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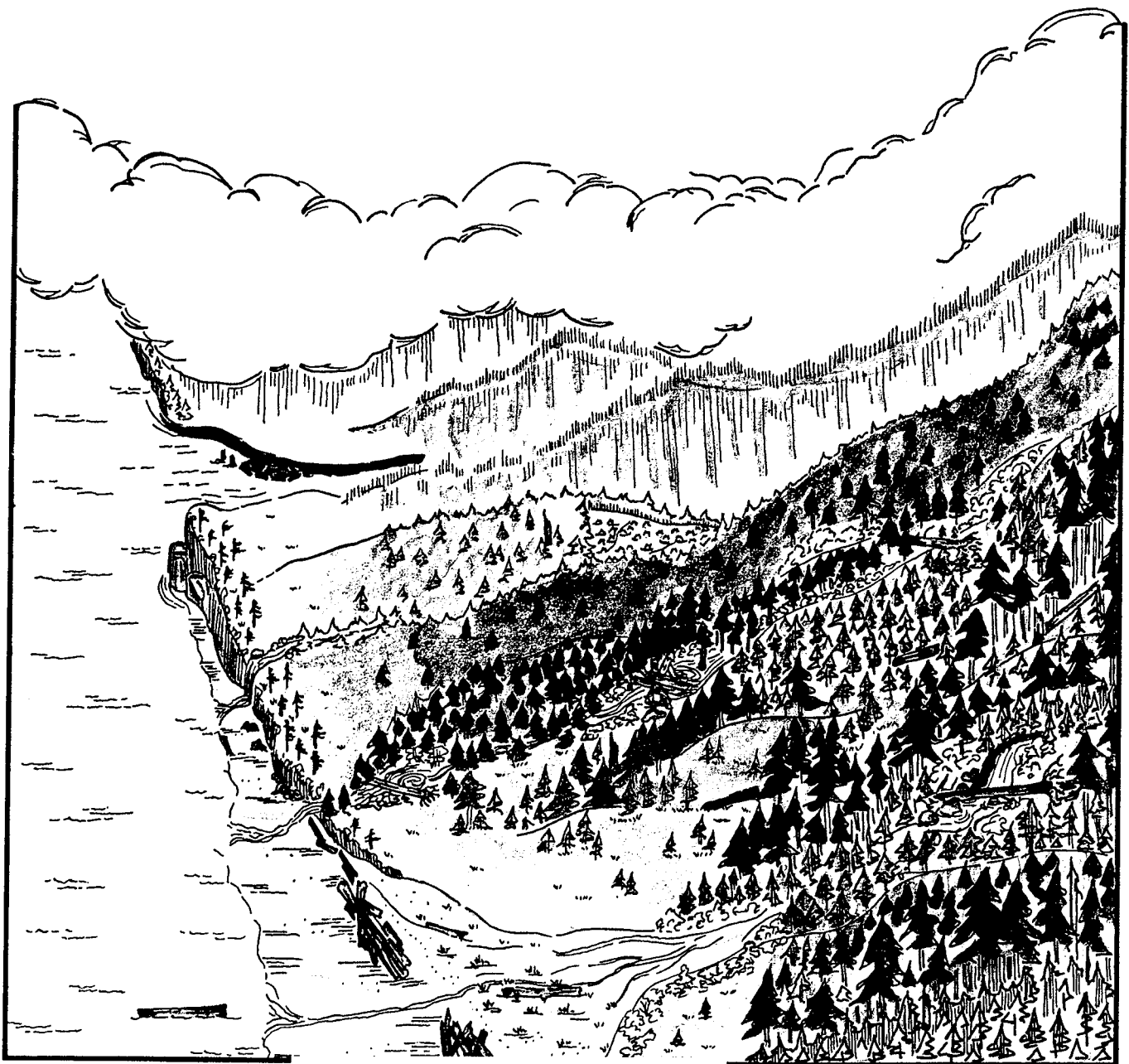
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**Bureau of
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September 1988

From the Forest to the Sea: A Story of Fallen Trees



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From the Forest to the Sea: A Story of Fallen Trees

**Chris Maser, Robert F. Tarrant,
James M. Trappe, and Jerry F. Franklin**
Technical Editors

**Pacific Northwest Research Station
U.S. Department of Agriculture
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Abstract

Large, fallen trees in various stages of decay contribute much-needed diversity of ecological processes to terrestrial, aquatic, estuarine, coastal beach, and open ocean habitats in the Pacific Northwest. Intensive utilization and management can deprive these habitats of large, fallen trees. This publication presents sound information for managers making resource management decisions on the impact of this loss on habitat diversity and on ecological processes that have an impact on long-term ecosystem productivity.

Keywords: Decomposition, fallen trees, habitat diversity, ecosystem function, land, water, sea.



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Introduction Robert F. Tarrant and Chris Maser

Forest productivity is declining over large areas of managed forest in central Europe (Cramer 1984, Schütt and Cowling 1985), China (Zhang and others 1980), and North America (Bruck and Roberge 1984, Knight 1987, Sheffield and others 1985, Siccama and others 1982, Zedaker and others 1987). In calling attention to this major problem several years ago, the Society of American Foresters (1984a) stated its concern: "In the face of mounting evidence that forest productivity is declining worldwide, researchers know too little about complex ecosystems and the cumulative effect of subtle stresses from atmospheric pollutants."

Certainly our knowledge of biological processes and their interactions within forest ecosystems is incomplete, and we know too little about the cumulative effect of a wide range of stresses on the ecosystem. But integrative research at the ecosystem level shows clearly that the many processes operating within forest systems interconnect in important ways (Waring and Schlesinger 1985). Further, diversity of microscopic and macroscopic plant and animal species is a key factor in maintaining these processes (Blaschke and Bäumler 1986, Durrieu and others 1984, Li and others 1986, Plochmann 1968, Franklin 1988, Froidevaux 1981).

The Congress of the United States addressed the matter of species diversity in the National Forest Management Act of 1976 (U.S. Laws, Statutes, etc. 1976): "...regulations, under the principles of the Multiple-use Sustained Yield Act of 1960...shall include...guidelines which...provide for diversity of plant and animal communities...." Elsewhere in the Act, the Congress offers a philosophical basis for constructive forestry goals: "...the Forest Service has both a responsibility and an opportunity to be a leader in assuring that the Nation maintains a natural resource conservation posture that will meet the requirements of our people in perpetuity...."

An underlying principle of the congressional direction is that people, as a significant part of the forest ecosystem, have the right and the obligation to manage biological processes to produce products and amenities afforded by forests. Such management, however, must be consistent with the need to maintain health of the biologically productive machinery over the long run. The 1986 "National Forum on Bio-Diversity," sponsored by the National Academy of Sciences and the Smithsonian Institution, was a needed step toward recognition of the problem. Now, forest scientists must be strongly challenged to define the relations between biological processes and forest health.

In this book, we document that a large dead tree is not a wasted resource; indeed, it continues to function as an important part of a terrestrial or water system, either while remaining on the site at which it once lived, or by becoming a structural part of an aquatic or marine habitat. We aim to help anyone interested in perpetual forest productivity to understand the importance of large, dead woody debris. The book develops certain principles and ideas in sequence from the forest to the sea. The dynamics of coarse woody debris (any dead standing or fallen tree stem on land or in water at least 4 inches in diameter at breast height on snags and at the large end on fallen trees) in forests and plantations of coastal Oregon are summarized in chapter 1; on the forest floor, chapter 2; in streams and rivers, chapter 3; and in estuaries

and the open ocean, chapter 4. Intensive and diversified management and the need for future research are examined in chapter 5. Most of the information is specific to the Coast Range of Oregon but also applies generally to western Oregon and western Washington, western British Columbia, and southeastern Alaska.

Oregon's coastal zone extends from the crest of the Coast Range to the Continental Shelf and contains some of the world's most inherently productive forest systems (Franklin and Dyness 1973, Fujimori 1971, Waring and Franklin 1979) (fig. 1.1; fig. 1.2, color). Here, a continuum of terrestrial, stream, estuarine, and coastal ocean

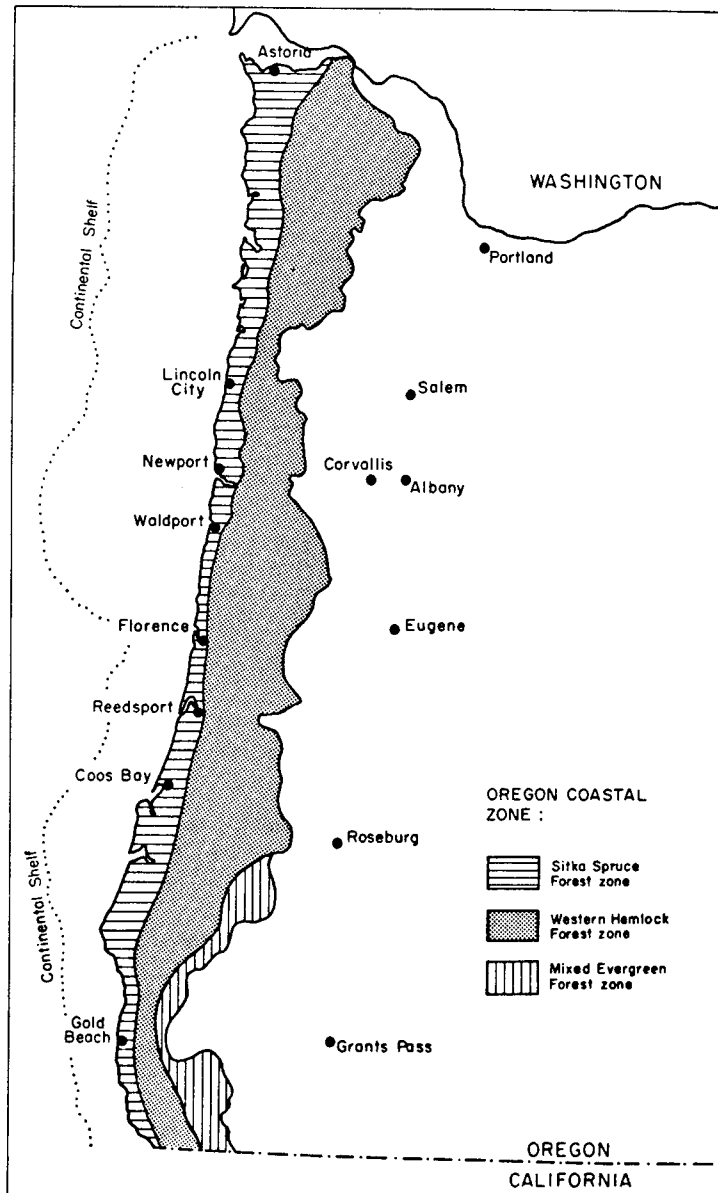


Figure 1.1—The Oregon coastal zone.

sites composes one macrosystem (Vannote and others 1980). The parts of this system are related by water and atmospheric transport of chemicals and organic and inorganic substances of various sizes along an elevational gradient from 4,000 feet above sea level to an ocean depth of 1,200 feet (200 fathoms).

Few regions of the world support vegetation that grows faster, more densely, and to greater heights than that along the Oregon coast. The mix of species and the structure of plant communities vary greatly, even over short distances, because of site-to-site differences in elevation, climate, geology, soils, and nutrient availability. Drought is not a problem along drainages where the soil is constantly wet and air humidity is high, but plants may suffer from lack of water on a sun-warmed hillside in midsummer. Most coastal soils are of medium texture, moderately deep, and reasonably well supplied with nutrients.

Along Oregon's northern coast, the vegetation is mainly of the same species seen in coastal Washington, British Columbia, and Alaska: Sitka spruce, western hemlock, huckleberry, salmonberry, and salal (see "Appendix" for scientific names). Along the southern Oregon coast, the species mixture is much richer—the "northern" species mix with California plants growing at or near their northern limits: redwood, tanoak, California laurel, western azalea, and blueblossom. The Klamath-Siskiyou Mountain region of the southern Oregon and northern California coast supports still other localized species such as Port-Orford-cedar.

The Oregon coast landscape was disturbed periodically long before human habitation. Floods and landslides are part of the natural geological aging of coastal mountains. Windstorms and wildfires set by lightning destroy vast tracts of forest. We may think such events now are unusual and catastrophic, but in fact they are very much a part of the natural cycle of events. After human settlement, additional massive changes in vegetation occurred. People frequently cause wildfires or convert large areas to agriculture and urban uses.

The native forest of the Oregon coast has undergone intensive commercial exploitation only in the past century, so biological stresses are probably less than in much of the world. Here, forest managers still have time to benefit from the long-term experience of others. And here especially, forest scientists and resource managers have the opportunity to work in concert in developing sound management systems that can also be models for achieving the recovery of declining forests elsewhere.



Figure 1.2—The coastal zone of Oregon extends from the crest of the Coast Range to the Continental Shelf.

In the following chapters, we synthesize existing research information and offer some hypotheses and conclusions based on current knowledge. We offer this information and our interpretations for consideration by forest managers and others interested in long-term forest productivity.

Chapter 1. Coarse Woody Debris in Forests and Plantations of Coastal Oregon

Thomas A. Spies and Steven P. Cline

Summary

The forest portion of the ecosystem is the sum of three diverse, mutually dependent components: physical structures, biological entities, and ecological functions. These components are dynamic, continually developing diversity.

Introduction

Diversity develops in a forest as a result of changes that occur at different rates at different places. Disturbances cause relatively rapid changes in ecosystems, whereas succession slowly returns ecosystems to previous conditions or directs them to new states. Structural diversity in the current mosaic of forest age classes was created by a variety of disturbances, such as fire and wind, and this mosaic changes from succession and new disturbances (*fig. 1.1, color*). Today's forested coastal landscape bears the legacy of many landscapes in the form of remnant old-growth trees, snags, fallen trees, landslides, and patches of young and mature forests.

The forest's character changes with succession. Net primary productivity is greater in young forests than in old ones. Old forests conserve nutrients, whereas very young forests are susceptible to erosion and nutrient loss (Franklin and others 1981). Forests of the Coast Range interior valleys produce less wood than do those on more moist sites nearer the ocean. And internally, the old unmanaged forest is more diverse than many young and mid-age forests. Old forests have deeper, multilayered canopies, larger accumulations of coarse woody debris (any dead standing or fallen tree stem at least 4 inches in diameter at breast height (d.b.h.) on snags and at the large end on fallen trees), and more specialized plants and animals than young forests have.

A coastal Oregon forest may change slowly through growth, succession, mortality, and decay, or it may be altered rapidly by catastrophic disturbance. Whatever the agent of change, the imprints of previous forests and disturbances persist into succeeding forest generations. Organic material in the form of dead tree stems is one of the more persistent legacies. This material exerts ecological influences on a site for hundreds and thousands of years; first, as snags and fallen trees; later, as fine organic matter in the soil. These organic remains create seed germination sites, moisture reservoirs during summer drought, sites of nutrient exchange for plant growth, habitat for forest organisms, and favorable soil structure.

The Unmanaged Forest

Forest Disturbances

The major agents of disturbance are fires, winds, insects, diseases, and accelerated mass soil and debris movements. Disturbance, along with forest stand development and plant succession, helps create the coarse woody debris that is part of the forest.

Wildfire of various intensities and sizes has been the most significant catastrophic disturbance throughout the Coast Range (Martin and others 1976). Some fires have burned more than a million acres, and many areas have reburned within 30 years.

Two of the many large wildfires in the Coast Range are especially impressive. In 1849, a fire between the Siletz and Siuslaw Rivers burned more than one-half-million acres (Morris 1936). Many fires have burned in a patchy manner, creating a very complex mosaic of dead and live trees. Humans have strongly influenced the dynamics of woody debris in the Coast Range through accidental or intentional setting of fires. Between 1933 and 1951, for example, the many Tillamook burns covered 335,000 acres, killing more than 13 billion board feet of timber (Lucia 1983). Large, severe fires add massive amounts of coarse woody debris to the ecosystem because large branches, stems, and most of the coarse woody debris are not consumed by the fire (Harmon and others 1986) (fig. 1.2).



Figure 1.2—Amounts of coarse woody debris after a fire that killed an old-growth stand.



Figure 1.3—Blowdown patch in a spruce-hemlock stand.

Windthrow, the next most important catastrophic forest disturbance, is common in the Coast Range where hurricane-force gales are recorded several times each year (Badura and others 1974). Such events in 1950, 1953, 1957, and 1958 caused extensive damage (Childs and Clark 1953, Lynott and Cramer 1966, Ruth and Yoder 1953). During the "Columbus Day" storm of October 12, 1962, 11 billion board feet of timber was blown down in western Oregon and western Washington (Orr 1963). Tree mortality from wind damage adds dead wood directly to the forest floor, in contrast to fire damage that usually leaves dead trees standing for many years (fig. 1.3).

Wind-caused mortality also creates a different successional pathway than does fire mortality. Wind increases the proportion of shade-tolerant species, such as western hemlock, because understory trees are released after the canopy dominants are removed. Thus, when trees in the released stand die, the contribution of dead wood is from smaller diameter, more rapidly decomposed western hemlock stems. Western hemlock stands lacking massive successional dominants, such as Douglas-fir or Sitka spruce, accumulate less coarse woody debris than do stands with these dominants.

