North American Journal of Fisheries Management 19:687–695, 1999

Effects of Immersion in Water on Deterioration of Wood from Five Species of Trees Used for Habitat Enhancement Projects

ROBERT E. BILBY,*[1] JOHN T. HEFFNER, BRIAN R. FRANSEN, AND JAMES W. WARD

Weyerhaeuser Company, Western Forestry Research, WTC 1A5, Tacoma, Washington 98477-0001, USA

PETER A. BISSON

U.S. Forest Service, Pacific Northwest Research Station, Olympia Forestry Sciences Laboratory, 3625 93rd Avenue South West, Olympia, Washington 98512-9193, USA

Abstract.—Logs of standard dimensions from five species of trees were submerged in a stream to evaluate changes in strength and decomposition over a period of 5 years. Changes in structural properties occurred only for wood near the outer surface of the logs. Nearly all bark was removed from the logs within 12 months. Diameter loss for the five species ranged from 10.6 mm (western hemlock *Tsuga heterophylla*) to 21.8 mm (bigleaf maple *Acer macrophyllum*) after 5 years. Decreases in the density of surface wood for the five species ranged from 23% (red alder *Alnus rubra*) to 31% (western hemlock). Modulus of rupture, modulus of elasticity, and wood density did not change for wood more than 12 mm from the log surface for any of the species. Bigleaf maple exhibited the highest resistance to rupture, and western redcedar *Thuja plicata* exhibited the lowest. Western redcedar was also the most easily flexed. Microbial activity on the surface of the logs was highest at the start of the experiment and decreased rapidly with time of immersion. The two hardwood species (bigleaf maple and red alder) generally had higher levels of microbial activity than the conifer species (Douglas fir *Pseudotsuga menzesii*, western hemlock, western redcedar) from 12 months through 60 months of immersion. Differences in the rate of decomposition between conifer and hardwood logs were much less than in terrestrial environments. Our results suggest that hardwood logs can be used in stream enhancement projects where the wood will be submerged.

Enhancement of salmon and trout habitat in streams of the Pacific Northwest frequently involves placing structures made of logs in the channel. Such habitat improvement has been applied for over 60 years (Tarzwell 1937). These structures have multiple purposes, including the formation of pools, retention of gravel used by fish for spawning, and provision of cover (House and Boehne 1986; Reeves et al. 1991b). The efficacy of this approach recently has been questioned due to the high rate of structure failure (Frissell and Nawa 1992) and the variable response of fish populations (House and Boehne 1986; Reeves et al. 1991a; Nickelson et al. 1992; Beschta 1997; Cederholm et al. 1997). Nonetheless, installation of wood structures in streams continues to be a popular enhancement technique. Thousands of projects have been completed in the last two decades (Duff et al. 1988; Reeves et al. 1991b) and this method of manipulating instream habitat is a prominent component of some regulatory approaches to stream habitat protection (Oregon Board of Forestry 1994). Thus, deliberate addition of wood to streams is likely to continue.

Conifer logs are preferred over hardwood logs for building wood structures in streams due to their larger size, greater stability (Bilby 1984), and slower rate of decomposition (Harmon et al. 1986). However, removal of streamside vegetation by various land-use practices over the last century has created conditions favoring the establishment of early-successional, hardwood trees in streamside areas and a reduction in conifers (Carlson 1991; Bisson et al. 1997). As a result, large conifer trees are often not available in the immediate vicinity of a planned habitat enhancement project.

The expense of many fish habitat enhancement projects is increased substantially by the need to purchase and transport conifer logs to the stream. For example, logs and rocks used to enhance a 500-m long section of stream in western Washington cost $17,000 (Cederholm et al. 1997). Most of this expense was for the purchase of large logs of Douglas fir *Pseudotsuga menzesii.* Cost of many

* Corresponding author: robert.bilby@noaa.gov

[1] Present address: National Marine Fisheries Service, Northwest Fisheries Science Center, 2725 Montlake Boulevard East, Seattle, Washington 98112-2097, USA.

Received February 9, 1998; accepted March 18, 1999

projects could be substantially reduced if locally available hardwood logs could be substituted for conifer logs. Use of trees available at the site also would reduce the use of heavy equipment to transport wood to the stream, reducing disturbance of the riparian area. Often, sites are eliminated from consideration for enhancement projects because of to the impracticability of transporting logs to the site. Enhancement projects could be conducted at many locations if hardwood trees growing near the site could be used.

Logs added to streams are typically subjected to considerable force from the flow in the channel. Therefore, resistance to breaking and flexing is an important consideration in selecting materials for enhancement projects. Because these projects are expensive, longevity of the structures added to the channel is also of key importance. Much is known about species-specific decomposition rates of wood in terrestrial environments (Harmon et al. 1986). However, in many enhancement projects pieces of wood are under water for most of the year. Very little information is available on the species-specific, temporal changes in physical properties of submerged wood. The objective of this study was to evaluate the differences in structural properties of wood from five species of trees common in the Pacific Northwest and determine how these properties change over time while immersed in stream water. We also examined temporal changes in decomposition rate of the five species.

