel might have been less subject to movement by the stream than pieces of CWD weakly embedded in the active channel.

The number of pieces of CWD with intact roots increased from 12 in Year 2 to 17 in Year 3 in Bark Creek, and from 18 to 30 in Hudson Creek in the corresponding period, due to the addition of newly windthrown alders. We observed that alders at the margins of the riparian clearcuts were disproportionately susceptible to windthrow compared to alders in the interior of the riparian stand, as was also observed by Steinblums et al. (1984). These trees were commonly recruited into the stream as CWD, as was described by Lisle and Napolitano (1998) and Nakamoto (1998). Particularly at Bark and Hudson creeks, alders windthrown after our treatment became traps for debris and functioned as we had expected the pulled-over alder key pieces to function. Windthrow of alders at the margins of the riparian clearcuts continued for 2 yr after the study ended.

Accumulations and Key Pieces of CWD

The spatial distribution of CWD in all three streams before treatment was more aggregated than a completely random pattern (P ≤ 0.05), as evidenced by high proportions of low-distance neighbors (Figure 6). Adding CWD immediately increased aggregation in Bark and Buttermilk creeks only slightly, but notably increased aggregation in Hudson Creek at the scale (lag) of 1–5 m (Figure 7, post-treatment curves).

Winter high flows after treatment increased aggregation of CWD in all three streams at least once (Figure 7). In Bark Creek, aggregation at the scale of 0.5–2 m increased continually during the study, but at other scales the spatial distribution of CWD remained similar. Annual changes in the spatial distribution of CWD in Buttermilk Creek were small or lasted just 1 yr. Annual movement of CWD in Hudson Creek increased aggregation at the scale of 0 to 2.5 m, which is a smaller scale than that at which aggregation was caused by treatment. Overall aggregation in all streams was still greater 3 yr after treatment than before, as evidenced by \( \hat{G}_{\text{post}} - \hat{G}_{\text{pre}} > 0 \) across all lags.

Accumulations of CWD associated with key pieces were larger after 3 yr than they were immediately after treatment (Figure 8). The accumulations grew for the first 2 yr after treatment but did not grow during the third year. By the third year, only 5 of the 21 key pieces were still in their original

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**Figure 7.** Effects of addition of coarse woody debris on its spatial distribution in three streams in the Oregon Coast Range over three years. For each stream, \( \hat{G}_{\text{post}} - \hat{G}_{\text{pre}} \) is the difference between the empirical distribution function for a given year and that before treatment.

**Figure 8.** Mean size of accumulations and mean annual changes in size of accumulations of coarse woody debris associated with key pieces placed in streams in the Oregon Coast Range. Annual reductions in number of key pieces (n) are due to losses of key pieces from experimental reaches, but not other movements of key pieces within the reaches. Error bars represent 90% confidence intervals on mean annual change. Means are pooled for three streams.
positions (Table 2); most key pieces had become part of an accumulation rather than creating one themselves. By then, few accumulations were anchored by the key pieces placed for this study.

All of the conifer key pieces placed in Bark and Hudson creeks moved at least 20 m downstream, and no conifer key pieces remained stable for the entire study period (Table 2). Half of the conifer key pieces moved downstream during the first 2 yr after treatment, even without any peak flows of return interval >5 yr. The conifer key pieces appear to have been too short to be stable, despite what we expected based on previous studies. In streams of similar size in the region, Lienkaemper and Swanson (1987) found CWD of 1.0 to 1.5 times as long as the width of the active channel was stable in flows of return interval less than 30 yr; Bisson et al. (1987) stated CWD =1.0 times as long as the width of the active channel was stable; and Heimann (1988) found that pieces 1.3 to 2.0 times as long as the width of the active channel commonly were stable enough to anchor accumulations of CWD. At 0.9 to 1.7 times the width of the active channel, most of the conifer key pieces were long enough to be within these ranges. Their instability might have been due to the very large flows during the study period. Also, CWD placed in streams is probably initially less stable than CWD that has already experienced high flows, which is what the prior studies examined. In addition, the fact that key pieces in this study were intentionally placed perpendicular to flow to create accumulations probably decreased their stability.

Pulled-over alders were more stable than the bucked conifer key pieces (Table 2). All five key pieces that remained in their original position for the entire study were pulled-over alders. Of these five, one spanned Buttermilk Creek ~1 m above the thalweg and never trapped any CWD. The other four were in Hudson Creek. Two of these did not trap other CWD because they were oriented almost parallel to the stream and were rarely in contact with the streamflow. The final two were pulled over across each other into an "X" spanning the channel 1–2 m above the thalweg. Only these two key pieces apparently trapped many of the pieces of CWD in their associated (and overlapping) accumulations; in general, most alder key pieces were continually stable only if they were ineffective in trapping other pieces.

Four of the 12 pulled-over alders were broken by the third year after treatment, though no conifer key pieces broke during the study (Table 2). Our observations were similar to those of Anderson et al. (1978), who reported signs of decay of fresh alder CWD after just 15 months, while adjacent debris of conifers remained nearly unchanged. In our study, most bark on the pulled-over alders had broken away, and there was notable decomposition of the phloem. In contrast, the conifer key pieces showed little decomposition, and all Douglas-fir logs retained their bark. The long-term effectiveness of alder for anchoring accumulations may be poor because of this rapid decay.