Although insects have occasionally caused catastrophic mortality in Coast Range forests, they usually inflict only scattered mortality. Outbreaks of the Douglas-fir bark beetle often follow other events that kill and damage trees (Furniss and Carolin 1977). Such an outbreak, a patchwork of small groups of trees in recently killed timber, spreads to nearby trees where the insects form galleries in the phloem and girdle the trees. The beetles also introduce a fungus that plugs the conductive tissues in the vascular system. Trees killed by bark beetles usually die standing, although decay has already begun.

Laminated root rot fungus is a primary pathogen of Douglas-fir and western redcedar in the Coast Range. This fungus is not a direct agent of catastrophic mortality because patches of mortality are relatively small (about 0.25 acre) and spread slowly (about 1 ft/yr) (Gedney 1981, Nelson and others 1981). It is, however, widespread in the Coast Range and predisposes many trees and stands to windthrow. Red ring rot fungus, another important organism that predisposes canopy trees to wind damage, starts the process of wood decay before the trees die.

Steep slopes are generally unstable as a result of high precipitation, unstable soils, and deeply weathered bedrock. Debris avalanches, rapid shallow soil movement (Swanson and others 1982), and floods can suddenly destroy small areas of forest. Debris avalanches are estimated at more than 2.5 avalanches per square mile every 2 years on part of the Siuslaw National Forest (Swanson and Lienkaemper 1985). These small events move an average 872 cubic feet of soil and occur most often in headwall areas of steep drainages. Despite their small size, they have a cumulative effect on coarse woody debris. Debris avalanches and floods knock down and uproot trees, tearing them out of streambanks. The coarse woody debris produced is often moved from the site, however, and redeposited downslope or in streams.

Forest Stand Development and Succession

Coastal Oregon's forest lands occupy three vegetation-type zones: western hemlock (72 percent), Sitka spruce (17 percent), and mixed-evergreen (11 percent) (Franklin and Dyrness 1973). After major disturbance, stand recovery rates and successional pathways vary by location, site, and vegetation type. Most forest stands, however, follow a similar course of successional development that proceeds through five stages (based on Oliver 1981):

1. Stand initiation.--Trees of the new stand occupy recently disturbed sites. Grasses, forbs, and shrubs may dominate for 20 to 30 years. On some coastal sites, however, 50- to 60-year domination is possible.

If wildfire destroyed the previous stand, regrowth will be dominated by newly established seedlings. If wind destroyed the previous stand, the new stand will develop from newly established seedlings plus newly released, shade-tolerant understory trees.

2. Stem exclusion.--Canopy closure prohibits further establishment of new trees. Vertical stratification develops among individuals and species of the canopy. Intense competition among densely spaced trees causes natural thinning of suppressed individuals that may last 10 to 30 years. Input of coarse woody debris begins as tree competition causes mortality.



3. Understory reinitiation.--Canopy dominance diminishes, allowing herbs, shrubs, and small trees to establish. Cavity-nesting birds begin to use dead trees, now 15 to 20 inches in diameter (Neitro and others 1985). Fallen tree stems are of sufficient size that they persist much longer than the small trees of the previous stage. This stage may last until shade-tolerant trees reach the canopy—100 to 150 years.

4. Old growth.--Shade-intolerant overstory dominants (Douglas-fir or Sitka spruce) die and are replaced by understory trees, such as western hemlock. This stage lasts 500 to 800 years or more. Stand structure includes a wide range of tree sizes, massive individual dominants, great accumulations of coarse woody debris, numerous foliage layers, and patchy tree distribution. The death of one dominant Douglas-fir can create more than 22 tons of dead wood, some of which can persist for hundreds of years (Harmon and others 1986).

5. Climax.--The forest reaches the climax stage when the shade-intolerant dominants have died and the stand is composed of only shade-tolerant species. Such stands are rare, however, because of the great longevity of Sitka spruce and Douglas-fir and because disturbance usually reinitiates succession. A climax forest contains less coarse woody debris than does the old-growth forest because it lacks the original overstory dominants.

Coarse Woody Debris

Rates of coarse woody debris inputs and loss by decay.--Coastal Oregon forests contain some of the world's largest accumulations of standing dead and fallen trees. Coarse woody debris may exceed 175 tons per acre (dry weight), more biomass than the total live and dead biomass of many deciduous forests (Harmon and others 1986). These large accumulations of coarse woody debris result from two processes: addition of newly dead material and slow loss from decay of older material. The balance between addition from dead trees and subtraction of decaying wood determines the amount and dynamics of coarse woody debris in a forest.

The amount of coarse woody debris that will accumulate in a stand can be predicted if rates of input and decay are assumed to be constant (fig. 1.4). Two to four percent of the dead wood in a stand decays annually, rates similar to those reported for other forests (Harmon and others 1986). Accumulations of coarse woody debris in the coniferous forests in western Oregon are much larger than in other forests, however, probably because of higher rates of input.

New coarse woody debris is not added to young Douglas-fir stands until the stem exclusion and understory reinitiation stages. Mortality rates for canopy trees in these stands are relatively high (1-2 percent/year) (Franklin and others 1986), but accumulations of coarse woody debris are low in young stands because many of the trees that die are below the minimum diameter of coarse woody debris (4 inches) and because the small stems decay more rapidly than larger ones (Harmon and others 1986). Coarse woody debris from the young stand accumulates slowly during the first 100 years, then rapidly between 100 and 400 years (fig. 1.5).

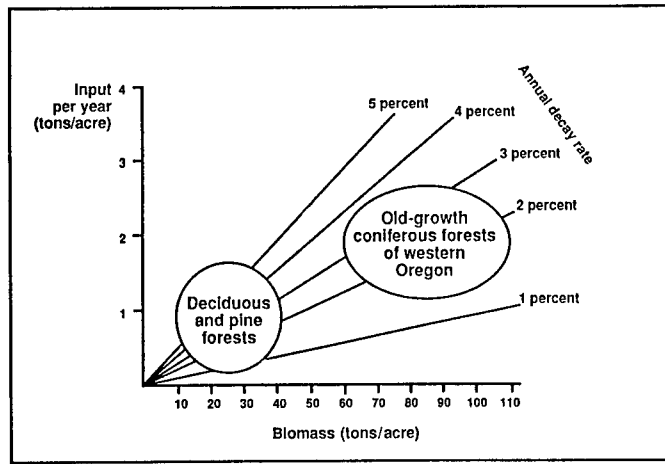


Figure 1.4—Relation between input rate of coarse woody debris and accumulation of coarse woody debris for different rates of decay of coarse woody debris; based on data from Harmon and others (1986) and adapted from an unpublished figure by M. Harmon.

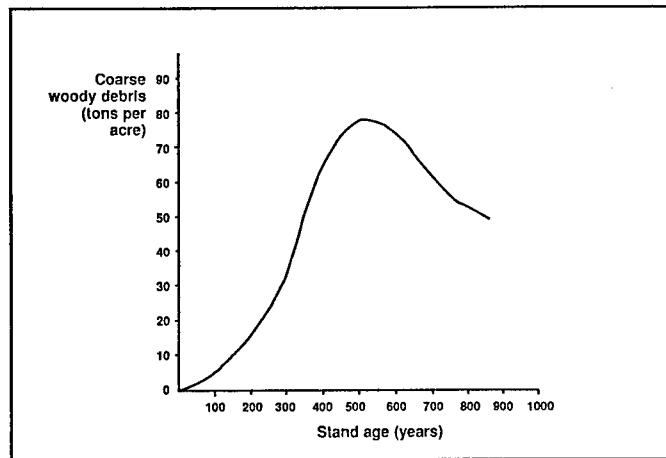


Figure 1.5—Accumulation of coarse woody debris in relation to stand age in Douglas-fir stands in western Oregon and Washington; based on data from Spies and others (in press).

In mature (late understory reinitiation stage) and old-growth stands, windthrow, diseases, and insects more than other agents cause most mortality in canopy trees. Mortality rates in old-growth stands decline to about 0.5 percent of all trees annually (Franklin and others 1986). Mortality rates are not constant, however, and windstorms or bark beetle outbreaks can cause sharp increases. Annual mortality in a 180-year-old stand of Douglas-fir near Coos Bay increased from less than 0.2 percent to more than 3 percent over 10 years after a Douglas-fir bark beetle outbreak (Wright and Lauterbach 1958). Woody debris averaged 7.6 tons per acre per year (Harmon and others 1986). Despite the relatively low mortality rate of mature and old-growth stands, coarse woody debris accumulation is high because massive trees decay more slowly than smaller ones. Input may reach 3 tons per acre per year (Grier and Logan 1977), several times that found in other temperate forest ecosystems (Harmon and others 1986).

Losses of coarse woody debris from decay result from several processes, such as organic matter leaching into the soil, physical and biological fragmentation (breaking off and loss of fine pieces), and respiration by microbes (Harmon and others 1986, Maser and Trappe 1984b). Loss rates from these and other processes depend on moisture, temperature, and stem size.

As snags and fallen trees decay, their chemical and physical nature changes. Douglas-fir wood density decreases by almost half during the first 100 years. Nitrogen concentration almost doubles during the same time (Franklin and others 1981). The physical appearance of fallen trees and snags also changes in cross-sectional shape from round to oval to flattened as the stem settles into the forest floor.

Amounts of snags and fallen trees.--The greatest amounts of coarse woody debris actually occur immediately after catastrophic wildfire or windthrow in early succession. Young stands (30 to 80 years) (*fig. 1.6, color*) in the Pacific Northwest have more snags and fallen trees and a greater volume and biomass of coarse woody debris than mature stands (80 to 200 years old) (*fig. 1.7, color*). Some young stands, however, contain fewer snags and fallen trees than do mature and old-growth stands (Spies and others, in press). For closed-canopy stands of the Pacific Northwest, old-growth (>200 years) contains the highest volume and biomass of snags and fallen trees (*fig. 1.8, color*).

The number of snags per acre differs with their diameter. In Douglas-fir stands in western Oregon and western Washington, the density of snags of all sizes is about 70/acre in young stands, 50/acre in mature stands, and 24/acre in old-growth stands (Spies and others, in press). This pattern is different, however, when only large snags (20 inches in d.b.h. and 16 feet tall) are considered; large snags are most abundant in old-growth (six/acre), less so in young stands (four/acre) and least abundant in mature stands (three/acre) (*fig. 1.9*). Large snags are most commonly used by cavity-nesting birds (Mannan and others 1980, Neitro and others 1985).

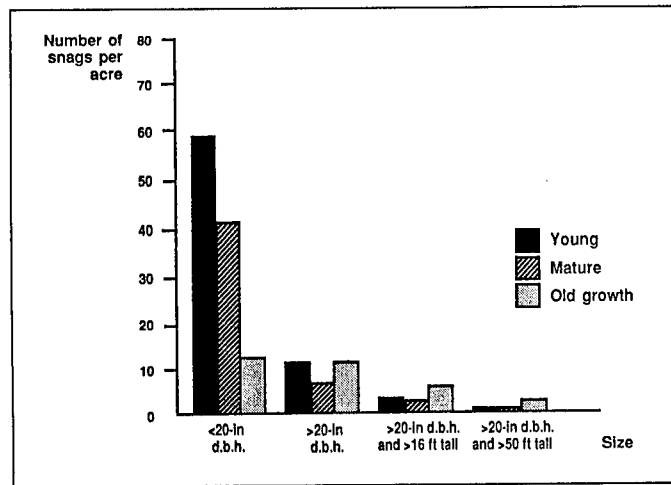


Figure 1.9—Number of snags per acre by size class in young, mature, and old-growth Douglas-fir stands in western Oregon and Washington; adapted from Spies and others (in press).

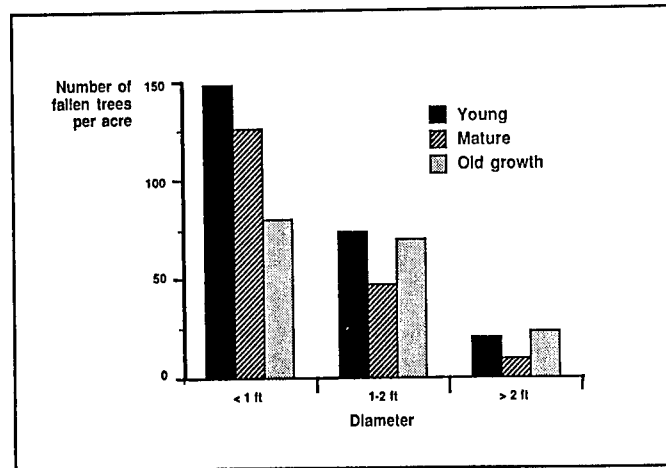


Figure 1.10—Numbers of fallen tree stems per acre by size class in young (Y), mature (M), and old-growth (O) Douglas-fir stands in western Oregon and Washington; adapted from Spies and others (in press).

Numbers of fallen trees in stands are generally similar to those of snags. Young stands often have the greatest numbers of fallen trees of all sizes, although old-growth stands have the highest numbers of large fallen trees (>24 inches) (fig. 1.10). Many young stands, probably established after fires in young- rather than old-growth forests, do not have large fallen trees and snags carried over from previous stands. Therefore, some young stands in the Coast Range do not fit this pattern; they have fewer fallen trees than old-growth stands have (Spies and others, in press).

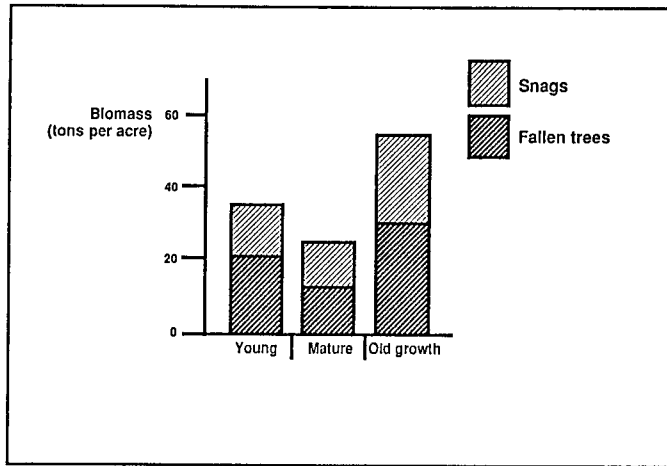


Figure 1.11—Mean biomass of total coarse woody debris in young, mature, and old-growth Douglas-fir stands in western Oregon and Washington; Spies and others (in press).

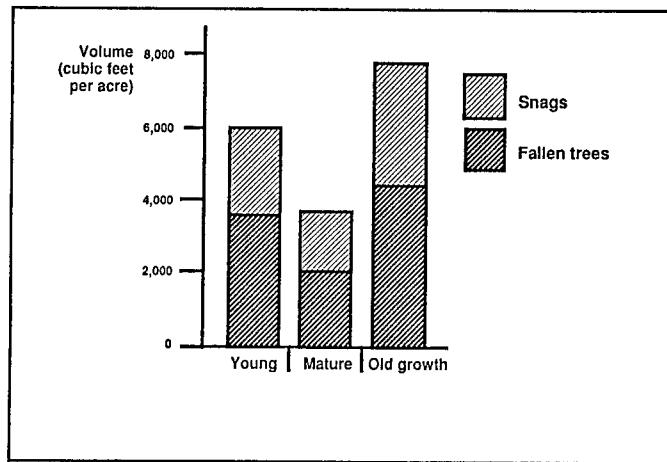


Figure 1.12—Mean volume of total coarse woody debris in young, mature, and old-growth Douglas-fir stands in western Oregon and Washington; adapted from Spies and others (in press).

In Douglas-fir forests of western Oregon and western Washington, the volume and biomass of woody debris in old-growth stands average about 7,175 cubic feet and 55 tons per acre, more than twice that of mature stands (figs. 1.11 and 1.12) (Spies and others, in press). The volume and biomass in many old-growth stands exceed 10,000 cubic feet and 76 tons per acre, and maximum values approach 24,300 cubic feet and 178 tons per acre. Young stands have intermediate levels of woody debris (figs. 1.11 and 1.12), whereas mature stands have the lowest volumes and biomasses.

Spatial distribution.--Coarse woody debris is unevenly distributed on the forest. The amount may vary tenfold between closely adjacent areas, and more than half the coarse woody debris may fall on less than one-fifth of the total area (Spies, unpublished data). Several factors contribute to such patchy distribution. The large successional overstory trees that contribute heavily to the dead wood supply are irregularly distributed. Mortality from natural causes is often patchy. Dead wood may be moved downslope to accumulate at a resting place on concave topography. In many old-growth stands, highly decayed wood is more evenly distributed than material of an intermediate decay level, although the opposite may be true in some young-growth stands because fires burn unevenly.

Stands on dry sites have less coarse woody debris than those of the same age on moist sites. In the east-central Coast Range, the amount of coarse woody debris in stands less than 150 years old is correlated with slope, aspect, and topographic position (Spies and others, in press). These relations may reflect differences in productivity between sites and in the frequency and severity of wildfire as it is affected by topography and dampness of sites.