Methods

Logs were cut from live trees of three conifer and two deciduous species. The conifer species were Douglas fir, western redcedar *Thuja plicata*, and western hemlock *Tsuga heterophylla*. The deciduous trees were red alder *Alnus rubra* and bigleaf maple *Acer macrophyllum*. These species are among the most common trees in coastal areas of the Pacific Northwest. All logs were 18–28 cm in mean diameter and 1.5 m in length. A numbered steel tag was nailed to the end of each log to enable future identification. Holes were drilled through one end of each log, and one log of each species was fastened together using 1-cm-diameter, galvanized steel cable. The five-log rafts were placed in pools in a third-order stream, a tributary to the Deschutes River in western Washington, and tethered to a tree on the bank. A total of 40 rafts (200 logs) were placed in the stream in summer 1988. A severe flood in January 1990 removed approximately 50% of the logs remaining in the stream at that time. An additional 20 rafts (100 logs) were placed in the stream in June 1990 to provide enough logs to complete the experiment.

We attempted to keep the logs in the water at all times. The rafts floated when initially placed in the stream, but all sank within 6 months. The rafts were inspected at least monthly and more frequently during the winter, when high flow occasionally washed rafts onto the bank. Rafts deposited on the bank were returned to the water.

Logs were analyzed when first installed in the stream (green), and after 1, 6, 12, 24, 36, 48, and 60 months of exposure. The project schedule was altered as a result of the January 1990 flood. Logs for the final samples were removed from the stream in June 1994.

Five, randomly selected rafts were removed from the stream on each sample date, providing five logs of each species for analysis. The diameter of each log was measured at the midpoint and 10 cm from each end at the time they were placed in the stream. The diameters were remeasured at the same three locations on the log when the pieces were removed from the stream for analysis. The proportion of the log's circumference covered with bark at each point where the diameters were taken also was measured.

A species-specific decay rate constant was determined from the initial and final diameters of the logs (Harmon et al. 1986). This value represents the relative rate of bark and bole mineralization and fragmentation over the 60-month experiment. The decay rate constant, k, is derived from the equation

$$D_t = D_0 \cdot e^{-kt}, \quad (1)$$

where D_t is log volume after 5 years (t) of exposure and D_0 is volume of the green log.

After measuring the diameter, the logs were cut into two pieces with a chain saw: one piece 1.2 m long the other 0.3 m long. Ten cores were cut from the surface of the smaller section of the log using a hollow punch with a 10-mm inside diameter. The cylindrical cores extended approximately 12 mm into the log. These cores were used to determine microbial activity and density of the surface wood. Core samples were inadvertently omitted from the analysis of the 48-month samples, so density of surface wood and microbial activity values are not available for this sample. The longer piece of the log was used to measure modulus of rupture, modulus of elasticity and density of the interior wood.

The shorter pieces of the logs were refrigerated until the cores could be extracted. This process was completed within 4 d after removal of the log from the stream. The cores from each log were placed in a biological oxygen demand (BOD) bottle filled with stream water that had been filtered through a 1-μm-pore glass-fiber filter. A total of 30 bottles were used for each trial, one for each log (five logs of each species × five species) and five containing filtered stream water alone as a control. Initial oxygen concentration was measured in each bottle using a Yellow Springs Instruments oxygen meter. The cores were incubated for 12 h in the dark at a constant temperature of 12°C, the approximate summer water temperature in the stream. Oxygen concentration was remeasured after incubation. Oxygen concentration changes in bottles containing cores were corrected for oxygen consumption by microbial activity in the water by subtracting average oxygen changes in the control bottles. Decreases in oxygen concentration in the control bottles were never greater than 0.1 mg/L. Daily oxygen consumption was expressed as mg/cm^2 log surface because microbial activity on saturated wood is restricted to the external surface of the piece (Savory 1954). After incubation, cores were removed from the bottles and dried at 60°C, and the surface area, volume, weight, and density of each core were then determined.

Modulus of rupture and modulus of elasticity were measured on five lengths of wood cut with a band saw from the longer section of each log. The pieces measured 3 cm × 3 cm × 1.2 m. One piece was cut from the center of the log and the other four pieces from each of the adjacent quadrants of the log. None of these pieces included wood from the outside surface of the log. Each piece was evaluated using standard testing protocols for the structural properties of lumber (American Society of Testing and Materials 1978). A hydraulic press was used to apply a stress to the midpoint of the long axis of each piece and the resultant degree of bending of the piece was recorded. Force applied was gradually increased until the piece broke. Modulus of elasticity is a constant describing the relation between force applied and degree of bending. Modulus of rupture reflects the force required to bend the piece to the point of failure. Due to the method used to calculate these parameters, modulus of elasticity is usually 2 or 3 orders of magnitude greater than modulus of rupture (American Society of Testing and Materials 1978). Wood density affects both modulus of elasticity and modulus of rupture. Therefore, results presented are normalized for the specific gravity of each piece. After testing, the pieces were dried at 60°C, and wood density was determined from measurements of each piece's volume and dry weight.