Two large accumulations of CWD in Bark Creek developed after the 25-yr-return-period flow before the survey in Year 3. During visits to Bark Creek in 1997 and 1998 (4 and 5 yr after logging), we observed that both had broken up, though a new one had formed downstream, on alders windthrown at the boundary of the buffer strip below the lower clearcut. Recently windthrown riparian alders in Hudson Creek trapped debris and caused a small accumulation of CWD during the third year after treatment.

Discussion

We observed high rates of movement for small CWD in this study, following the observations of Bilby (1984), Bisson et al. (1987), and Andrus et al. (1988). In view of the changes of 4–40% in the total loadings of CWD in all three streams every year (Figure 3), it is clear that flushing and recruitment of CWD is a constant, continuing process, although our data are not sufficient to evaluate whether the high rates of movement of CWD were due solely to its small size. The particularly large flows during the study period also moved many large pieces.

The association of accumulations of CWD with key pieces does not mean that the accumulation was caused by these key pieces. The causes of accumulations of CWD can be difficult to ascertain. Many accumulations of CWD formed in combination with some factor other than one of our added key pieces, such as a meander bend; large, stable, pretreatment CWD; large rocks; a change in gradient; newly windthrown trees; or multiple key pieces. Thus, the key pieces might simply have been taking part in a larger trend toward aggregation (Figure 6) without causing it. Braudrick et al. (1997) showed that high loadings of CWD in flumes can result in congested downstream transport that causes accumulations to form more frequently than when loadings are low. It therefore seems reasonable to expect that simply increasing the amount of CWD in a stream above the threshold of congested transport would allow smaller pieces of CWD to act together to reduce movement of CWD. As examples of this in natural streams, Ralph et al. (1994) observed accumulations of small CWD forming in meander bends and along stream margins without key pieces, and Bisson et al. (1987) described small debris and logging slash commonly forming small, mobile accumulations. Our treatment may have locally increased loadings of CWD above the level of congested transport, creating small, mobile accumulations. Even if these are not stable for long periods, as our study indicates, they may provide some value for aquatic habitat and affect the channel.

The continuing trend of accumulation even in the absence of spatial stability may be evidence that the treatments were at least somewhat successful. Kauffman et al. (1997) recognized that accumulations formed where CWD was placed in the stream are not necessarily of greater value than those later reworked by the stream. Thus, the failure of our key pieces to remain stable and form accumulations in place does not necessarily indicate failure of the treatment to achieve management goals.

Even when no accumulations form, the effect on channel morphology per piece of CWD can be greater when loadings are high than when they are low. Andrus et al. (1988) and Montgomery et al. (1995) observed that at low loadings, individual pieces of CWD were more likely to have a negligible influence in forming pools than when loadings were
higher. In our study, loading of CWD may have exceeded the threshold at which its effects are negligible.

While this treatment appeared to have been effective in increasing loadings of CWD in streams, its potential effects in the larger context of hydrology and stream ecology must be considered before it is implemented as a management tool. The disturbance to the riparian zone, though allowing the establishment of conifers for future sources of high-quality conifer CWD, may result in short-term effects on the stream’s suitability for salmonids. For example, removing the riparian canopy increases insolation, which increases stream temperature, biological productivity, and biochemical oxygen demand (Brown 1988). Despite extensive study of the complex effects of clearcuts on stream ecology (e.g., Meehan 1991), most effects cannot be easily predicted.

Conclusions

This study has shown that it is possible to affect loadings, dynamics, and accumulations of CWD using relatively small pieces. As we hypothesized, the relatively small CWD added to the streams increased loadings and accumulations of CWD for more than 1 yr of high flows after treatment. Even though there were large peak flows of up to 50-yr-return-period magnitude during the study period, there was consistently more CWD in all three streams during the 3 yr after treatment than before treatment, and this CWD was generally more spatially aggregated than was the CWD before treatment. Using logging slash and on-site CWD appears to be a viable way to increase loadings and accumulations that can potentially affect the channel and aquatic habitat.

Our hypothesis that key pieces would trap smaller CWD into accumulations was partially confirmed. Accumulations that did form on key pieces were not stable, but in years with smaller peak flows, the effectiveness of the key pieces we placed might have been different. Although tree-length alder debris anchored to the bank with attached roots was clearly effective in trapping CWD and forming accumulations, its effectiveness appears short-lived. By the third year after treatment, the pulled-over alders were losing structural integrity due to advancing decay and breakup. As long as the alders remained intact, however, their length and anchoring by roots appeared to make them more stable and effective than the conifer key pieces. The conifer logs placed as key pieces were neither stable nor effective in creating accumulations, apparently because they were too short in the face of high flows.

The unplanned recruitment of windthrown riparian alder trees from the edge of the riparian clearcuts often trapped other CWD in accumulations. Because windthrow most often occurs at edges of stands, creating edges near the stream (as our treatment did) probably increases the likelihood that windthrown riparian trees will be recruited to the stream. The recruited alders appeared to function similarly to the pulled-over alders and were an unexpected effect of the riparian clearcuts.

Although the accumulations resulting from treatment were not persistent and were mobile in high flows, they often reformed downstream from their original location. These movements took place during very large flows; the response to a series of smaller peak flows is unknown, but it is likely that movement would be less.

Literature Cited


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