Many mature stands on the west slope of the Coast Range have much more coarse woody debris than do mature stands on the east slope. High amounts of coarse woody debris in young and mature stands may result from cool-burning wildfires that kill only portions of the original old-growth stands in scattered patches, leaving many large snags and surviving old-growth trees. Large accumulations of coarse woody debris in the subsequent stand result from mortality of remnant old-growth trees, some of which were weakened by the fire.

Distribution of Coarse Woody Debris by Decay Class

Physical changes in snags and fallen trees have been arranged into five decay classes, based on readily observed physical characteristics (Cline and others 1980, Fogel and others 1973) (table 1.1). The distribution of total coarse woody debris biomass in these five decay classes varies with stand age (fig. 1.13). In the average young stand in the region, the highest biomass occurs in decay class IV. In mature and old-growth stands, the greatest proportion of woody debris often occurs in decay class III. The proportion of total biomass in highly decayed material (decay classes IV and V) generally decreases with stand age. Material from decay classes IV and V accounts for 57 percent of the total biomass in young stands but only 26 percent of the total biomass in old-growth stands. Across all age classes, however, differences in the absolute amounts of highly decayed material are relatively small. The relative differences among the age classes typically are least for decay class V and greatest for decay class III; the higher decay classes are a relatively more stable, slowly changing component of the dead wood in the system.

Table 1.1—A 5-class system of decay based on fallen Douglas-fir trees^a

Characteristics of fallen trees	Decay class				
	I	II	III	IV	V
Bark	Intact	Intact	Trace	Absent	Absent
Twigs, 1.18 inches	Present	Absent	Absent	Absent	Absent
Texture	Intact	Intact to partly soft	Hard, large pieces	Small, soft blocky pieces	Soft and powdery
Shape	Round	Round	Round	Round to oval	Oval
Color of wood	Original color	Original color	Original color to faded	Light brown to reddish brown	Red brown to dark brown
Portion of tree on ground	Tree elevated on support points	Tree elevated on support points but sagging slightly	Tree is sagging near ground	All of tree on ground	All of tree on ground
Invading roots	None	None	In sapwood	In heartwood	In heartwood

^a Adapted from Maser and others (1979).

The ratio of woody debris in fallen trees to woody debris in snags increases as decay increases. Fallen trees constitute 32 percent of the woody debris in decay classes I and II and 71 percent in decay classes IV and V; most dead standing trees decay partially before falling. In the Coast Range, fallen trees constitute 42 percent of the material in decay classes I and II, a higher value than the regional estimate, perhaps because of the greater incidence of wind-related mortality in the Coast Range.

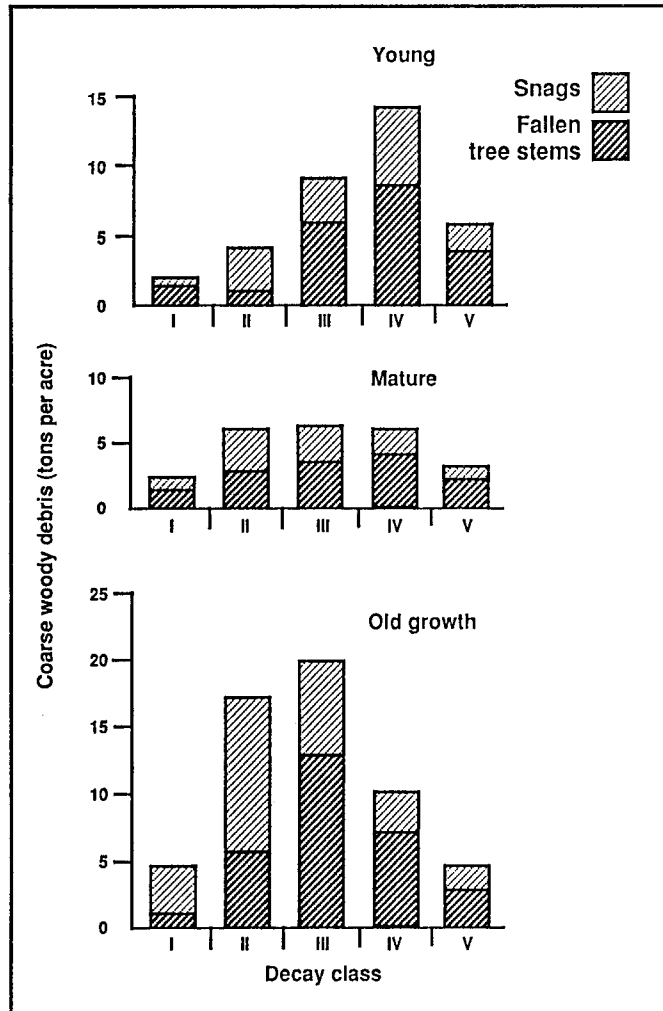


Figure 1.13—Distribution of mean total coarse woody debris by decay class in young, mature, and old-growth Douglas-fir stands in western Oregon and Washington; adapted from Spies and others (in press).

Carryover Woody Debris

Carryover woody debris is the coarse woody debris in a current stand that was laid down in the previous stand, often old-growth. Young stands with large amounts of coarse woody debris inherited it from the previous stand. Those that have small amounts are mostly in the south and east Coast Range where multiple wildfires in the past 150 years consumed much of the coarse woody debris.

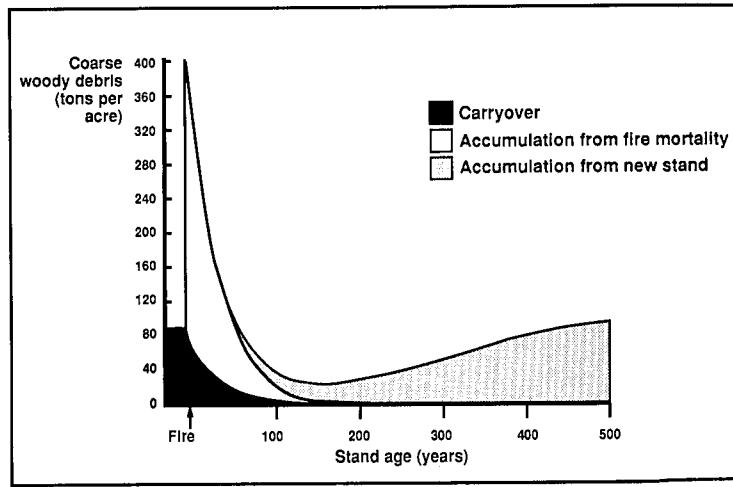


Figure 1.14—Predicted changes in coarse woody debris after a catastrophic fire in a 450-year-old Douglas-fir—western hemlock forest; adapted from Spies and others (in press).

Cycles of Woody Debris Accumulation

Several patterns of accumulation of woody debris occurred in the past. A simple scenario would be a major disturbance killing an old-growth Douglas-fir stand and a new stand becoming established and growing for hundreds of years before a major disturbance (fig. 1.14). At stand age 500 years, about 80 tons/acre of coarse woody debris is present. Then a major stand-replacing fire occurs, consuming some woody debris, although about 67 tons/acre remains. Large amounts of new coarse woody debris are added by the fire, which destroys few large live stems. This sudden injection of dead wood adds 180 to 450 tons/acre. A new Douglas-fir stand is established soon after the fire. A period of 30 to 40 years passes before the canopy closes and mortality adds more coarse woody debris to the site. Decay reduces coarse woody debris by more than 50 percent during this time, but amounts are still high because of large input after the fire. By age 100, the accumulation of coarse woody debris is at a low point because almost all the coarse woody debris present immediately after the disturbance is now gone, and additions of new dead wood from the developing stand are less than losses from decomposition. At this point, more than 50 percent of the coarse woody debris is inherited from the previous stand.

After age 100, coarse woody debris increases gradually as a result of mortality of the canopy trees. As canopy tree size increases, coarse woody debris also increases and probably peaks somewhere between 400 and 600 years. New woody debris comes increasingly from the death of western hemlocks at about age 500. The standing crop of woody debris decreases gradually toward a lower equilibrium, after 1,000 years, when Douglas-fir passes from the stand. The last Douglas-fir dies at age 1,200 years, and evidence of it can still be found 300 or more years later.

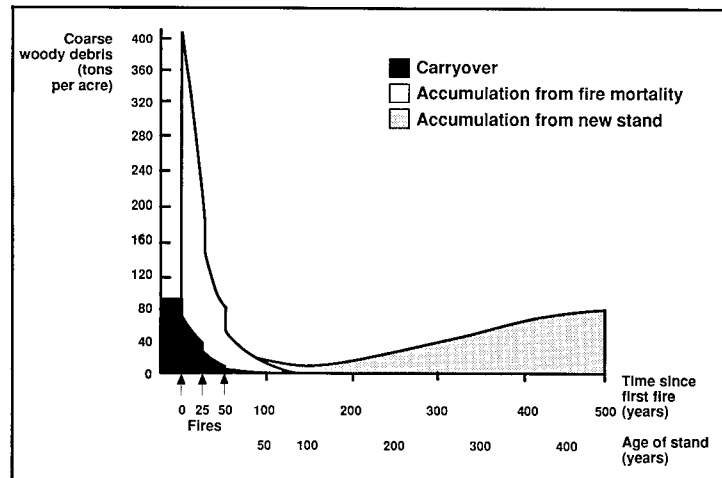


Figure 1.15—Predicted changes in coarse woody debris after a catastrophic fire in a 450-year-old Douglas-fir—western hemlock forest and two fires 25 and 50 years later; adapted from Spies and others (in press).

The scenario above is probably not the most common because disturbances, such as fire, may recur several times, especially in the first 30 to 50 years of a new stand when fine fuel levels are high. Multiple fires would consume more woody debris and live biomass over time than a single fire and would reduce the amount of woody debris for 200 to 300 years (fig. 1.15). Multiple fires would delay the addition of new material and prolong the period of low accumulation, which would reduce the minimum accumulation.

The Intensively Managed Plantation

Effect of Plantation Management on Coarse Woody Debris

Thus far, we have discussed the unmanaged forest, which is rapidly being replaced by plantations in which various phases of biological development are controlled to produce maximum wood fiber in the shortest time. Plantation establishment decides species distribution and initial tree density. Periodic mechanical thinning and removal of logs replaces the self-thinning of unmanaged stands that provided coarse woody debris from dead stems. In the plantation, production of coarse woody debris is minimized, and uniformity—rather than diversity—is fostered.

Most plantations in the Douglas-fir region are established after an old forest has been clearcut. The first step in plantation establishment is to reduce the coarse woody debris accumulated before and during logging. Coarse woody debris is reduced most often for three reasons: to increase use of woody debris, to clear sites for tree planting, and to reduce fire risk.

Wood utilization standards assume that any piece of dead wood that has sufficient strength to withstand yarding is usable (Howard 1981). At least 14 variables may influence the amount of coarse woody debris that remains after logging (Howard 1978):

1. Stand age
2. Gross cruise volume per acre
3. Percentage of stand defect
4. Average slope percent
5. Size of clearcut
6. Average stand diameter
7. Percentage of exportable volume
8. Estimated distance to nearest processing center
9. Estimated hauling distance on secondary roads
10. Percentage of whitewoods in stand
11. Percentage of western redcedar
12. Appraised stumpage value
13. Current utility lumber price index
14. Current general lumber price index

Unusable material is often yarded into piles close to roads. Much of the heavily decayed material is broken into fine organic matter. Most logged areas then are broadcast burned to remove remaining coarse woody debris and finer woody material for easier tree planting. Such fire consumes fine fuels—limbs, branches, and litter.

To help us understand the effects of intensive removal of coarse woody debris, we used a model to simulate the dynamics of coarse woody debris in Douglas-fir plantations (fig. 1.16). The model represents a Douglas-fir stand established naturally on site II land. The stand was precommercially thinned to 300 trees/acre at age 11 years; commercially thinned at ages 31, 40, 53, 68, and 83; and harvested at age 100 (table 10C in Curtis and others 1982). We assumed that this stand became naturally established after an old-growth Douglas-fir stand was clearcut. The stand had a harvest volume of about 100,000 board feet per acre and a coarse woody debris volume of 10,000-11,400 cubic feet/acre (80-89 tons/acre) (Spies and others, in press). In this example, the minimum diameter of woody debris is 3 to 4 inches, depending on data source. The rate of disappearance of coarse wood was assumed to be 3 percent per year (Graham 1982; Sollins 1982; Sollins and Cline 1987; Spies and others, in press).

The model assumes that 80 tons/acre of coarse woody debris are on the site before logging. By the end of the first 100 years of the plantation, only 20 tons/acre remain and only 4 of the original 80 tons are still on the site. New coarse woody debris would be added as logging slash (62 percent) and dead trees (38 percent) at a rate of about 0.4 ton/acre between age 30 and final harvest (fig. 1.16).

During a second 100-year rotation of the simulated, manipulated forest, total coarse woody debris decreased from 24 tons/acre at the beginning of the rotation to only 5 tons at the end of 100 years, before harvest.

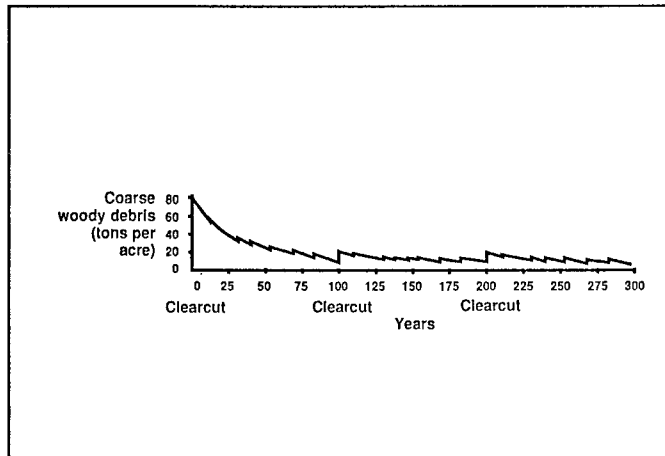


Figure 1.16—Predicted changes in coarse woody debris in three rotations of an intensively managed forest after clearcutting of a 450-year-old Douglas-fir—western hemlock stand. The small peaks represent accumulations of coarse woody debris after thinnings. The peaks also include natural mortality that occurred between thinnings.

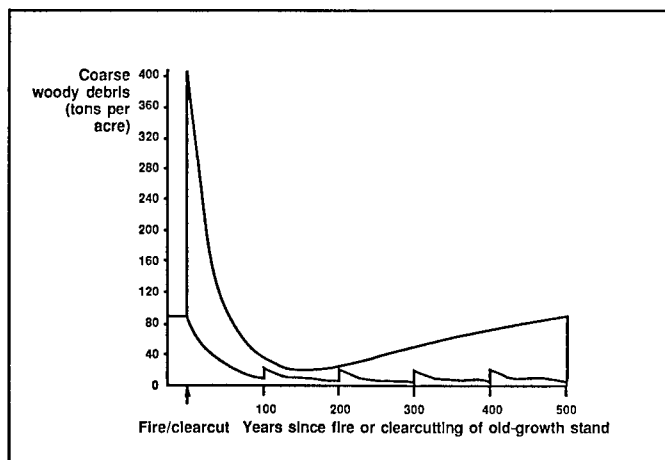


Figure 1.17—Comparison of predicted changes in coarse woody debris during 500 years of natural Douglas-fir forest development and five rotations of an intensively managed Douglas-fir forest.

We have compared coarse wood loadings during the life of a 500-year-old forest with five 100-year plantation rotations (fig. 1.17). Several major differences between coarse woody debris in a forest and in plantations occur over the five centuries. At least six times more wood carries over after wildfire in old growth than would have carried over after logging in an old-growth stand. The carryover coarse woody debris after wildfire is abundant the next 90 to 100 years. On the plantation, more than 8,500 cubic feet/acre of the large wood that would have carried over is removed as

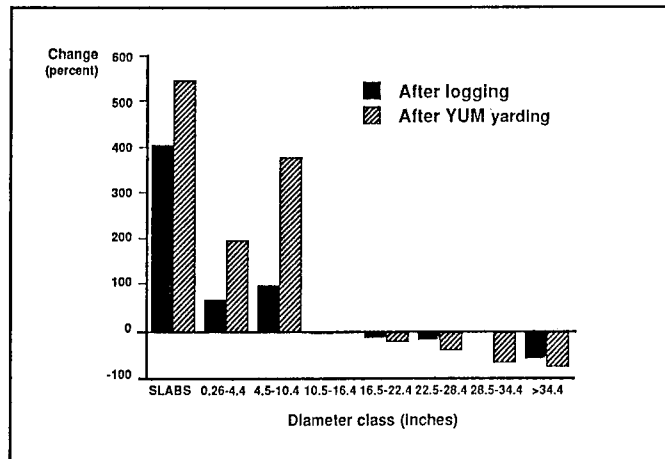


Figure 1.18—Relative change in percentage of volume of woody residue by size class after logging and yarding unmerchantable material (YUM) in two Douglas-fir stands in western Oregon (after Pong and Henley 1978).

a product. Coarse woody debris cannot accumulate to levels reached by the 500-year-old forest if 100-year rotations are the maximum prescribed. Coarse woody debris follows a variable pattern during formation of the 500-year-old forest. After decreasing from a maximum after wildfire to a minimum at 100-150 years, coarse woody debris accumulations begin to increase as large trees die.