Measured parameters were compared among species and over time using two-factor analysis of variance (ANOVA) with species and exposure time as the factors. Thus, there were five species and eight exposure times for modulus of rupture, modulus of elasticity, and density of interior wood and five species and seven exposure times for exterior wood density, change in diameter, loss of bark and oxygen uptake. All analyses, except diameter change and loss of bark, included five samples in each time × species cell. Diameter loss and loss of bark included 15 samples in each time × species cell. When significant differences among means were detected, a Tukey multiple comparison test was employed to compare between species and exposure intervals. Differences were considered significant at $P \leq 0.05$.

Results

The force needed to break wood samples cut from the logs did not change significantly over the 60-month exposure in the stream for any species (Table 1). There were large differences in the resistance to breaking among the five species. Bigleaf maple was significantly more resistant to breaking on all sample dates than western redcedar and western hemlock. Maple also was more resistant to breaking than Douglas fir for the first three sample periods but not for samples collected after 6 months. Douglas fir had significantly greater breaking resistance than western redcedar, except at 6 months. Red alder had greater breaking resistance than western redcedar for all samples.

Modulus of elasticity did not change significantly for any of the species over the 60-month exposure period (Table 2). Western redcedar exhibited less resistance to bending than all other species for all exposure periods after 6 months. Douglas fir and bigleaf maple were consistently the most resistant species to bending and did not differ from one another for any exposure period. Douglas fir was more resistant to bending than western hemlock for all exposure periods except 6 months.

There were no changes in the density of interior wood for any species over the 60-month exposure period (Table 3). Bigleaf maple consistently exhibited the highest density and cedar the lowest. Densities of these two species were significantly

TABLE 1.—Effect of submersion in stream water on modulus of rupture (means ± SE) for wood from five species of trees (N = 5 for each species in each exposure group). Results of two-way analysis of variance for species: F = 44.96, $P = 8.5 \times 10^{-12}$, df = 4; exposure: F = 1.88, P = 0.12, df = 7; interaction: F = 0.96; P = 0.17, df = 28. Letters following the means indicate those species with significantly different values for that exposure period, where a = red alder, c = western redcedar, f = Douglas fir, h = western hemlock, m = bigleaf maple, All = different from all other species.

Exposure time (months)	Modulus of rupture (kPa × 10^3) for: Red alder (a)	W. redcedar (c)	Douglas fir (f)	W. hemlock (h)	B. maple (m)
0	5.58 ± 1.04 cm	4.70 ± 1.09 afm	6.30 ± 0.95 chm	4.82 ± 0.51 fm	7.90 ± 1.73 All
1	4.98 ± 1.08 cfm	4.05 ± 0.80 All	6.85 ± 0.94 ach	5.54 ± 1.01 cfm	7.31 ± 0.94 ach
6	6.18 ± 1.10 cm	5.14 ± 1.14 All	5.73 ± 1.19 cm	5.73 ± 0.65 cm	7.60 ± 1.51 All
12	6.69 ± 1.00 All	4.55 ± 0.74 All	5.87 ± 1.05 acm	5.67 ± 0.69 acm	7.51 ± 1.30 All
24	6.64 ± 0.95 cm	4.93 ± 0.89 All	7.28 ± 0.88 cm	6.59 ± 0.93 cm	8.01 ± 1.54 All
36	6.38 ± 0.47 cm	4.20 ± 0.87 All	6.70 ± 0.97 cm	6.16 ± 1.24 cm	7.53 ± 1.48 All
48	6.95 ± 1.21 ch	4.82 ± 0.70 All	6.31 ± 0.74 chm	5.38 ± 0.80 All	7.13 ± 1.57 cfh
60	6.56 ± 1.02 chm	4.35 ± 0.78 All	6.98 ± 0.77 ch	5.75 ± 0.94 All	7.35 ± 1.30 ach

different for all sample dates. Red alder, western hemlock and Douglas fir exhibited no significant differences in the density of interior wood after the 6-month sample.

Density of surface wood declined significantly for all species during the study: 23% for red alder, 31% for western redcedar, 24% for Douglas fir, 31% for western hemlock, and 28% for bigleaf maple (Table 4). However, the temporal pattern of change in density varied among species. Western redcedar and red alder rapidly decreased in density during the first 12 months of immersion but slowed thereafter. The other three species declined in density as much, or more, after 12 months of exposure as before 12 months. Density of surface wood of western redcedar was lower than the other species on all sample dates.

Diameter decreased significantly for all species over the 60-month period of exposure (Table 5). Diameter loss after 60 months ranged from 21.8 mm for maple to 10.6 mm for hemlock. Diameter of maple logs decreased significantly more than the other four species. Diameter changes among the other four species were not significantly different for the 60-month exposure period. Relatively little change in diameter occurred during the first 12 months of exposure, but diameter decreased for all species between 12 and 24 months. Diameter changed little after 24 months.

Decay rate constants (k) based on diameter change over the 60-month exposure period for the three conifer species were lower than the hardwood species, Douglas fir and western redcedar exhibiting the slowest rates of deterioration (Table 6). These decay rate constants reflect both the fragmentation of the bark and loss of a small amount of surface wood.

The large change in diameter between 12 and

TABLE 2.—Effect of submersion in stream water on modulus of elasticity (means ± SE) for wood from five species of trees (N = 5 for each species in each exposure group). Results of two-way analysis of variance for species: F = 24.08, $P = 1.0 \times 10^{-8}$, df = 4; exposure: F = 1.10, P = 0.39, df = 7; interaction: F = 1.01; P = 0.18, df = 28. Letters following the means indicate those species with significantly different values for that exposure period, where a = red alder, c = western redcedar, f = Douglas fir, h = western hemlock, m = bigleaf maple, All = different from all other species.

Exposure time (months)	Modulus of elasticity (kPa × 10^6) for: Red alder (a)	W. redcedar (c)	Douglas fir (f)	W. hemlock (h)	B. maple (m)
0	1.16 ± 0.24 cfm	0.95 ± 0.20 afm	1.46 ± 0.25 ach	0.97 ± 0.14 fm	1.52 ± 0.33 ach
1	0.98 ± 0.22 fm	0.87 ± 0.14 fhm	1.36 ± 0.34 ach	1.14 ± 0.20 cf	1.30 ± 0.28 ac
6	1.14 ± 0.17 c	0.91 ± 0.21 afm	1.15 ± 0.30 c	1.03 ± 0.15 m	1.24 ± 0.26 ch
12	1.21 ± 0.14 ch	0.66 ± 0.16 All	1.18 ± 0.19 ch	0.92 ± 0.14 All	1.17 ± 0.20 ch
24	1.19 ± 0.14 cf	0.77 ± 0.23 All	1.50 ± 0.18 All	1.23 ± 0.22 cf	1.22 ± 0.27 cf
36	1.19 ± 0.11 cf	0.68 ± 0.15 All	1.45 ± 0.25 All	1.23 ± 0.25 cf	1.06 ± 0.31 cf
48	1.40 ± 0.23 ch	0.80 ± 0.17 All	1.26 ± 0.17 ch	1.02 ± 0.10 All	1.25 ± 0.19 ch
60	1.21 ± 0.10 c	0.62 ± 0.20 All	1.31 ± 0.16 ch	1.08 ± 0.17 cf	1.24 ± 0.17 c

TABLE 3.—Change in density of interior wood (means ± SE) from five species of trees after immersion in stream water (N = 5 for each species in each exposure group). Interior wood density was measured on pieces cut from the center of each log that were also used to determine modulus of rupture and modulus of elasticity. Results of two-way analysis of variance for species: F = 84.63, P = 5.7 × 10^{-19}, df = 4; exposure: F = 1.56, P = 0.18, df = 7; interaction: F = 1.09; P = 0.40, df = 28. Letters following the means indicate those species with significantly different values for that exposure period, where a = red alder, c = western redcedar, f = Douglas fir, h = western hemlock, m = bigleaf maple. All = different from all other species.

Exposure time (months)	Wood density (g/cm³) for: Red alder (a)	W. redcedar (c)	Douglas fir (f)	W. hemlock (h)	B. maple (m)
0	0.39 ± 0.02 chm	0.30 ± 0.01 All	0.40 ± 0.03 chm	0.34 ± 0.02 All	0.49 ± 0.02 All
1	0.35 ± 0.02 cfm	0.30 ± 0.01 All	0.43 ± 0.02 ac	0.39 ± 0.02 cm	0.44 ± 0.02 ach
6	0.37 ± 0.01 cm	0.31 ± 0.02 All	0.37 ± 0.02 cm	0.35 ± 0.02 cm	0.49 ± 0.03 All
12	0.38 ± 0.01 cm	0.29 ± 0.02 All	0.36 ± 0.03 cm	0.35 ± 0.06 cm	0.47 ± 0.03 All
24	0.38 ± 0.02 cm	0.31 ± 0.03 All	0.41 ± 0.02 cm	0.39 ± 0.03 cm	0.47 ± 0.03 All
36	0.37 ± 0.01 cm	0.29 ± 0.03 All	0.40 ± 0.04 cm	0.41 ± 0.04 cm	0.47 ± 0.02 All
48	0.40 ± 0.02 cm	0.31 ± 0.02 All	0.39 ± 0.03 cm	0.37 ± 0.02 cm	0.45 ± 0.02 All
60	0.40 ± 0.02 cm	0.30 ± 0.03 All	0.40 ± 0.03 cm	0.39 ± 0.02 cm	0.49 ± 0.03 All

24 months was primarily due to the loss of bark from the logs (Table 7). All bark remained on the logs after 1 month of exposure and nearly all after 6 months. However, by the end of the first year more than 80% of the bark had been removed from all species. The proportion of log covered by bark was low but variable from 12 through 60 months. All bark was stripped from cedar logs by 24 months. The variability in bark cover after 1 year was partially due to the degree of abrasion to which the logs were subjected. Some log rafts were exposed to very swift currents during high flows, whereas others were in more protected locations.

Although bark removal accounted for a substantial proportion of the reduction in diameter, significant loss of wood also occurred for all species except western hemlock (Table 8). Initial bark thickness was comparable for all five species, ranging from 4.0 to 5.1 mm. Bigleaf maple lost about three times as much wood as the other four species, loss of bark accounting for only 40% of the diameter decrease. Conifers lost relatively little wood. Western hemlock exhibited no detectable loss of wood, and bark loss alone accounted for more than 75% of the diameter decrease in Douglas fir and western redcedar.