A second difference between the forest and plantations lies in the size of the trees and their wood quality. The short-rotation plantation produces smaller diameter trees that disappear more rapidly than large trees because they decay faster.

The size of wood left after disturbances differs greatly between forests and plantations. In the forest, disturbances leave large pieces of coarse woody debris. In the plantation, clearcutting leaves relatively small material—branches and small-diameter tops (figs. 1.18 and 1.19). Inherited coarse woody debris, especially class IV and V material, is broken up during harvest.

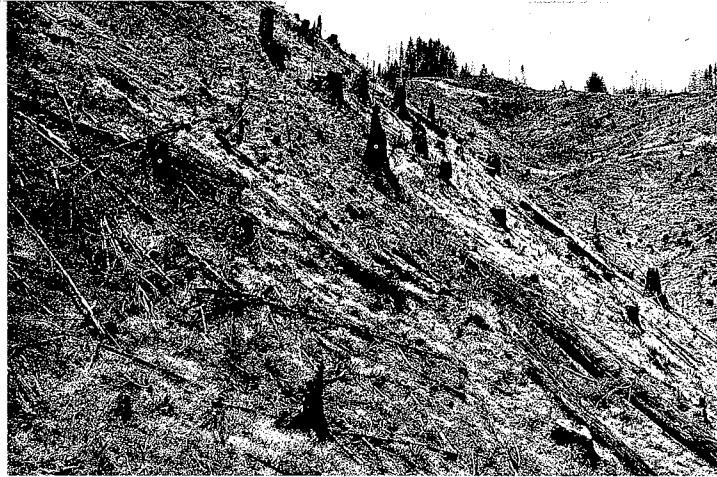


Figure 1.19—Clearcut 2 years after harvest showing low carryover of coarse woody debris.



Figure 1.20—Size and pattern of forest "disturbances" in a managed landscape.

A final difference in coarse wood dynamics between forests and plantations is in the input rate during stand development. In the forest, self thinning and other mortality proceeds uninhibited and woody debris accumulates. In a plantation, loss of trees is substantially slower, and the trees that do die are harvested.

Short-rotation plantations greatly reduce coarse woody debris, which changes the functional characteristics of the ecosystem. Drastically reduced accumulations of coarse woody debris could seriously impair the function of plantations as vertebrate habitat and might reduce productivity (Bartels and others 1985, Maser and Trappe 1984b, Neitro and others 1985). In the intensively managed landscape, no more periodic large inputs of coarse woody debris is expected; and the size, severity, and pattern of the disturbances will vary less (fig. 1.20). Ecological diversity will be greatly reduced.

The intensively managed landscape differs from the unmanaged landscape in how it changes with time. The levels of coarse woody debris in the managed landscape will change little. In the unmanaged landscape, irregularity in the frequency of past disturbances ensures that, during a several-hundred-year period, a given site will experience periods of both very high and relatively low accumulations of woody debris. These periodic large inputs, which help maintain soil organic matter and site productivity, are not planned for plantations in which many rotations may pass without large inputs of woody debris.



Figure 1.1—Mosaic of stands created by wildfire, showing patches of snags and trees that survived the fire.



Figure 1.6—Young stand with moderate accumulations of coarse woody debris.



Figure 1.7—Mature stand with low accumulations of coarse woody debris.



Figure 1.8—Old-growth stand with large accumulations of coarse woody debris.



Chapter 2. What We Know About Large Trees That Fall to the Forest Floor

Chris Maser, Steven P. Cline, Kermit Cromack, Jr.,
James M. Trappe, and Everett Hansen

Summary

This chapter explains how living and dead trees are linked together in the living machinery of a forest.

Introduction

Pacific Northwest forests contain an array of fallen trees in various stages of decay, both in young and old-growth stands, in natural, managed, and recently clearcut stands. Most trees of Douglas-fir region forests are conifers, of which there are six major lowland species north of the Siskiyou Mountains (table 2.1). In total, these temperate forests contain 25 conifer species, many of which are the largest and longest lived of their genera (Waring and Franklin 1979). Large, fallen trees are unique, critical components of forest systems (Franklin and Hemstrom 1981, Franklin and others 1981, Maser and others 1979).

Future forests will contain much less coarse woody debris (CWD), and that debris will be smaller and of different quality than that seen today. We have the technology to remove most coarse woody debris from the forest; in fact, current wood utilization standards encourage such removal (fig. 2.1). Moreover, converting natural forests to intensively manipulated stands reduces tree lifespans from centuries to decades; future trees will be much smaller than they are today, and wood quality will undoubtedly be different from that of today's forests.

Individual trees have different characteristics that produce diversity within the forest. Trees can live for hundreds or even thousands of years because they produce new functional tissues every year, but most die much earlier from injury, disease, or both.

The cause of death (table 2.2) determines diversity of the structural and functional roles served by the dead tree in its tenure on the forest floor. When a tree dies and remains standing as a snag, this new, different structural and functional unit adds diversity to the system, diversity important to many forest organisms (fig. 2.2; tables 2.3, 2.4, 2.5). When a snag or a green tree falls to the forest floor, diversity again is added (figs. 2.1, 2.3, 2.4; tables 2.6, 2.7).

Table 2.1—Typical and maximum ages and diameter at breast height attained by 6 species of coniferous trees on fertile soils in forests of the Pacific Northwest^a

Species	Typical			Maximum	
	Age	Diameter	Height	Age	Diameter
	<i>Years</i>	<i>Inches</i>	<i>Feet</i>	<i>Years</i>	<i>Inches</i>
Overstory trees:					
Douglas-fir	>750	60 to 88	228 to 260	1,200	174
Grand fir	>190	36 to 48	163 to 195	—	72
Western hemlock	>400	36 to 48	163 to 211	>500	104
Siika spruce	>500	72 to 92	228 to 244	>750	210
Western redcedar	>1,000	60 to 120	>195	>1,200	252
Understory trees:					
Pacific yew	>90	6 to 12	20 to 40	425	18 to 30

^a Adapted from Peattie (1953), Sudworth (1967), and Waring and Franklin (1979).



Figure 2.1—A clearcut on Marys Peak in which most of the large woody debris has been removed. Note how small the remaining pieces are.

Table 2.2—Some causes of death and the type of dead tree produced

Cause of death	Type of dead tree			
	Standing		Fallen	
	Whole	Piece(s)	Whole	Piece(s)
Physical damage:				
Ice, snow		●	●	●
Lightning	●	●		●
Wind—				
Stem breakage		●		●
Uprooting			●	
Falling trees—				
Stem breakage		●		●
Uprooting			●	
Injuries to bark, by vertebrates		●		
Fire	●			
Insects:				
Bark beetles	●			
Defoliators	●			
Diseases:				
Rots and cankers—				
Of stem	●			
Of base and roots	●		●	
Mistletoe, foliage	●			
Suppression and competition	●			

Sources: Aho (1966, 1982); Bull and others (1980); Crouch (1969); Etheridge (1973); Hadfield (1985); Hawksworth and Wiens (1972); Houston (1981); Johnson and others (1964); Koonce and Roth (1980); Krebill (1968); Leaphart (1959); Maser (1967); Neff (1928); Poelker and Hartwell (1973); Roth (1970); Ruth and Yoder (1953); Sanders (1964); Schowalter (1985); Shigo (1973, 1979); Shigo and Marx (1977); Shortle (1979); Wargo (1984); Wright and Harvey (1967).



Figure 2.2—Snags are important structural components of the forested landscape.

Table 2.3—Physical characteristics of Douglas-fir snags by deterioration stage, western Oregon^a

Item	Stage of deterioration				
	1	2	3	4	5 ^b
Snag characteristic:^c					
Limbs and branches	All present	Few limbs, no fine branches	Only limb stubs	Few or no stubs	None
Top	Pointed	Broken			
Diameter, broken top	Increases at decreasing rate				
Height	Decreases at decreasing rate				
Bark remaining (percent)	100	Varies	Varies	Varies	>20
Sapwood:					
Presence	Intact	Sloughs	Sloughs	Sloughs	Gone
Condition	Sound, incipient decay, hard, original color	Advanced decay, fibrous, firm to soft, light brown	Fibrous, soft, light to reddish brown	Cubical, soft, reddish to dark brown	
Heartwood condition	Sound, hard, original color	Sound at base, incipient decay in outer edge of upper stem, hard, light to reddish brown	Incipient decay at base, advanced decay throughout upper stem, fibrous, hard to firm, reddish brown	Advanced decay at base, sloughing from upper stem, fibrous, or cubical, soft, dark reddish brown	Sloughing, cubical, soft, dark brown, or fibrous, very soft, dark reddish brown, encased in hardened shell
Estimated age at which snags reach a given stage of deterioration:					
4-18 inches in d.b.h. ^d	0-4 years	5-8 years	9-17 years	>17 years	Fallen
8-19 inches in d.b.h. ^e	0-5 years	6-13 years	14-29 years	30-60 years	>60 years
>19 inches in d.b.h. ^f	0-6 years	7-18 years	19-50 years	51-125 years	>125 years

^a Adapted from Cline and others (1980).

^b Mostly remnant snags.

^c Characteristics of a snag at each of the 5 stages of deterioration.

^d Characteristic in Douglas-fir forests <80 years old; mean d.b.h. 5 ± 1 (SE) inch.

^e Characteristic in Douglas-fir forests 80-200 years old; mean d.b.h. 13 ± 3 inches.

^f Characteristic in Douglas-fir forests >200 years old; mean d.b.h. 39 ± 16 inches.

Table 2.4—Some uses of snags by selected wildlife species^a

Use	Pileated woodpecker	Red-breasted sapsucker	Acorn woodpecker	Turkey vulture	Owls and raptors	Osprey	Bald eagle	Flycatchers	Brown creeper	Bats	Raccoon and black bear	Small mammals	Source
Cavity nest sites	●	●	●		●					●	●	●	Bull 1978, Gale 1973, Jackman 1974a, Maser and others 1981
Nesting platforms						●	●						Miller and Miller 1980, Zarn 1974
Feeding substrate	●	●	●						●				Bull 1978, Evans and Conner 1979, Raphael and White 1976, White and Raphael 1975
Plucking posts					●								Miller and Miller 1980
Singing or drumming (communication)	●	●	●										Bull 1975, Jackman 1974b, Rushmore 1973
Food cache or granary			●									●	Balgooyen 1976, Scott and others 1980, Swearingen 1977
Location of courtship	●	●	●										Jackman 1974b, Jackson 1976, Kilham 1979
Overwintering sites	●		●		●					●	●	●	Bent 1964, McClelland 1979
Roosting	●	●	●	●	●	●	●			●			Maser and others 1981, Scott and others 1980
Lookout posts				●	●	●	●	●					Miller and Miller 1980

See footnote at end of table.

Table 2.4—Some uses of snags by selected wildlife species (continued)^a

Use	Pileated woodpecker	Red-breasted sapsucker	Acorn woodpecker	Turkey vulture	Owls and raptors	Osprey	Bald eagle	Flycatchers	Brown creeper	Bats	Raccoon and black bear	Small mammals	Source
Hunting and hawking perch					●	●	●	●					Gale 1973, Scott and others 1980, White and Raphael 1975
Fledging site						●	●						White and Raphael 1975
Dwelling or dens										●	●	●	Maser and others 1981, Scott and others 1980, Thomas and others 1979
Loafing sites				●		●	●						Scott and others 1980
Nesting under bark									●	●		●	Harrison 1978, Maser and others 1981, Miller and Miller 1980, Scott and others 1980
Communal nesting or nursery colonies			●							●			Bull 1978, Jackman 1974b, Maser and others 1981, Scott and others 1980
Anvil sites			●							●			Miller and Miller 1980, Swearingen 1977
Thermally regulated nests	●	●	●		●					●	●	●	Beebe 1974, Conner 1979, Maser and others 1981, McComb and Noble 1981

^a Adapted from Neitro and others (1985).

Table 2.5—Snag diameters and decay stages most often used for cavity nesting by woodpeckers^a

Species	Snag d.b.h., with bark	Decay stages ^b	
		Hard 2-3	Soft 4-5 ^c
	<i>Inches</i>		
Downy woodpecker	11+		● ^d
Hairy woodpecker	15+		● ^d
Red-breasted sapsucker	15+	●	
Acorn woodpecker	17+	●	
Lewis woodpecker	17+		●
Northern flicker	17+		●
Pileated woodpecker	25+	● ^e	

^a Adapted from Mannan and others (1980), Neitro and others (1985), Raphael and White (1984).

^b From Cline and others (1980).

^c Stage 5 snags, except those with a hard outer casing, are too decomposed to be used for nesting by most primary excavators.

^d May also use decay stages 2-3.

^e Also use hard snags of decay stage 1.



Figure 2.3—Fallen trees add a critical dimension of diversity to the forest floor. The man is 6 feet 7 inches tall.

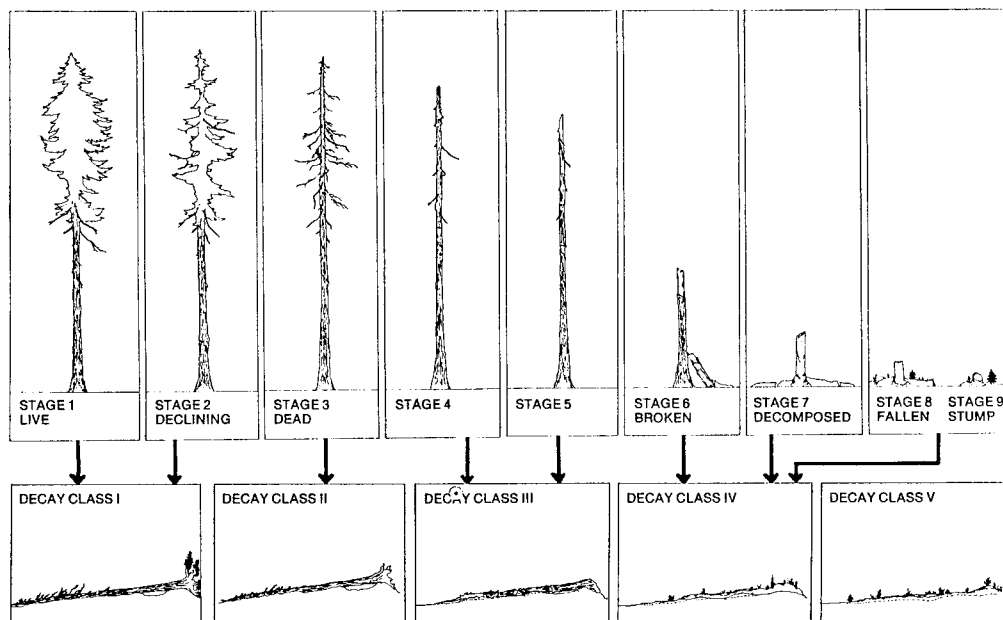


Figure 2.4—When they fall, trees and snags immediately enter one of the first four decay classes (modified from Maser and others 1979).

Table 2.6—A 5-class system of decay based on fallen Douglas-fir trees^a

Characteristics of fallen trees	Decay class				
	I	II	III	IV	V
Bark	Intact	Intact	Trace	Absent	Absent
Twigs, 1.18 inches	Present	Absent	Absent	Absent	Absent
Texture	Intact	Intact to partly soft	Hard, large pieces	Small, soft blocky pieces	Soft and powdery
Shape	Round	Round	Round	Round to oval	Oval
Color of wood	Original color	Original color	Original color to faded	Light brown to reddish brown	Red brown to dark brown
Portion of tree on ground	Tree elevated on support points	Tree elevated on support points but sagging slightly	Tree sagging near ground	All of tree on ground	All of tree on ground
Invading roots	None	None	In sapwood	In heartwood	In heartwood

^a Adapted from Maser and others (1979).

Table 2.7—Stage and condition of snag by decay class of fallen tree,^a and fallen trees by decay class in an old-growth Douglas-fir stand^b

Snag stage and condition	Decay class of fallen trees	Number of fallen trees per acre
1-3, hard snag	I	11
4-5, hard snag	II	6
5-6, soft snag	III	13
7, soft snag, 70+ percent soft sapwood	IV	16
Fallen snag	V	75
Total		121

^a Adapted from Maser and others (1979).

^b Adapted from MacMillan and others (1977).

Forest Floor Diversity

The forest floor is the interface between the belowground and the aboveground components of the forest. As a center of intense physical, chemical, and biotic activity, it both influences and reflects ecosystem functions. In turn, ecosystem functions reflect the array and quality of processes resulting from structural diversity.

Physical Diversity

When a tree falls—be it a wind-uprooted, healthy tree or a decomposing snag—a sequence of ecological consequences begins. The fall of understory trees, usually western hemlock or western redcedar, is caused by wind being funneled below the overstory canopy. Falling of understory trees does not visibly affect the overstory canopy, but additional light is admitted to the forest floor. The falling of an overstory Douglas-fir, however, creates an evident canopy opening in which shade-tolerant understory trees will be released to grow.