Rate of oxygen consumption by the wood cores changed over time and varied significantly among the species (Figure 1). After 60 months, rate of oxygen consumption had declined significantly for all species: 83% for Douglas fir, 88% for western redcedar, 84% for western hemlock, 68% for red alder, and 79% for bigleaf maple. During the first 6 months of exposure, rate of oxygen consumption by maple was greater than that of the other four species. Oxygen consumption for the conifer spe-

TABLE 4.—Change in density of surface wood (means ± SE) from five species of trees after immersion in stream water (N = 5 for each species in each exposure group). Surface wood density was determined from 10 × 12-mm cores cut from the outer surface of the logs. Results of two-way analysis of variance for species: F = 85.88, P = 1.1 × 10^{-36}, df = 4; exposure: F = 24.03, P = 2.0 × 10^{-19}, df = 6; interaction: F = 1.03; P = 0.43, df = 24. Letters following the means indicate those species with significantly different values for that exposure period, where a = red alder, c = western redcedar, f = Douglas fir, h = western hemlock, m = bigleaf maple, All = different from all other species, and x = values significantly different from the preceding exposure interval for the same species.

Exposure time (months)	Wood density (g/cm³) for: Red alder (a)	W. redcedar (c)	Douglas fir (f)	W. hemlock (h)	B. maple (m)
0	0.49 ± 0.02 All	0.35 ± 0.02 All	0.46 ± 0.03 All	0.41 ± 0.05 All	0.52 ± 0.03 All
1	0.46 ± 0.04 chm x	0.34 ± 0.01 All	0.47 ± 0.02 ch	0.43 ± 0.02 All	0.49 ± 0.02 ach x
6	0.44 ± 0.03 All	0.30 ± 0.02 All x	0.38 ± 0.02 All x	0.35 ± 0.03 All x	0.48 ± 0.03 All
12	0.40 ± 0.13 cm x	0.28 ± 0.02 All	0.40 ± 0.04 cm	0.40 ± 0.05 cm x	0.46 ± 0.02 All
24	0.44 ± 0.02 chm x	0.31 ± 0.05 All x	0.43 ± 0.05 chm x	0.40 ± 0.05 All	0.51 ± 0.02 All x
36	0.40 ± 0.03 cfm x	0.29 ± 0.05 All	0.44 ± 0.04 All	0.41 ± 0.06 cfm	0.47 ± 0.04 All x
60	0.38 ± 0.04 cfh	0.25 ± 0.02 All x	0.35 ± 0.04 All x	0.29 ± 0.03 All x	0.38 ± 0.05 cfh x

TABLE 5.—Decrease in diameter of logs (means ± SE) for five species of trees after immersion in stream water (N = 15 for each species in each exposure group). Results of two-way analysis of variance for species: $F = 3.14$, $P = 0.014$, df = 4; exposure: $F = 233.9$, $P = 2.5 \times 10^{-140}$, df = 6; interaction: $F = 4.45$; $P = 4.95 \times 10^{-11}$, df = 24. Letters following the means indicate those species with significantly different values for that exposure period, where a = red alder, c = western redcedar, f = Douglas fir, h = western hemlock, m = bigleaf maple, All = different from all other species, and x = values significantly different from the preceding exposure interval for the same species.

Exposure time (months)	Change from original diameter (cm) for:				
	Red alder (a)	W. redcedar (c)	Douglas fir (f)	W. hemlock (h)	B. maple (m)
1	−0.03 ± 0.08	0.02 ± 0.19	0.13 ± 0.49	0.26 ± 0.35	0.10 ± 0.15
6	−0.01 ± 0.14	−0.13 ± 0.16	0.01 ± 0.13	0.01 ± 0.10	−0.01 ± 0.11
12	−0.07 ± 0.34	−0.07 ± 0.29	−0.39 ± 0.34	−0.21 ± 0.26	−0.11 ± 0.18
24	−0.95 ± 0.54 All x	−1.59 ± 0.35 a x	−1.62 ± 0.43 a x	−1.51 ± 0.59 a x	−1.49 ± 0.68 a x
36	−1.29 ± 0.44 m	−1.47 ± 0.33	−1.51 ± 0.50	−1.43 ± 0.39 m	−1.94 ± 2.05 ha
48	−1.34 ± 0.50 m	−1.79 ± 0.36 fm	−1.00 ± 0.39 ch	−1.71 ± 0.46 fm	−0.76 ± 0.61 ach x
60	−1.43 ± 0.40 m	−1.32 ± 0.42 m	−1.30 ± 0.27 m	−1.26 ± 0.49 m x	−2.18 ± 2.13 All x

cies declined more rapidly than for the hardwoods. At 12 months, rates of oxygen utilization by alder and maple were not different but were higher than the rates exhibited by the other three species. This difference between hardwoods and conifers occurred at 36 months and 60 months as well. At the end of the study oxygen consumption rates for alder and maple were approximately equal but more than double the rates for Douglas fir and western redcedar.

Discussion

Changes in all measured parameters were seen in surface wood, which exhibited decreased density, loss of bark, and loss of diameter over the 60 months of immersion. In contrast, interior wood of the logs exhibited no changes in measured properties during the study for any of the five species. Effects were limited to the log surface due to saturation with water. Saturation has been shown to decrease oxygen concentrations in the wood to levels low enough to prevent penetration by fungal hyphae (Savory 1954). Fungi are primarily responsible for wood decomposition in terrestrial environments (Harmon et al. 1986), but bacteria are most commonly responsible for decomposition of saturated wood (Crawford and Sutherland 1979) and operate only on the surface where oxygen concentrations are adequate (Aumen 1985). Deterioration of the wood surface by microbes facilitates sloughing of material from the log due to abrasion.

Oxygen utilization by the microbial community on the surface of the logs decreased rapidly with exposure for all species. The decline is due to the relatively high content of decay-promoting substances, such as sugars in the inner bark (Smith and Zavarin 1960). These materials are rapidly used by the microbes and rate of oxygen use decreases once they have been depleted. Hardwood trees contain more sugars, starches, proteins, and nutrients in the inner bark and the sapwood than do conifers (Harmon et al. 1986), which contributes to the higher rate of oxygen use in bigleaf maple and red alder from 12 months through 60 months. The combined processes of microbial action followed by removal of the weakened, surface wood by abrasion caused loss in log diameter. The higher rate of decomposition of the surface wood is responsible for the greater decrease in log diameter for the two hardwood species.

Decay rate constants derived from our experiments are lower than those reported for wood of

TABLE 6.—Changes in initial volume of 1-m-long logs from five species of trees after 5 years of immersion in stream water, resulting from losses in diameter. Volumes are based on 15 measures of diameter taken on green logs (before immersion) and after 60 months of immersion. The decay-rate constant, k, is derived via equation (1).

Species	Initial volume (m^3)	Final volume (m^3)	Decay-rate constant (k)
Douglas fir	0.032 ± 0.003	0.028 ± 0.002	0.026
Western redcedar	0.032 ± 0.004	0.028 ± 0.004	0.026
Western hemlock	0.030 ± 0.001	0.025 ± 0.001	0.031
Red alder	0.028 ± 0.002	0.024 ± 0.002	0.033
Bigleaf maple	0.032 ± 0.003	0.027 ± 0.002	0.038

TABLE 7.—Mean proportion of bark remaining on the logs on each sample date. Standard errors are shown except when all samples were fully covered with bark (100%) or when bark was absent on all samples (0%); $N = 15$ for each species in each exposure group.

Exposure (months)	Percent of piece covered with bark (±SE)				
	Red alder	W. redcedar	Douglas fir	W. hemlock	B. maple
1	100	100	100	100	100
6	100	100	87.3 ± 33.4	86.9 ± 34.6	87.1 ± 33.9
12	1.0 ± 1.5	19.8 ± 40.7	14.0 ± 25.4	14.0 ± 29.3	13.9 ± 35.0
24	25.3 ± 30.3	0	5.7 ± 12.1	2.3 ± 6.2	11.3 ± 26.9
36	15.7 ± 20.2	0	10.4 ± 27.0	2.9 ± 8.3	14.6 ± 24.2
48	7.9 ± 15.7	0	19.3 ± 27.0	2.7 ± 5.4	50.3 ± 45.2
60	3.6 ± 6.7	0	1.4 ± 5.3	0	0

the same or similar species in terrestrial environments (Harmon et al. 1986). Decay rate constants for Douglas fir snags in terrestrial environments range from 0.014 to 0.354, smaller-diameter boles like those used in this experiment exhibiting higher values (Cline et al. 1980; Graham 1982). Graham (1982) reported a decay rate constant for western hemlock snag fragmentation of 0.067, about double the value we found for submerged hemlock. Few data are available on fragmentation rates of red alder and bigleaf maple in terrestrial environments. However, mineralization rates for other hardwood species in terrestrial environments are much higher than for conifers, values ranging from 0.049 for aspen *Populus tremuloides* to 0.520 for tulip poplar *Liriodendron tulipifera* (Harmon et al. 1986). The decomposition rates we obtained for submerged red alder and bigleaf maple logs are lower than terrestrial rates for other hardwood species and only slightly higher than the rates we obtained for the conifer species.

TABLE 8.—Initial bark thickness, total decrease in diameter after 5 years of immersion, and diameter decrease due to loss of wood for the five species of trees evaluated. Values for bark thickness and diameter loss are means ± SE ($N = 50$ for initial bark thickness measurements and $N = 15$ for diameter loss values). Species exhibiting statistically significant wood loss are marked with an x, indicating that total diameter decrease could not be accounted for simply by loss of bark (t-test; $P \leq 0.05$).