The opening increases considerably if the falling tree causes successive uprooting and breaking of neighboring trees. The probability of a tree causing such a domino effect when it falls increases with its size and vigor. A large, healthy tree is more likely to fell the trees it strikes than is a decayed snag, which is more likely to break or shatter. A large snag falling in a young stand is more likely to knock over a smaller live tree than is one falling in a mature or old-growth stand.

The effect on canopy space is less dramatic when a tree dies standing and becomes a snag. The snag occupies space and casts shade that affects the understory vegetation. Over time, however, the snag deteriorates, its effect changing as decomposition advances and pieces slough off.

Fallen trees create opportunities for new plants to become established. An old-growth Douglas-fir may be uprooted or may break off at or above the ground, depending on its health (*fig. 2.5, color*). Trees that break near the ground are infected with butt or stem rots. The roots and stump decompose in place, leaving understory vegetation intact and creating few new sites for establishment of vegetation. A tree with root rot may be uprooted, but the roots break off instead of being pulled from the soil.

In contrast, when roots of a healthy tree are pulled out of the ground when it falls, bare soil is exposed as an extensive root-pit and mound (*fig. 2.6, color*). The bare mineral soil of a root-pit and mound—and with time the fallen tree itself—presents habitats readily colonized by tree seedlings and other plants (Christy and others 1982).

The surface of a forest floor is roughened by fallen tree stems, their uprooted butts, and the pits and mounds left after the uprooting (*fig. 2.7, color*). Living trees roughen the surface of the forest floor by sending roots outward along slopes, often near the litter layer. Tree stems also affect the surface by sloughing bark, which arrests soil creep at their bases. Of all the factors affecting surface microtopography, the pit-and-mound topography produced by uprooting trees is best known (Beatty 1984, Bratton 1976). Topography is a major influence in creating and maintaining species richness of the herbaceous understory (Bratton 1976, Thompson 1980) and on the success of tree regeneration (Henry and Swan 1974). Pit-and-mound topography is common in all types of forests and is a major cause of soil mixing (Stephens 1956).

Live tree roots increase soil shear strength; as dead roots decompose, soil strength declines. For this reason, mass soil movement on slopes increases after clearcutting (Burroughs and Thomas 1977, O'Loughlin 1974, Ziemer 1981).

As tree stumps and roots decompose, they often form interconnected, surface-to-bedrock channels that rapidly drain excess water (Beasley 1976, de Vries and Chow 1978, Gaiser 1952) (*fig. 2.8, color*). The collapse and plugging of these channels during latter stages of decomposition are believed to foster slope instability after logging by forcing more runoff to drain through the soil matrix, reducing soil cohesion and increasing hydraulic pressure (Chamberlin 1972).

Large, stable tree stems lying along slope contours reduce erosion by forming a barrier to downhill soil movement (*fig. 2.9, color*). Soil and forest floor materials deposited along the upslope side of a fallen tree reduce nutrient loss and form an excellent site for establishment and growth of vegetation.

Chemical Diversity

Fallen trees are a major source of soil organic material in Pacific Northwest forests. They also contain essential nutrients that are released during decomposition by micro-organisms and plants, fungi, and animals, such as termites (*fig. 2.10*), that derive nutrients from the micro-organisms. The decomposer community is adapted to the relatively low nutrient concentrations in wood; wood-decomposing fungi can survive and function at nitrogen concentrations about one-third those usually found in undecomposed wood (Cowling and Merrill 1966).

The five decay classes (*table 2.6*) of fallen trees have different concentrations of nutrients—the higher the decay class, the higher the nutrient concentration (*tables 2.8 and 2.9*). As carbon compounds in wood decay to carbon dioxide, water, and residual compounds, their nutrient contents, such as nitrogen, are released from the wood matrix. Micro-organisms and the larger creatures that decompose the wood for energy and structure concentrate these nutrients in their tissues as they metabolize the carbon compounds.

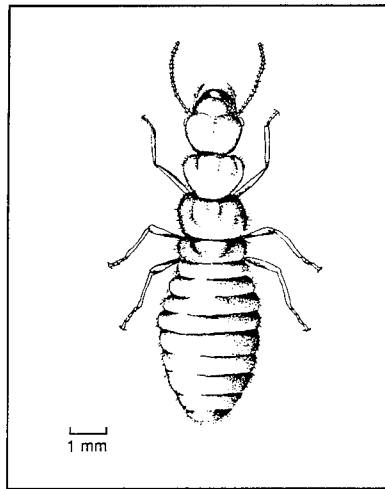


Figure 2.10—A Pacific dampwood termite worker. A termite can digest the wood it eats because of a mutually beneficial, three-way relation between the individual termite, cellulose-digesting protozoa, and nitrogen-fixing bacteria that live in its gut. The protozoa digest the cellulose in the wood and convert it to a form that the termite can use as food. In turn, the termite's body provides an anaerobic chamber that is replete with food for the protozoa. Wood particles eaten by the termite pass into the chamber and are engulfed by the protozoa, which in turn ferment the cellulose. Major products of fermentation are carbon dioxide, hydrogen, and acetic acid. The acetic acid is absorbed through the wall of the termite's hindgut and is oxidized as energy (Breznak 1975).

Nitrogen concentrations can increase severalfold during progressive stages of decay (table 2.8), in part because of biological nitrogen fixation by free-living bacteria in the wood (Silvester and others 1982). Absolute gains or losses of nitrogen or other elements depend on the balance between nutrient inputs and losses during decay. Nutrients that are conserved by plants and animals during decomposition include nitrogen, calcium, magnesium, and sodium. Others, such as potassium, usually are leached and recycled (Grier 1978, Yavitt and Fahey 1982).

Fallen trees are a substantial reservoir of soil organic matter in old-growth Douglas-fir forests (table 2.10). In two Douglas-fir forests, the organic matter from all decay classes of fallen trees older than 500 years represented about 30 percent of the total soil organic matter (Means, Cromack, and MacMillan, unpublished data). Nutrients are less concentrated in fallen trees in all decay classes than in leaf, twig, and root components of the forest floor (table 2.9). Because of the great amount of large wood in an old-growth Douglas-fir forest, however, the total amount of nutrients in fallen tree stems is still important (table 2.10). The proportion of the total soil organic matter contributed by fallen trees can be nearly fourfold greater than that of the other forest floor materials (table 2.10). Litter components take 10-50 years to decompose (Fogel and Cromack 1977), whereas fallen trees take as long as several centuries (Means and others 1985). Thus, the nutrient pool of a fallen tree cycles on a much longer time scale than that of the rest of the forest floor.

The forest floor and its decaying wood receive nutrients from throughfall (rain, snow, or dew that picks up nutrients as it falls through the canopy) (fig. 2.11). If fallen trees occupy, say, 10 percent of the ground surface in an old-growth Douglas-fir forest, and if they remain in place for 100 years, they potentially could accumulate nutrients equivalent to 10 times the nutrients carried in the average yearly throughfall (table 2.11).

Table 2.8—Representative data for decay classes, nitrogen, carbon, and C:N ratios of decaying fallen trees in western coniferous forests

Ecosystem and tree species	Decay class	N	C	C:N
<i>Percent</i>				
H.J. Andrews Experimental Forest, ^a old-growth Douglas-fir	I	0.08	52	655
	II	.09	53	615
	III	.10	54	534
	IV	.13	55	411
	V	.23	56	244
Sequoia National Park, ^b mixed conifers:				
	White fir			
	I	.10	49	488
	II	.13	50	384
	III	.17	49	287
	IV	.25	53	213
Jeffrey pine	I	.09	51	572
	II	.15	51	338
	III	.12	50	419
	IV	.36	52	144
Sugar pine	I	.11	50	457
	II	.19	54	282
	III	.22	52	234
	IV	.20	55	276
Olympic National Park: ^c Western hemlock	I	.10	50	500
	II	.14	50	357
	III	.11	50	454
	IV	.26	50	200
Sitka spruce	I	.08	50	625
	II	.08	50	625
	III	.10	50	500
	IV	.23	52	217

^a Sollins and others (1980).

^b Harmon and others, in press.

^c Graham and Cromack (1982).

Table 2.9—Nutrient concentrations in the forest floor and in fallen trees in an old-growth Douglas-fir forest on the H.J. Andrews Experimental Forest in the western Cascade Range in Oregon^a

Component	N	P	K	Ca	Mg	Na
	<i>Percent</i>					
Total forest floor	0.50	0.098	0.11	0.87	0.26	0.014
Fallen tree stems ^b	.10	.0031	.0111	.076	.0076	.0024

^a The forest is a site class III, and elevation ranges from 1,400 to 2,080 feet. The data are from Sollins and others (1980).

^b Weighted average concentration of fallen tree decay classes II-IV.

Table 2.10—Mass and nutrient content of the forest floor and fallen trees in an old-growth Douglas-fir forest on the H.J. Andrews Experimental Forest in the western Cascade Range in Oregon^a

Component	Organic matter	N	P	K	Ca	Mg	Na
	<i>Pounds per acre</i>						
Total forest floor	45,568	228	44.7	50.1	396.4	118.5	6.4
Fallen tree stems	191,350	191	6.0	21.3	145.4	14.5	4.7

^a The forest is a site class III, and elevation ranges from 1,400 to 2,080 feet. The data are from Sollins and others (1980).

Decomposition of fallen trees is aided by a variety of micro- and meso-organisms that live in, on, or near them (Elton 1966, Harmon and others 1986). Potential thus exists for considerable uptake, utilization, and export of nutrients from fallen trees during decomposition. Substantial cycling of nutrients occurs, for example, in decayed, fallen lodgepole pine (Yavitt and Fahey 1985), especially after snowmelt. Decomposition of fallen trees releases nutrients for microbial and plant growth (Yavitt and Fahey 1985). Fruiting bodies of hypogeous mycorrhizal fungi produced in association with tree roots in rotten wood provide nutrients and energy to insects, mollusks, and mammals (Maser and others 1979).

Woody litter, regardless of type or size, takes considerably longer to decompose than does needle and leaf litter (table 2.12). Needles, leaves, and small twigs decompose faster than larger woody material and nutrients are thereby recycled faster in the forest floor. About 140 years are needed for nutrients to cycle in large, fallen trees and more than 400 years for such trees to become incorporated into the forest floor; they therefore interact with the plants and animals of the forest floor and soil over a long period of forest and stand successional history (table 2.12). During this time, a variety of shrubs and trees, such as western hemlock and Sitka spruce, have the opportunity to develop part or all of their root systems within rotting wood (Harmon and others 1986).



Figure 2.11—Large fallen trees decay slowly and over time receive nutrients from such ecological processes as rain falling through a nutrient-rich canopy.

Table 2.11—Nutrient content of fallen trees compared with annual throughfall nutrient inputs in an old-growth Douglas-fir forest on the H.J. Andrews Experimental Forest in the western Cascade Range in Oregon^a

Component	N	P	K	Ca	Na
	<i>Pounds per acre</i>				
Total annual throughfall	4.9	1.2	12.5	6.7	5.9
Fallen tree nutrient content	191	6.0	21.3	145.4	4.7
Throughfall on fallen trees in 100 years	49	12	125	67	59

^a The forest is a site class III, and elevation ranges from 1,400 to 2,080 feet. The data are from Sollins and others (1980).

Release of nutrients, especially nitrogen, from forest litter is a function of the decomposition rates and the ability of micro-organisms to retain the nitrogen in their tissues (Mahendrappa and others 1986). Work of Bosatta and Staff (1982) suggests that, for slower decomposing substrates, such as wood, the rate of nitrogen release per unit of carbon mineralized increases as the decomposition rate decreases. Nitrogen concentration is an important variable in the regulation of decomposition, especially in the earlier stages of decay. Lignin is important in later decomposition because it affects the proportions of different residues that may be incorporated into humic materials (Berg 1986) (table 2.13).

Table 2.12—Annual rate of decomposition and time estimated for 95-percent decay of forest litter in the Pacific Northwest^a

Species and litter component	Location	Annual decomposition rate	Time for 95-percent decay
		<i>Percent</i>	<i>Years</i>
Douglas-fir:			
Needles	Oregon, Cascade Range	23.0	11
Small branches	Oregon, Cascade Range	8.5	34
Cones	Oregon, Cascade Range	6.5	45
Bark	Oregon, Cascade Range	3.4	86
Fallen trees	Oregon, Cascade Range	.7	429
Western hemlock, fallen trees	Coastal Washington	1.0	273
Sitka spruce, fallen trees	Coastal Washington	1.0	273

^a Decomposition data for needles, leaves, and small woody litter are taken from Fogel and Cromack (1977) and Edmonds (1980); decomposition data for fallen trees are from Graham and Cromack (1982) and Means and others (1985). The time for 95-percent decay is calculated from Olson (1963).

Table 2.13—Quality of Pacific Northwest forest litter components for carbon and nitrogen^a

Species and litter component	C	N	C:N	Lignin	Lignin:N
	<i>Percent</i>			<i>Percent</i>	
Douglas-fir:					
Needles	5	0.820	61	22	27
Small branches	49	.150	333	43	289
Cones	49	.240	208	44	184
Bark	56	.190	289	59	308
Fallen trees	50	.100	500	27	270
Western hemlock, fallen trees	50	.076	658	29	381
Sitka spruce, fallen trees	50	.098	510	27	275

^a Data on nitrogen and carbon are from Cromack and Monk (1975), Fogel and Cromack (1977), Graham and Cromack (1982), and Petersen (1984).

Woody litter components are generally higher in initial lignin than are nonwoody components (table 2.13); high lignin content results in formation of large quantities of humus in the latter stages of decay (Berg 1986; Berg and McClaugherty, in press; de Hann 1977). High concentrations of initial lignin and higher lignin-to-nitrogen ratios in woody substrates mean they decompose slowly (Melillo and others 1982).

Humus formation is important in regulating the incorporation of nitrogen into humic materials (Allison 1973, Broadbent 1970, Mahendrappa and others 1986, Russell 1973). Because of its high cation exchange capacity and slow decomposition, rotten wood can retain available mineral nitrogen from throughfall and decomposition as well as organic nitrogen compounds mineralized within the wood chemical matrix. Roots and mycorrhizae of plant species that colonize decaying wood use its available nitrogen.

Animals facilitate the process of microbial colonization of fallen trees by such activities as boring and tunneling (Elton 1966, Maser and Trappe 1984a). Ants and termites excavate 10-18 percent of the fallen trees, such as Jeffrey pine and sugar pine, in Sequoia National Park, California (Harmon and others, in press). Ants also extensively excavate decaying mountain hemlock near Waldo Lake, west-central Oregon Cascades (Cromack, unpubl. data). In addition to excavating, termites have internal nitrogen-fixing micro-organisms in their intestines (Breznak 1975, Elton 1966).

Nitrogen limits forest productivity in the Pacific Northwest, so it is important that decaying, fallen trees are sites of nitrogen fixation by free-living bacteria (Cornaby and Waide 1973, Silvester and others 1982). The rates of nitrogen fixation in decaying wood are relatively low compared with those of symbiotic nitrogen-fixing plants, such as red alder and snowbush (Binkley and others 1984, McNabb and Cromack 1983, Tarrant and Miller 1963, Youngberg and Wollum 1976). About 1 pound per acre per year of nitrogen is fixed in decaying wood (Sollins and others 1986). About half the volume of the annual input of nitrogen is in rainfall (Sollins and others 1980).

The long-term input by nitrogen fixation in decaying fallen trees and by canopy-inhabiting lichens maintains a positive balance of nitrogen in the ecosystem. Little nitrogen is lost through soil erosion and leaching in undisturbed forests, so additions through relatively small rates of nitrogen fixation and input from precipitation gradually accumulate to significant amounts. This positive balance permits periodic, large losses of nitrogen by fire and accelerated erosion to be more than recovered when added to large inputs of belowground nitrogen fixation from early successional, nodulated species, such as red alder and snowbush.

The net gains of nitrogen through time have led to substantial accretion of nitrogen and associated soil organic matter in many undisturbed forests of the Pacific Northwest. Nitrogen in these forests has accumulated from about 17,800 pounds/acre on highly productive sites to 2,670-4,450 pounds/acre on poor sites. Even forests low in nitrogen, such as a mountain hemlock forest growing on tephra deposited by the eruption of Mount Mazama about 6,700 years ago, has gained 1,335-1,602 pounds/acre of nitrogen in the absence of major nitrogen-fixing plants (Boone 1983). This gain may be due in part to the presence of coarse woody debris and some nitrogen-fixing lichens.

Classical agricultural soil theory suggests that nitrogen is available to plants only when the C:N ratio is less than about 25:1 (Russell 1973). Even in advanced decay, the C:N ratio in fallen trees remains consistently much higher than that of the forest floor. An important new hypothesis, however, suggests that nitrogen availability is controlled as much by the availability of easily decayed carbon substrates as by nitrogen concentration per se (McClaugherty and Berg, in press). Wood-rotting fungi can extract nitrogen from substrates with a C:N ratio of 1800:1 (table 2.8), nearly three times as much as sound wood of typical western conifer species. Mycorrhizal fungi, the major organs of nutrient uptake by the roots, also have decomposing capability (Durall, Todd, and Trappe, unpubl. data). Thus, decaying wood has long-term potential for contributing nitrogen for tree growth as residual lignin and humus are decomposed.