Species	Initial bark thickness (mm)	Total diameter loss (mm)	Loss of wood[a] (mm)
Douglas fir	5.1 ± 1.1	13.0 ± 2.70	2.8 x
Western redcedar	4.4 ± 0.9	13.2 ± 4.20	4.4 x
Western hemlock	4.0 ± 0.9	10.6 ± 4.90	2.6
Red alder	5.1 ± 0.9	14.3 ± 4.00	4.1 x
Bigleaf maple	4.4 ± 0.8	21.8 ± 6.30	13.0 x

[a] Loss of wood = mean total diameter decrease minus 2× the initial bark-thickness mean.

Differences in decomposition rate between conifer and hardwood species may have been partially obscured by the relatively short duration of our experiment. Decomposition did not extend to the heartwood of any of the logs we examined. Heartwood contains compounds that retard decomposition and these compounds are typically at much higher levels in conifers than in hardwoods (Scheffer and Cowling 1966). Western redcedar, in particular, accumulates large quantities of these chemicals in its heartwood (Scheffer and Cowling 1966). In addition, the logs we used had small diameters and were from relatively young trees containing little heartwood. Had we examined larger logs and extended our study over a longer period, it is possible that the differences in rate of decomposition between the hardwood and conifer species would have become more pronounced. However, the slow rate of decomposition exhibited by all the species indicates that submerged pieces of wood will decay at much slower rates than in a situation where the wood is periodically wetted and dried.

Our results suggest that logs from hardwood trees can be used in stream habitat enhancement projects under the appropriate conditions. The relatively short duration of our experiment precluded estimation of log longevity in the stream. However, decay rate should slow over time, rather than accelerate; therefore, the wood from all the species we examined may, when under the water most of the time, persist for several decades, including the hardwoods. In addition, red alder and bigleaf maple have structural characteristics that are well suited to stream habitat enhancement projects. Both species exhibited high resistance to rupture and levels of stiffness, comparable to western hemlock and Douglas fir. Western redcedar, which is often preferred material for enhancement projects, exhibited the lowest resistance to rupture and flex-

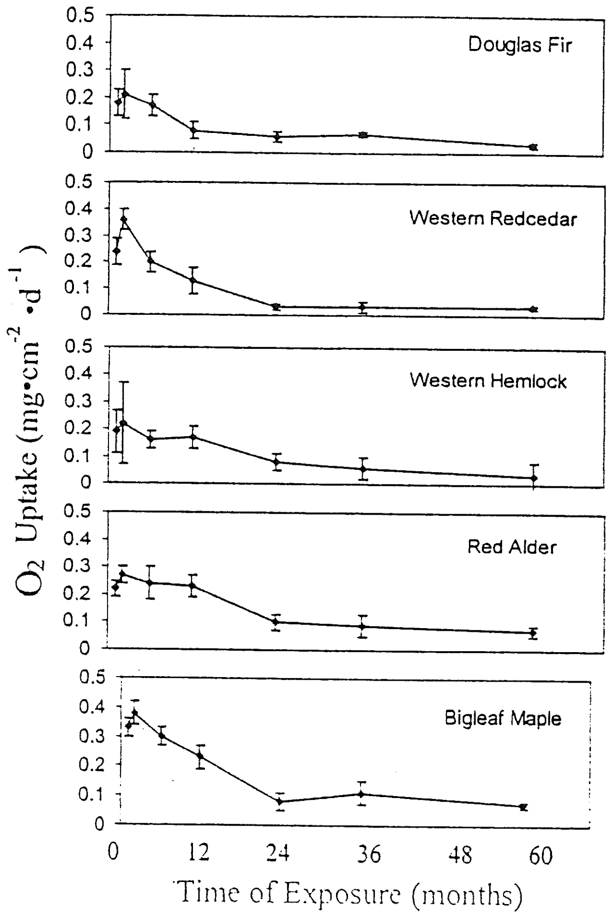

FIGURE 1.—Rate of O^2 utilization by wood samples cut from the surface of the logs. Values are means (±SE); $N = 5$ for each species for each exposue interval. Results of two-way analysis of variance for species: $F = 30.54$, $P = 2.8 \times 10^{-18}$, df = 4; exposure: $F = 75.69$, $P = 1.7 \times 10^{-41}$, df = 6; interation: $F = 3.16$, $P = 1.2 \times 10^{-5}$, df = 24. Rate of O^2 utilization decreases significantly for all species between 1 month and 60 months immersion. Species with the same parenthetical group are not significantly different (a = red alder, c= western redcedar, f = Douglas fir, h = western hemlock, m = bigleaf maple): 0 months: (m) (a,c,f,h); 1 month: (m) (c,h) (a, f); 6 months: (m) (a, c, f, h); 12 months: (a, m) (h, c) (c, f); 24 months: (m, a, h, f, c); 36 months: (m, a) (a, f, h, c); 60 months: (a, m) (m, h, f, c).

ing of all the species. However, red alder and bigleaf maple do not achieve the diameter or height of the conifer species and will not persist in situations where they are exposed to air for extended periods (Swanson and Lienkaemper 1978). Partially submerged red alder logs that were added to a stream in western Washington to improve habitat exhibited significant degradation after only 3 years (Cederholm et al. 1997). Therefore, conifer logs will function best in situations where a large piece of wood is needed or where the log will be repeatedly wetted and dried as stream level fluctuates. Nonetheless, the use of hardwood logs in appropriate situations can potentially reduce costs and effort of enhancement projects, enable projects to be implemented in locations where transport of conifer logs to the site is not feasible, and minimize the disturbance to riparian areas caused by transport of large numbers of conifer logs to the site.

References

American Society for Testing and Materials. 1978. Standard methods of testing small, clear specimens of timber. Annual book of standards, part 22. American Society for Testing and Materials, ASTM D143–52, Washington, D.C.

Aumen, N. G. 1985. Characterization of lignocellulose decomposition in stream wood samples using ^{14}C and ^{15}N techniques. Doctoral dissertation. Oregon State University, Corvallis.

Beschta, R. L. 1997. Restoration of riparian and aquatic systems for improved aquatic habitats in the upper Columbia River basin. Pages 475–492 *in* D. J. Stouder, P. A. Bisson, and R. J. Naiman, editors. Pacific salmon and their ecosystems. Chapman and Hall, New York.

Bilby, R. E. 1984. Post-logging removal of woody debris affects stream channel stability. Journal of Forestry 82:609–613.

Bisson, P. A., G. H. Reeves, R. E. Bilby, and R. J. Naiman. 1997. Watershed management and Pacific salmon: desired future conditions. Pages 447–474 *in* D. J. Stouder, P. A. Bisson, and R. J. Naiman, editors. Pacific salmon and their ecosystems. Chapman and Hall, New York.

Carlson, A. 1991. Characterization of riparian management zones and upland management areas with respect to wildlife habitat. Washington Department of Natural Resources, Washington Timber/Fish/Wildlife Report T/F/W-WLI-91-001, Olympia.

Cederholm, C. J., R. E. Bilby, P. A. Bisson, B. R. Fransen, W. J. Scarlett, and J. W. Ward. 1997. Response of juvenile coho salmon and steelhead trout to the placement of large woody debris in a coastal Washington stream. North American Journal of Fisheries Management 17:947–963.

Cline, S. P., A. B. Berg, and H. M. Wight. 1980. Snag characteristics and dynamics in Douglas-fir forests, western Oregon. Journal of Wildlife Management 44:773–786.

Crawford, D. L., and J. B. Sutherland. 1979. The role of actinomycets in the decomposition of lignocellulose. Developments in Industrial Microbiology 20:143–151.

Duff, D. A., N. Banks, E. Sparks, W. E. Stone, and R. J. Poehlmann. 1988. Indexed bibliography on stream habitat improvement (4th revision). U.S. Forest Service, Intermountain Region, Ogden, Utah.

Frissell, C. A., and R. K. Nawa. 1992. Incidence and causes of physicxal failure of habitat structures in streams of western Oregon and Washington. North American Journal of Fisheries Management 12: 182–197.

Graham, R. L. 1982. Biomass dynamics of dead Douglas fir and western hemlock boles in mid-elevation forests of the Cascade Range. Doctoral dissertation. Oregon State University, Corvallis.

Harmon, M. E., and twelve coauthors. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133–302.

House, R. A., and P. L. Boehne. 1986. Evaluation of instream enhancement structures for salmonid spawning and rearing in a coastal Oregon stream. North American Journal of Fisheries Management 5:283–295.

Nickelson, T. E., M. F. Solazi, S. L. Johnson, and J. D. Rodgers. 1992. Effectiveness of selected stream improvement techniques to create suitable summer and winter rearing habitat for juvenile coho salmon (*Oncorhynchus kisutch*) in Oregon coastal streams. Canadian Journal of Fisheries and Aquatic Sciences 49:790–794.

Oregon Board of Forestry. 1994. Oregon forest practices regulations. Oregon Department of Forestry, Salem.

Reeves, G. H., K. M. Burnett, F. H. Everest, J. R. Sedell, D. B. Hohler, and T. Hickman. 1991a. Responses of anadromous salmonid populations and physical habitat to stream restoration in Fish Creek, Oregon. U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Project Report 84–11, Portland.

Reeves, G. H., J. D. Hall, T. D. Roelofs, T. L. Hickman, and C. O. Baker. 1991b. Rehabilitating and modifying stream habitats. Pages 519–557 *in* W. R. Meehan, editor. Influences of forest and rangeland management salmonid fishes and their habitats. American Fisheries Society, Special Publication 19, Bethesda, Maryland.

Savory, J. G. 1954. Breakdown of timber by ascomycetes and fungi imperfecti. Annals of Applied Biology 41:336–347.

Scheffer, T. C., and E. B. Cowling. 1966. Natural resistance of wood to microbial deterioration. Annual Review of Phytopathology 4:147–170.

Smith, L. V., and E. Zavarin. 1960. Free mono- and oligosaccharides of some California conifers. TAPPI (Technical Association of the Pulp and paper Industry) 43:218–221.

Swanson, F. J., and G. W. Lienkaemper. 1978. Physical consequences of large organic debris in Pacific Northwest streams. U.S. Forest Service, General Technical Report PNW-69.

Tarzwell, C. M. 1937. Experimental evidence on the value of trout stream improvement in Michigan. Transactions of the American Fisheries Society 66: 177–187.