The new theory regarding nitrogen availability suggests that decomposing wood loses easily biodegradable carbon substrates faster than do other litter components, such as leaves (Berg 1986; McClaugherty and Berg, in press). Consequently, nitrogen from decaying wood becomes available for plant growth at the higher C:N ratios.

Wood appears to facilitate colonization by long-lived decomposer and mycorrhizal fungi that capture nutrients, such as nitrogen, within a chemical matrix that promotes nitrogen retention. A slow-release nitrogen system operates in coarse woody debris because nitrogen has the potential for becoming available for plant growth at higher C:N ratios than in typical agricultural residues (Berg 1986; McClaugherty and Berg, in press). Other beneficial properties of large, fallen trees in forests include high water-holding capacity and cation-exchange capacity (Means and others 1985, Sollins and others 1986), and habitat for micro-organisms, invertebrates, vertebrates, and higher plants (Maser and Trappe 1984a) (fig. 2.9).

Biotic Diversity

The manner in which a fallen tree comes to rest on the forest floor greatly influences subsequent diversity of both external and internal plant and animal habitats. The decomposing fallen tree provides a changing spectrum of habitats over many decades—even centuries. It provides diversity within a given successional stage and forms a physical-chemical link through the many successional stages of a forest.

Placement of fallen trees—how they lie on the landscape—determines the chain of events leading to diversity. The cause of tree death and characteristics of the site and its forest stand mainly determine the initial placement of a fallen tree (fig. 2.12). In the absence of human interference, the ultimate placement is determined by how it decomposes and becomes incorporated into the soil (Franklin and others 1981, Maser and Trappe 1984a).

A fallen tree performs various ecological functions between the time it falls and the time it is finally incorporated into the soil. If it lies up-and-down slope or falls across other downed trees, most of its volume is initially suspended above the ground. Such elevated relief adds complexity to the forest floor by creating cover and shade.



Figure 2.12—Diversity on the forest floor is created by the way trees fall; here a Douglas-fir tree, decay class I, fell before the Douglas-fir snag, which entered decay class III.

When a fallen tree decomposes, unique new habitats are created within its body as the outer and inner bark, sapwood, and heartwood decompose at different rates. The quality of the habitat depends on its physical and chemical properties (fig. 2.13).

A fallen tree interacts with its environment through internal surface areas. A newly fallen tree is not yet a habitat for plants or most animals. But once organisms gain entrance to the interior, they consume and break down wood cells and fibers. Larger organisms—mites, collembolans, spiders, millipeds, centipedes, amphibians, and small mammals—must await the creation of internal spaces before they can enter. The flow of plant and animal populations, air, water, and nutrients between a fallen tree and its surroundings increases as decomposition continues (fig. 2.14).

Internal space develops in a fallen tree through physical and biological processes. A tree cracks and splits when it falls and dries. Microbial decomposition breaks down the cell wall and further weakens the wood. Wood-boring beetle larvae and termites tunnel through the bark and wood, not only inoculating the substrates with microbes but also opening the tree to colonization by other microbes and small invertebrates. Wood-rotting fungi produce zones of weakness, especially between annual rings, by decaying spring wood faster than summer wood. Plant roots that penetrate the decayed wood split and compress it as the roots elongate and grow in diameter. Because of all this internal activity, the longer a fallen tree rests on the forest floor, the greater the development of the surface area of its internal cavities. Most internal surface area results from biological activity, the cumulative effects of which not only increase through time but also act synergistically—insect activity promotes decomposition through microbial activity that encourages establishment and rooting of plants.

Decay rate	IB	>	SW	>	HW	>	OB
Soluble carbohydrates	IB	>	SW	>	HW	>	OB
Taxifolin content	IB	<	SW	<	HW	<	OB
Nitrogen content	IB	>	OB	>	SW	>	HW
Mineral content	IB	>	OB	>	SW	>	HW
Water content	SW	>	IB	>	OB	>	HW
Lignin content	OB	>	IB	>	SW	≈	HW
Total extractives	OB	>	IB	>	HW	>	SW
Cellulose content	HW	>	SW	>	IB	>	OB
C:N ratios	HW	≈	SW	>	IB	>	OB
Density	OB	≈	IB	>	HW	>	SW

Figure 2.13—Relative decay rates and composition of different substrates of fallen trees: OB = outer bark; IB = inner bark; SW = sapwood; HW = heartwood (adapted from various sources).

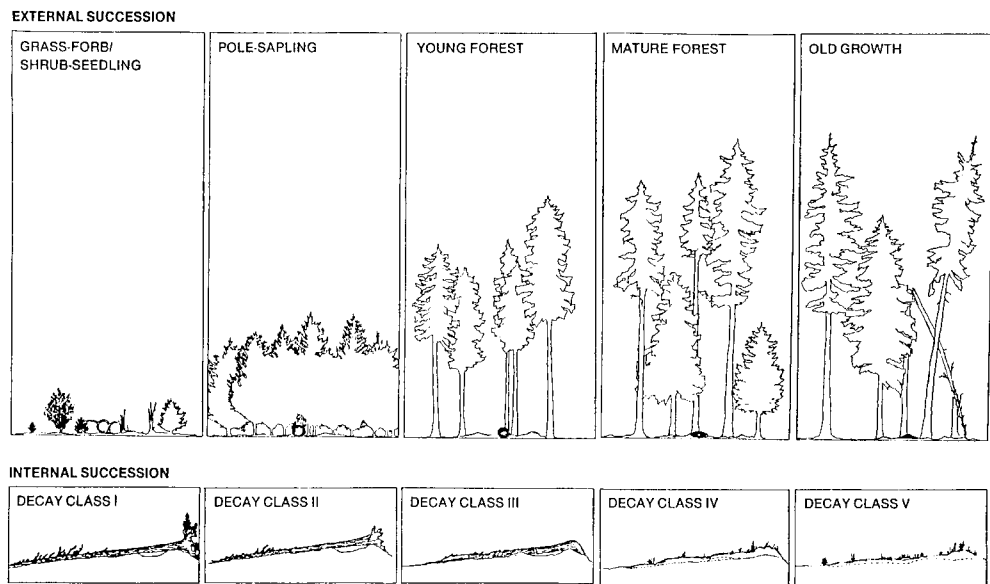


Figure 2.14—Fallen trees progress through two simultaneous successional processes—internal and external (modified from Maser and others 1979).

Numerous physical and chemical changes occur as fallen trees decay: (1) density decreases; (2) water content increases until decay classes III and IV are reached, at which time the water content stabilizes (fig. 2.15); (3) mineral and nitrogen contents increase; (4) cellulose content decreases; (5) relative lignin content increases; (6) C:N ratio decreases (Fogel and Cromack 1977, Foster and Lang 1982, Graham and Cromack 1982, Grier 1978, Lambert and others 1980, Sollins 1982); and (7) internal temperature fluctuations are buffered as the fallen tree comes in contact with the ground (Sollins and Cline, unpubl. data).

Habitats, both external and internal, are influenced by tree size. An uninterrupted supply of new, immature wood in young forests decomposes and recycles nutrients and energy rapidly. Habitats provided by the death of young trees are short lived and rapidly changing. In contrast, the less frequent, more irregular mortality of large trees in old forests is analogous to slow-release fertilization. The lasting quality of large fallen trees creates stable habitats in which large woody debris accumulates (fig. 2.16, color). Scattered accumulations of large woody debris are associated with openings in the forest canopy (Stewart 1984). Large fallen trees in such an area often contact each other physically, creating external habitats of intense biological activity (Maser and others 1979, Neitro and others 1985, Stewart 1984, Thornburgh 1967).

Conclusions

Decaying, fallen trees contribute to long-term accumulation of soil organic matter, partly because the carbon constituents of well-decayed wood are 80-90 percent residual lignin and humus (Means and others 1985). Decaying wood in the soil and establishment of conifer seedlings and mycorrhizal fungi on dry sites are positively correlated (Harvey and others 1987). Fallen trees also create and maintain diversity in forest communities. Soil properties of pits and mounds differ from those of surrounding soil (Beatty and Stone 1985); such chemical and topographic diversity in turn affects forest regeneration processes (Lyford and MacLean 1966). All this, especially large fallen trees that reside on the forest floor for long periods, adds to spatial, chemical, and biotic diversity of forest soils, and to the processes that maintain long-term forest productivity.

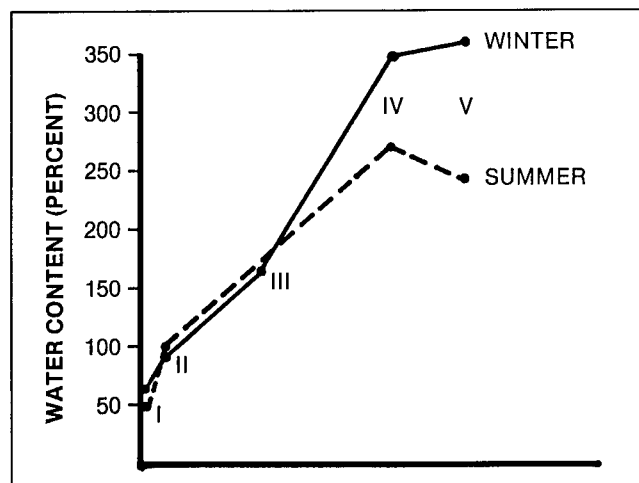


Figure 2.15—Water content of fallen Douglas-fir trees in winter and summer; each point represents a decay class from I (newly fallen trees) to V (fallen trees decomposed to a mound of brown cubical rotted wood).



Figure 2.5—Wind may break unhealthy trees above the ground.



Figure 2.6—Wind blows over healthy trees and pulls their roots from the soil.



Figure 2.7—Forest floor diversity is partly maintained by windthrown trees that create a pit-and-mound topography as they are uprooted.



Figure 2.8—Large stumps from old-growth trees are a finite resource, and their loss from the forest affects both soil shear strength and watershed hydrology.



Figure 2.9—A fallen tree oriented along the contour of a slope. The upslope side is filled with humus and inorganic material that allows invertebrates and small vertebrates to tunnel alongside. The downslope side provides protective cover for larger vertebrates. When under a closed canopy, such trees are also saturated with water and act as a reservoir during the dry part of the year.



Figure 2.16—Large fallen trees are a finite resource that create a myriad of changing habitats through time as they decompose and recycle into the forest soil and new, living trees.



Chapter 3. What We Know About Large Trees That Fall Into Streams and Rivers

James R. Sedell, Peter A. Bisson, Frederick J. Swanson, and Stanley V. Gregory

Summary

The most productive habitats for salmonid fish are small streams associated with mature and old-growth coniferous forests where large organic debris and fallen trees greatly influence the physical and biological characteristics of such streams.

Introduction

In western Oregon, most of the 17,000 miles of fish-bearing waterways are small streams averaging less than 10 feet wide; shown below is the mileage by ownership:

Owner	Miles	Source
Private	9,144	Oregon Department of Fish and Wildlife; Oregon Department of Forestry
Bureau of Land Management	2,025	U.S. Department of the Interior
USDA Forest Service	5,800	Everest and Summers (1982)
<hr/>		
Total	16,969	

Dense vegetative canopies help keep waters cool, and falling tree litter delivers nutrients to the stream portion of the ecosystem. Large organic debris and fallen trees greatly influence the physical and biological characteristics of small streams that may contain as much as 200-700 tons/acre of such material (Anderson and others 1978, Bisson and others 1987, Franklin and others 1981, Harmon and others 1986, Keller and Swanson 1979, Swanson and Lienkaemper 1978).

History of Wood in Northwest Streams and Rivers

Most early descriptions of streams and rivers in the Northwest were recorded in British and United States army journals. Valleys were so wet that early travel was confined to edges of the hills (Dicken and Dicken 1979). Oregon's Tualatin Valley was "mostly water connected by swamps" (Ogden 1961, p. 122). Much of this flooding resulted from beaver dams, accumulated sediment, fallen trees, and living vegetation in the channels. The valley bottoms had long accumulated alluvial silt and organic material, so the land was drained for agriculture early in the time of settlement.

The condition of Willamette Valley streams in 1910 was described by Williams (1914, p. 13):

Many of the smaller streams...through these flat sections of the valley flow sluggishly and frequently overflow their banks during periods of heavy winter rainfall.... Most of these have sufficient grade to carry even more water than ordinarily comes to them; seldom less than 3, and usually more, feet of fall per mile. The annual overflow is caused from the obstructing of the channel by the growth of trees and the extension of their roots, the dams thrown across the channels by beavers and the consequent accumulation of sediment and other debris.... It is common condition, however, and usually all that is necessary is a clearing out and opening up of the clogged channel of the stream to afford entire relief...to the farmer....

Streams of the Puget Sound lowland in Washington State were also a network of sloughs, islands, beaver ponds, and driftwood dams with no main channel. The Skagit River lowlands encompass about 198 square miles, of which more than 50 square miles were once marsh, sloughs, and wet grass meadows. Maps of the lower Nooksack and Snohomish Rivers show large areas of sloughs, swamps, and grass marshes before 1900 (Reports of the Secretary of War 1875-1921).

The channels of both high- and low-gradient rivers contained large amounts of woody debris, regardless of the bed material. The lower Siuslaw River and North Fork Siuslaw River were so filled with fallen trees that trappers could not explore much of these systems in 1826 (Ogden 1961).

In 1870, the Willamette River flowed in five separate channels between Eugene and Corvallis. Reports of the Secretary of War (1875-1921) describe many obstacles to navigation of the Willamette River above Corvallis and say that the riverbanks were heavily timbered for half a mile on either side. More than 5,500 drifted, dead trees were pulled from a 50-mile stretch of river in a 10-year period. These trees ranged from 5 to 9 feet in diameter and from 90 to 120 feet in length. The river was also confined to one channel by engineering activities.

Many other rivers in Oregon and Washington were completely blocked by driftwood in the lower, main channels; the Skagit River had a driftwood jam three-fourths of a mile long and one-fourth of a mile wide. The Stillaguamish River was closed by six driftwood jams from the head of tidewater to river mile 17. Drifted, dead trees were so numerous, so large, and so deeply imbedded in the bottom that a steam "snag boat" operated for 6 months to open a channel only 100 feet wide.

Driftwood in high-gradient river systems often jams where the channel gradient is abruptly decreased. A section of the South Fork Nooksack River was described by Morse (1883, p. 9):

...we came to a place where the river, during freshets had ground sluiced all the earth away from the roots of the trees, and down some 6 feet to the gravel. This covered a region of country a mile in width by five in length. Overgrown yellow fir timber had once covered most of that section. If the river below there was only clear of jams that place would be paradise of hand loggers. On the gravel lay many million feet of sound fir timber, which only needed to be junked up during the summer and the winter freshets would float the logs down to the sea. Immediately below this place, the jams first extend clear across the river, and for the next 20 miles there is a jam across the river nearly every mile.

Large, woody debris was obviously an important part of early river systems of the Pacific Northwest; however, human objectives dictated that debris be cleared from river channels. Throughout North America, people have systematically cleaned downed trees and woody debris from streams for more than 150 years (Sedell and Luchessa 1982, Sedell and others 1982b). From the mid-1800's to about 1920, large and intermediate-size rivers in North America were cleaned so steamboats and rafts could navigate. From the 1880's to about 1915, small rivers and streams were cleaned so logs could be transported from the woods to the mills (fig. 3.1). Splash dams were built on many streams to temporarily augment the flow so logs could be floated (Sedell and Duval 1985, Sedell and Luchessa 1982) (fig. 3.2). Such channel clearance and splash damming removed large quantities of woody debris from medium to large streams, which significantly changed the physical and biological conditions of the streams (Harmon and others 1986).

During the 1950's and 1960's, west coast fishery managers feared that woody debris in streams restricted fish passage, supplied material for log jams, and caused channel scouring during floods (Hall and Baker 1982, Narver 1971). The great ecological value of organic debris was not yet known, and during times of extreme waterflow, all the managers' fears might be realized (Gharrett and Hodges 1950, McKernan and others 1950). The result of these fears was that fishery biologists were forced into the role of river engineers, a part for which they were not trained.

Debris is not now removed on the same scale as in the 1950's and 1960's, but removal is still a large part of salmon enhancement programs in several Western States and is mandated by virtually every State Forest Practices Act in the western United States and Canada. The combination of removal of debris in watershed headwaters so that fish could pass, splash damming, and removal of drifting wood and log jams from large rivers has left entire drainage systems almost devoid of large wood (Sedell and Swanson 1984).



Figure 3.1—Logs in a small stream awaiting enough water to be floated to the mill (photo from USDA Forest Service historical files).

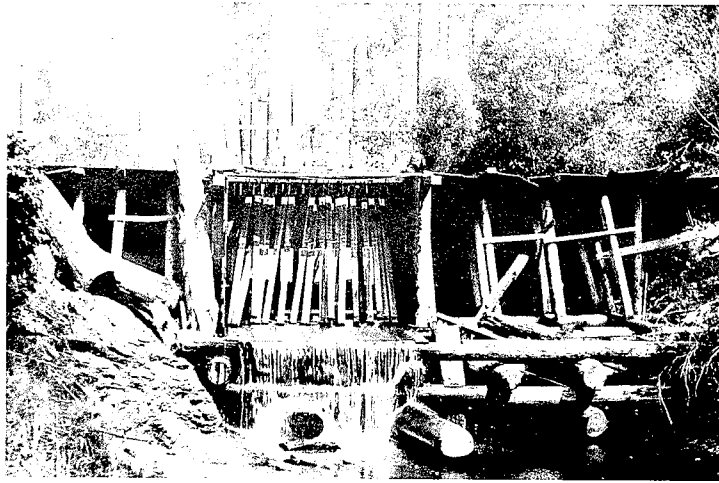


Figure 3.2—A splash dam at Austin Place, Hamilton Creek, Oregon, August 16, 1907. Such dams were used to regulate the flow of water to float logs down a stream to the mill (historical photo, courtesy of the Horner Museum, Oregon State University).

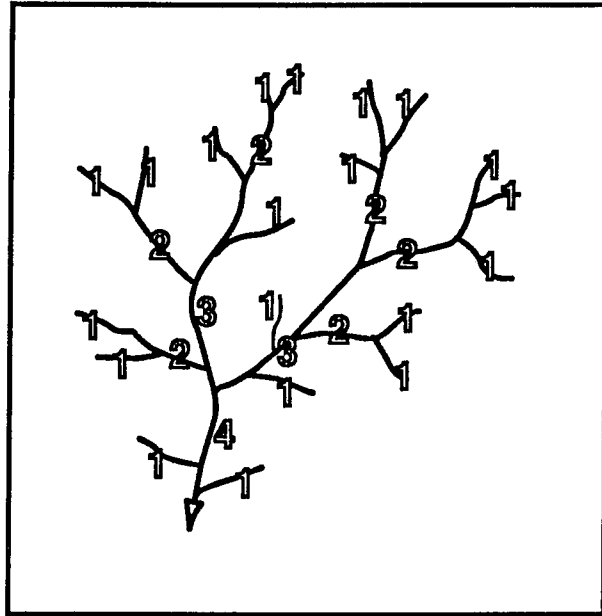


Figure 3.3—Stream order (after Strahler 1957) in a typical watershed. The majority of stream mileage is in first- and second-order tributaries in all watersheds of western Oregon and Washington.

Stream Categorization

Streams are characterized by their "order" (Strahler 1957) (fig. 3.3). Headwater stream channels are designated first-order; two first-order streams combine to form a second-order stream. Two second-order streams combine to form a third-order, and so forth.

In western Oregon, first- and second-order streams constitute 79 percent of the total stream mileage (Boehne and House 1983) (table 3.1). Such streams rise in very small watersheds with limited water storage capacity. These streams may have only scanty or intermittent flow during the dry season, but during high flows they may move large amounts of sediment and woody debris. Headwater streams mainly determine the type and quality of downstream fish habitat.

First- and second-order streams are influenced by the geomorphology, soils, and vegetation of their channels. Large woody debris is common, covering as much as 50 percent of the channel (Anderson and Sedell 1979, Swanson and Lienkaemper 1978, Triska and others 1982). The stream is continuously shaded by vegetation. Flow energy in the channel is continually dissipated by woody material and vegetation that slow erosion and foster deposition of organic and inorganic materials. The average gradient of these streams often exceeds 10 percent, but the channels usually have a stairstep configuration of flat reaches connected by riffles and low falls. Salmonid reproduction may be sufficient, even in some ephemeral streams, to furnish fry to larger waters downstream (Everest 1973, Everest and others 1985).

Table 3.1—Stream order analysis^a

Number of order	Total streams	Length	Average length	Average watershed area	Density
	<i>Number</i>	<i>-----Miles-----</i>		<i>Acres</i>	<i>Miles/acre</i>
Coastal watersheds.^b					
1	20	5.0	0.25	25	0.010
2	20	24.0	1.20	146	.008
3	20	94.9	4.70	410	.012
4	19	303.4	16.00	1,823	.010
5	9	393.3	43.70	4,635	.010
Cascade Range watersheds.^b					
1	20	5.0	.25	35	.007
2	20	27.9	1.40	222	.008
3	19	101.9	5.00	876	.008
4	20	407.9	20.40	2,761	.009
5	7	249.9	35.70	4,649	.008

^a Adapted from Boehne and House (1983).

^b Ordered on 1:12,000 scale.

Third- and fourth-order streams usually flow continuously. Average gradient is less than 5 percent, but there may be intermittent stretches of rapids or falls. Woody debris usually covers less than 25 percent of the channel. High flows may flush woody material from the system or deposit it in jams. The vegetative canopy over third- and fourth-order streams varies in density. These streams can transport large amounts of sediments, which are often deposited around channel obstructions, in narrow, winding areas, or in other areas of low velocity—accretion bars, estuaries, and the flood plain.

The direct influence of riparian areas is moderated in fifth-order and larger streams but remains important. Canopies of large, old-growth trees provide some shade, vegetated riparian zones keep the main channel confined, and the largest stems of down trees that remain in the stream provide important summer and winter salmonid habitat. Flood plains of the larger streams contain complex arrays of side channels, overflow channels, and isolated pools. Side channels are often created and maintained by large woody debris (Bisson and others 1987, Sedell and others 1984). The gradient in large streams is usually less than 1 percent, but rapids and falls may occur. Alluvial material and woody debris may be deposited in quiet areas, but accumulations are flushed and rearranged during high flows.

Table 3.2—Physical variables in relation to stream order in 2 Oregon watersheds^a

Watershed type and physical variable	Unit	Stream order			
		2	3	4	5
Coastal watersheds:					
Gradient	Percent	18	6	4	3
Width	Feet	2	5	10	11
Depth	Inches	8	16	16	33
Pool	Percent	22	27	31	37
Riffle	Percent	78	73	69	63
Spawning gravel	Square yards per mile	121	455	1,176	63
Bottom substrate—					
Bedrock	Percent	2	16	14	9
Boulder	Percent	11	15	15	14
Cobble	Percent	26	15	17	19
Rubble	Percent	9	10	15	11
Gravel	Percent	36	29	27	27
Fines	Percent	16	16	12	20
Cascade watersheds:					
Gradient	Percent	11	9	6	3
Width	Feet	4	7	9	24
Depth	Inches	2	4	8	12
Pool	Percent	55	56	58	49
Riffle	Percent	45	44	42	51
Spawning gravel	Square yards per mile	73	125	376	1,321
Bottom substrate—					
Bedrock	Percent	—	—	—	—
Boulder	Percent	—	—	—	—
Cobble	Percent	—	—	—	—
Rubble	Percent	—	—	—	—
Gravel	Percent	13	16	18	20
Fines	Percent	3	4	5	3

— = not available.

^a Adapted from Boehne and House (1983).

Most salmonids spawn in fourth-order coastal streams and fifth-order watersheds in the Cascade Range (table 3.2). Resident salmonids use some second-order coastal streams but are nearly always found in third-order or larger streams. Fourth- and fifth-order streams in western Oregon can support rearing of anadromous salmonids unless barriers or gradients of more than 12 percent stop upstream movement of adults.

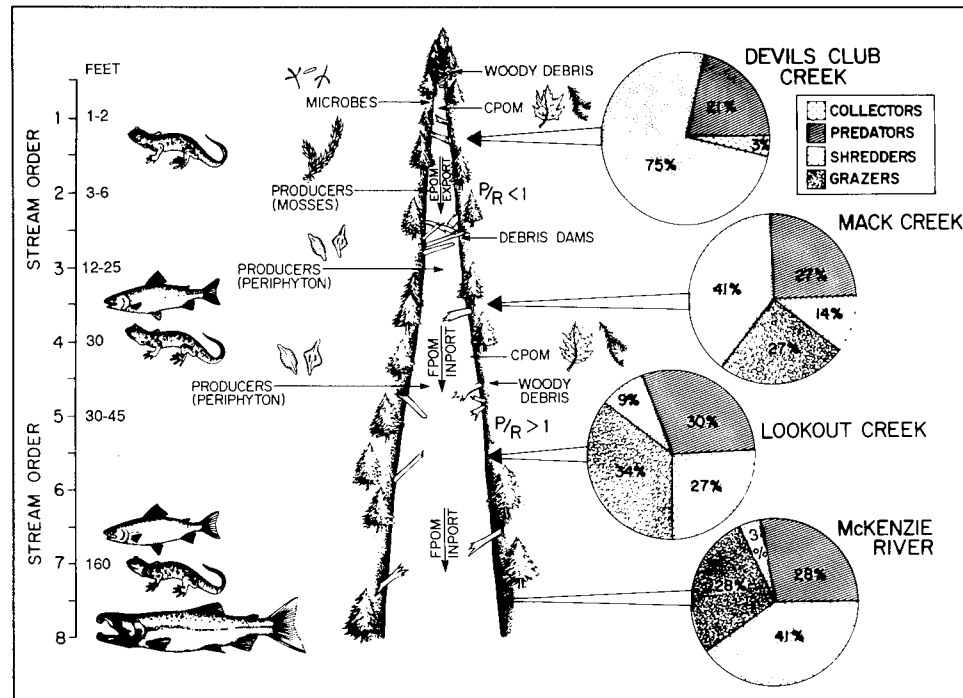


Figure 3.4—Diagram of first- to eighth-order streams showing width, dominant predators, producer groups, P:R (production:respiration) ratios, importance of wood, and proportion of invertebrate functional groups (adapted from Vannote and others 1980); CPOM = coarse particulate organic matter, FPOM = fine particulate organic matter.

Ecosystem Structure and Function in Unmanaged Streams

The stream network is a spectrum of physical environments and associated biotic communities (Vannote and others 1980). Streams form a longitudinally linked system in which downstream processes (cycling of organic matter and nutrients, ecosystem metabolism, new metabolism) are linked to upstream processes. The spectrum concept is a good framework for studying and managing streams as heterogeneous systems (O'Neil and Reichle 1980). Useful generalizations can be developed about magnitude and variation of organic matter through time and space, the structure of invertebrate and fish communities, and resource partitioning along the entire river.

First- and second-order streams feed third- and fourth-order streams with partially used food, the amount of which becomes progressively smaller as stream order increases. Small streams derive much food for invertebrates from wood or leaf litter under old-growth forests. The forest influence diminishes as streams become progressively larger and the stream energy base comes more from algae and less from forest litter (fig. 3.4). The forest influence is greatest in very small streams, but most diverse organic input mechanisms and habitats are in third- to fifth-order streams. Invertebrates reflect these downstream shifts with fewer shredders (leaf eaters) and more grazers (algal feeders) in small rivers (fig. 3.4). Dominant organisms change as the size of a forested stream changes, as does the role of each functional group of organisms in using organic materials (fig. 3.4).



Figure 3.5—Woody debris in a small pristine stream.

Consider a first-order woodland stream and a sixth-order stream (intermediate-size river) in the context of continuums of communities with associated abiotic factors (fig. 3.4). Both systems include the same organic processing components, but they vary in relative magnitude of the components, rates and amounts of organic transfer between components, and species engaged in the transfers. The two systems are essentially modifications of the same trophic scheme, so the entire stream-to-river complex can be considered a single system composed of a series of communities along a continuum.

The continuum example deals primarily with food resources for organisms ranging from invertebrates to fish. More important to resource management, however, is the ecological rationale for a protective vegetation zone along streams and rivers of all sizes. Streamside vegetation zones are justified on the grounds of stream temperature control, bank stabilization, and food resources. Streamside vegetation is also the primary supplier of large organic debris—snags or tree stems 8 inches in diameter with the rootwads attached, or tree branches more than 8 inches in diameter.

Forests adjacent to streams supply large debris (stems, rootwads, large limbs) (fig. 3.5). Erosion may contribute debris to streams and account for water transporting pieces of debris. Organic debris in streams increases aquatic habitat diversity by forming pools and protected backwater areas, provides nutrients and substrate for biological activity, dissipates energy of flowing water, and traps sediment.

Aquatic ecologists, hydrologists, and geomorphologists only recently have recognized that large organic debris has always been an important part of forested streams. For western streams, such recognition developed from the following viewpoints: manipulation by humans (Bisson and others 1987, Froehlich 1973, Heede 1972, Marzolf 1978), functions of the ecosystem (Bilby 1981, Bilby and Likens 1980, Harmon and others 1986, Meehan and others 1977, Sedell and Swanson 1984, Swanson and others 1976, Triska and others 1982), and the historical aspect (Sedell and Froggatt 1984, Sedell and Luchessa 1982, Sedell and others 1982a, Triska 1984).

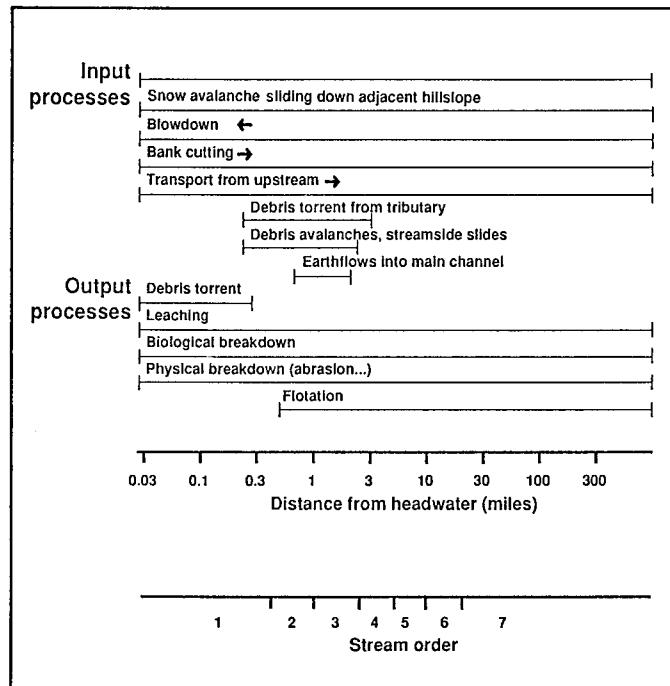


Figure 3.6—Debris input and transport processes by stream order in the McKenzie River system of western Oregon. Arrows indicate direction of increasing importance (adapted from Keller and Swanson 1979).

Several mechanisms transfer large woody debris to stream channels: bank undercutting and collapse, tree blowdown, tree collapse from snow or ice, snow avalanches, and mass soil movements (Keller and Swanson 1979). Each of these mechanisms contributes in some way to channel, slope, forest stand processes, watershed geology, and stream size.

The processes of transferring large pieces of wood from forests to stream channels are: chronic—frequent inputs irregular in time and space; and episodic—infrequently spaced, often very large inputs (fig. 3.6). Chronic input processes include tree mortality from disease and insects combined with windthrow or gradual stream undercutting of root systems. Episodic input processes include large-scale epidemics of insects or diseases, extensive blowdown (fig. 3.7), logging, debris avalanches, and massive erosion of banks during major floods.

Forest succession alters the composition of woody material entering streams through mortality and bank undercutting, causing trees to fall after logging. In young-growth plantations of the Pacific Northwest, low- to mid-elevation riparian zones are dominated by deciduous species, such as red alder, if no mature conifers remain along the stream after logging. Most trees that enter stream channels in young-growth sites are red alder (fig. 3.8, color), which has a shallow root system, and therefore, low resistance to undercutting. The rate of input of young-growth conifer debris is slow and does not increase until about 60 years after logging (Grette 1985) (fig. 3.9).



Figure 3.7—Blowdown is a major cause of large woody debris in streams.

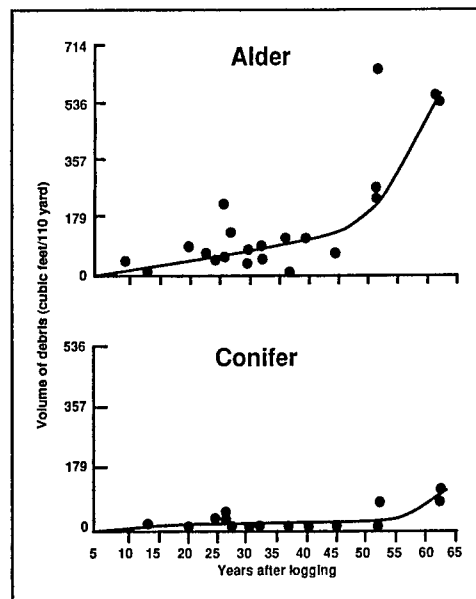


Figure 3.9—Red alder and conifer debris in small streams in second-growth forests in western Washington (adapted from Grette 1985).

Chronic inputs of woody debris larger than 20 inches in diameter are more common in mature and old-growth forests because of tree mortality than in young-growth stands where most or all of the trees are small. Inputs of smaller debris (less than 4-inch diameter) from young stands may, however, equal or exceed the rate of input of small debris from old-growth forests (Long 1987).

Distribution of Fallen Trees

The location, stability, and longevity of debris influence the quality of habitat in all fish-bearing streams, although the arrangement of woody debris varies according to stream size and valley morphology (Swanson and others 1976). Spacing of individual pieces of debris or clumps of pieces can be strongly influenced by input processes. If the dominant input is from bank undercutting of living trees or direct falling of dead trees, debris is spaced at random intervals along very small channels where discharge is insufficient to carry the debris pieces downstream. In most fish-bearing streams, however, there is some degree of debris clumping, the magnitude and spacing of which generally increases downstream. In streams wider than 5 to 7 feet (usually third- to fourth-order), woody debris enters the stream after bank undercutting. Trees that fall directly into the stream are moved during storms and deposited on channel obstructions and on the outsides of river bends near the high water line. Deposited debris may greatly increase width of the channel, produce midchannel bars, and facilitate the formation of meander cutoffs (Keller and Swanson 1979). Short, braided stream reaches and secondary channel systems formed in this manner are especially productive sites for rearing salmon and trout in Pacific Northwest rivers (Sedell and others 1984).

A major flood moves live trees to the stream, but downed trees and stumps can enter or leave streams annually with smaller floods. Large streams that flow through steep, narrow valley walls (for example, ravines) often cannot develop deposition zones, so they become dominated by boulders rather than by large woody debris.

Clumps caused by debris avalanches, extensive blowdown, or movement of large amounts of material from the flood plain in a major flood tend to be more widely spaced and of greater volume than those in streams where the foregoing input processes do not occur frequently.

Yet another input process is the debris torrent, a slurry of debris, soil, and water that can occur when a landslide enters a steep headwater channel (Swanson and Swanson 1976). Large logs jam at the terminus of a debris torrent, along with much sediment and debris, but the torrent itself scours the channel as it travels downstream. The result is a track that may be nearly devoid of debris and sediment—very poor fish habitat (Swanson and others 1976). A study of channels scoured by debris torrents in the Queen Charlotte Islands, British Columbia, revealed that debris remaining in torrent tracks usually lie parallel to the streamflow direction, in contrast to the more common diagonal orientation found in streams of unlogged areas or of channels with no torrents. This shift in orientation reduces channel width, depth variability, cut banks, pool areas, and channel stability, and thus reduces fish habitat diversity and quality. The debris dam formed by a torrent can be so extensive that it forms a major barrier to fish passage. Such dams are commonly found near tributary junctions where small first- and second-order channels that have suffered a debris torrent empty into larger, low-gradient streams.

Debris torrents usually travel short distances and may not affect large rivers unless a headwater channel discharges directly into a mainstream, as is the case in many glacial valleys. Large woody debris, however, can still be clumped along intermediate and large rivers as a result of infrequent events, such as major floods (Swanson and Lienkaemper 1978). Movement of floatable debris from headwaters or flood plains may form massive accumulations of driftwood wherever the channel narrows or low gradient depositional zones occur. Extensive driftwood dams, common in coastal streams before river clearance, are now rare (Sedell and Luchessa 1982). More common now are sporadic large accumulations of debris deposited on upper stream-banks and flood plain terraces inundated only during floods. Such debris is normally above the water line, so its use by fish is limited to high flows. The temporary refuge provided by inundated debris accumulations along the upper banks of streams with well-established flood plains, however, may be very important to survival of fish when main channel velocity is high (Tschaplinski and Hartman 1983).

Forest type and successional stage, disturbance history, and channel size all influence the amount of wood in streams. Woody biomass ranges widely—from 2 to 400 pounds per square yard (table 3.3)—as does woody volume, from 0.08 to 144 cubic feet per yard (Harmon and others 1986).

Stream biomass is also strongly influenced by geomorphic processes. Loss or deposition of sediment in channels may change the measurable biomass in streams (Harmon and others 1986).

Numbers of downed trees and large pieces of woody debris vary among streams in mature and old-growth forests, young-growth forests, and blowdown vegetation (table 3.4). Streams flowing through young-growth forests and recently harvested areas contain from one-fifth to one-twentieth the number of large woody pieces found in streams in mature forests.

Average length and frequency of large pieces of wood in pristine forested streams are greater than those of wood in manipulated streams or salvage-logged areas (fig. 3.10). Total pieces of wood and their average diameter and length were determined in two small Coast Range streams (fig. 3.11; Sedell, unpublished data). One stream drains a wilderness area; the other stream drained an area of which about 95 percent had been harvested over the past 30 years. The wilderness stream has more than one hundred times more pieces of wood and downed trees per unit length of channel. The average diameter class of wood for both streams was about 20 inches, but the average length of wood in the logged watershed was about 16 feet compared with 33 feet in the pristine stream. The role of wood in shaping and stabilizing habitats has been greatly diminished in the harvested watershed.

Table 3.3—Biomass of large woody debris in streams flowing through unmanaged old-growth forests along the Pacific Northwest coast

Location and dominant riparian tree species	Sample size ^a	Mean channel width	Large woody debris biomass	
			Mean	Range
	<i>Number</i>	<i>Feet</i>	<i>Pounds/square yard</i>	
Prince of Wales Island, Alaska:				
Sitka spruce and western hemlock	4	0.00 - 16.40	15.43	4.41 - 19.84
	1	32.81 - 49.21	26.46	—
Coastal British Columbia, Canada:				
Sitka spruce and western hemlock	1	32.81 - 49.21	39.68	—
	3	49.21 - 65.62	48.50	46.30 - 50.71
West slope Cascade Range, Oregon:				
Douglas-fir	19	0.00 - 16.40	55.12	4.41 - 121.25
	5	16.40 - 32.81	57.32	28.66 - 74.96
	1	32.81 - 49.21	50.71	—
	2	49.21 - 65.62	22.05	13.23 - 30.86
	2	>65.62	13.23	4.41 - 19.84
Northwest coast, California:				
Coast redwood	6	0.00 - 16.40	295.42	22.05 - 396.83
	4	16.40 - 32.81	141.09	39.68 - 242.51
	1	32.81 - 49.21	149.91	—
	1	49.21 - 65.62	35.27	—
Klamath Mountains, California:				
Douglas-fir	8	0.00 - 16.40	33.07	4.41 - 101.41
	2	16.40 - 32.81	55.12	2.20 - 110.23
	1	32.81 - 49.21	2.20	—

— = not available.

^a The number of stream reaches surveyed (from Harmon and others 1986).

Table 3.4—Number of large pieces of woody debris per 100 yards of stream length in streams with drainage areas less than 6 square miles, by forest condition^a

Forest condition	Stream location	Pieces of woody debris per 100 yards of stream reach
Old-growth or mature forest:		
Mack Creek	Oregon, Cascade Range	22 - 28
Lookout Creek	Oregon, Cascade Range	18 - 20
Lobster Creek	Oregon coast	18
Sheehan Creek	Southeast Alaska	33 - 45
Cummins Creek	Oregon coast	20 - 23
South Fork Hoh River tributaries	Washington, Olympic Peninsula	18 - 20
Young growth:		
Knowles Creek	Oregon coast	1 - 3
Lobster Creek	Oregon coast	1 - 2
Fish Creek (repeatedly salvaged)	Oregon, Cascade Range	4 - 5
Blowdown buffer strip:		
Sheehan Creek	Southeast Alaska	135

^a Adapted from Sedell and others (1984).



Figure 3.10—The average length of large pieces of downed wood in pristine forested streams, such as those shown, is greater than those in streams in managed forests.

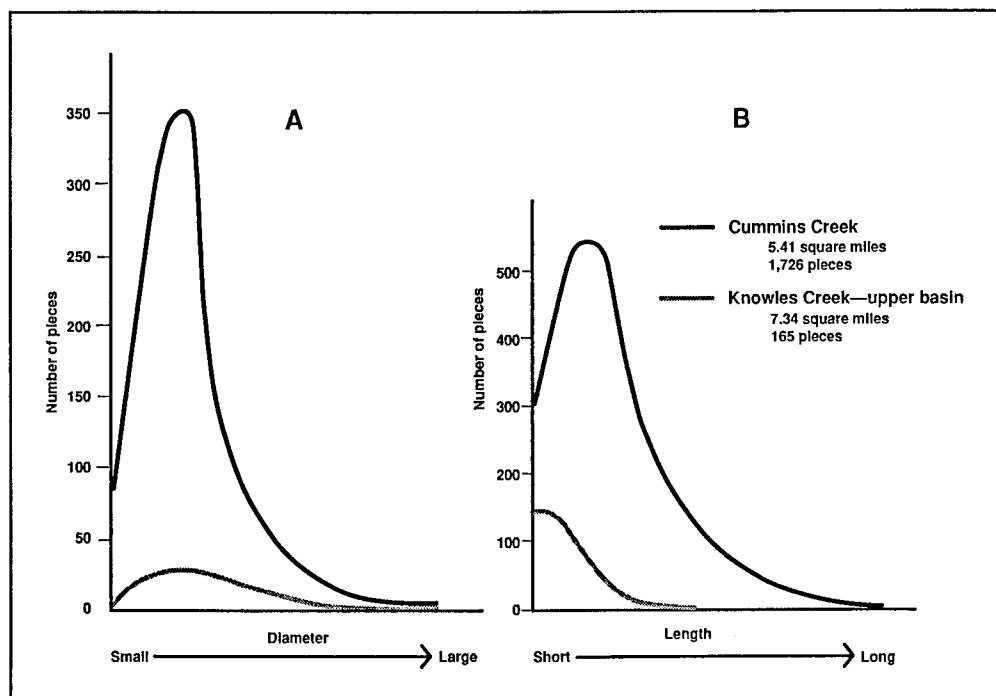


Figure 3.11—Instream frequency trends for an old-growth forested watershed (Cummins Creek) and a second-growth (less than 30 years) watershed (Knowles Creek) in the central Oregon Coast Range: A. Diameter of woody debris. B. Length of woody debris.

The North Fork Breitenbush, a high gradient, sixth-order stream in the central Cascades of Oregon, at bank-full stage is often wider than 98 feet, large enough to move even the largest and longest, downed trees. The river is divided by a wilderness boundary. Salvage logging had been carried out several times since 1965 on the lower 60 percent of the fish-bearing channels of the river. The average length of wood pieces in the managed stream was about 26 feet compared with 48 feet in the wilderness stream (fig. 3.12). Between 49 and 64 percent of the total large pieces of wood were less than 15 feet long in the managed stream compared with less than 18 percent in the wilderness stream. Pieces of wood longer than 50 feet accounted for more than 41 percent of the total wood in the wilderness stream compared with 8 to 17 percent in the managed stream (fig. 3.13). About 67 percent of the pieces of wood with a rootwad attached were longer than 49 feet in the wilderness stream compared with 14 to 23 percent in the logged stream. Stumps made up more than 60 percent of the wood in the managed stream compared with less than 6 percent in the wilderness stream. Total volume of wood had not changed for the wilderness or the managed streams, but the pieces were much less stable in the salvage-logged stream where the channel had widened by 40 percent. Clearly, the trend is toward smaller and fewer pieces of wood in stream channels of all sizes in the logged areas (fig. 3.14; compare with fig. 3.10). In addition, stream channels in the logged area are wider and less stable. The volume of wood may be the same in the managed and the unmanaged streams, but it is more clumped in the managed forest and volume per unit of stream area is less.

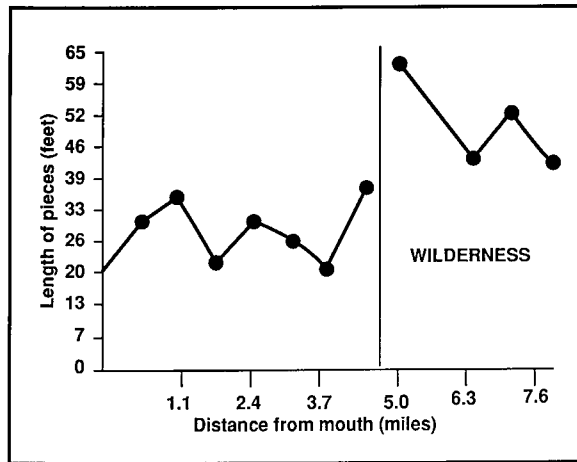


Figure 3.12—Length of pieces of wood in the North Fork Breitenbush River.

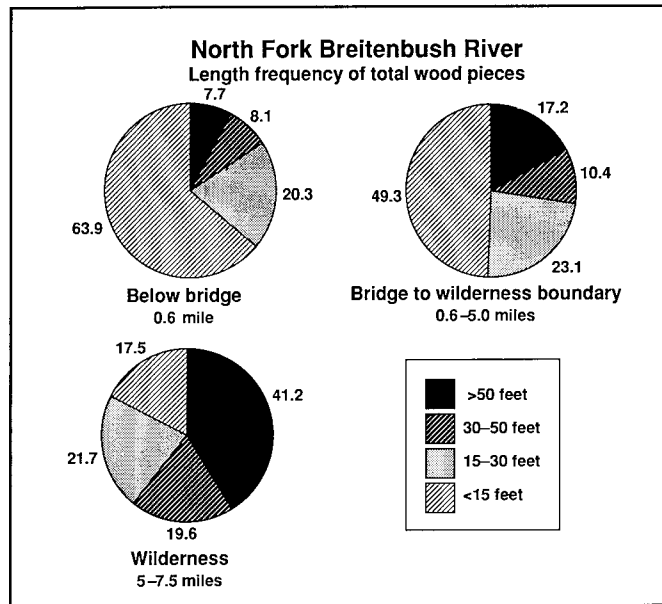


Figure 3.13—Frequency of wood pieces with rootwads, North Fork Breitenbush River.



Figure 3.14—The trend is toward smaller and fewer pieces of wood in channels of streams running through managed forests.

Residence Time and Stability of Fallen Trees

Longevity

The residence time of woody debris in stream channels is affected by transport processes, chemical constituents of the wood that affect decomposition rates, and resistance to breaking and abrasion. Dendrochronologic dating of instream debris in coniferous forests of the Pacific Northwest has identified pieces that have been in channels for 200 years or more (Keller and Tally 1979, Swanson and others 1976). Old-growth conifer debris is estimated to decay at a rate of 1 percent per year, although the rate may vary among tree species (Grette 1985). Western redcedar resists decomposition in streams better than does Douglas-fir or western hemlock, but all three conifer species far outlast red alder (Anderson and others 1978).

Logging alters the composition of riparian vegetation by reestablishing early successional stages. Debris from young-growth stands has a shorter residence time in stream channels than debris from preharvest forests. The frequency of red alder debris in young-growth forested streams is about twice that of alder in old-growth streams (Grette 1985). Red alder disappears from streams in young-growth forests more rapidly, however, than does conifer debris (primarily hemlock and spruce) because the alder debris is shorter, of smaller diameter, more easily broken, and less well anchored than conifer debris from the preharvest forest. The rate of input of alder debris from young-growth stands exceeds the input rate of conifer debris, but the reduced longevity of alder debris results in streams with less cover and fewer pools than streams in unlogged forests. Loss of cover in streams in young-growth forests has the most significant impact on salmonid populations in winter, when fish are strongly attracted to debris (Grette 1985) (fig. 3.15).





Figure 3.15—Loss of cover in streams in young-growth forests has the most significant impact on salmonid populations in winter.

Stability of Fallen Trees

Stable debris accumulations are assumed to be important for maintaining good fish habitat. If debris does not move frequently, its functions of pool anchoring, cover, and substrate storage are increased over those of unstable accumulations (Bryant 1983). Size, including length and diameter (fig. 3.16), is a major factor contributing to debris stability (Bilby 1984, 1985; Bryant 1983; Grette 1985; Toews and Moore 1982). Other dimensions, such as the presence of a rootwad or branches, also influence when or where a piece of debris will move. Debris length appears to be most important to its stability where stream discharge is sufficient to float large diameter stems (Bilby 1985, Swanson and others 1984). Branches and rootwads add to the stability of debris pieces by increasing the mass and surface area available for snagging on instream obstructions; whole trees are thus potentially more stable than tree fragments. Tree fragments, about half the width of a bank-full channel, were floated downstream during winter storms, but large stems with intact rootwads remained in place for at least 70 years in small, low gradient streams in southeast Alaska (Bilby 1981, Swanson and others 1984). Relatively short pieces of debris can be stable in narrow channels, but longer pieces are necessary for stability in wider channels. Trees whose length exceeds that of a bank-full channel may have much of their weight supported by ground outside the channel where they lodge against standing trees during high streamflow (Swanson and others 1984).

Other aspects of debris that influence stability include orientation, degree of burial, and the proportion of the piece that lies in water. Whether a piece is buried depends in part on the rate of sediment input to the channel and the longevity of the piece. Pieces are stable if their angle of orientation relative to the axis of flow is less than 30 degrees; they are likely to move, however, if their angle of orientation is greater than 60 degrees (Bryant 1983). The degree of burial strongly influences debris movement; pieces with both ends anchored to the streambed or bank move less than pieces with only one or neither end buried. The degree of burial also influences potential movement (Bilby 1984). Partial burial is less effective than complete or nearly complete burial in preventing downstream transport during storms (Grette 1985, Toews and Moore 1982).

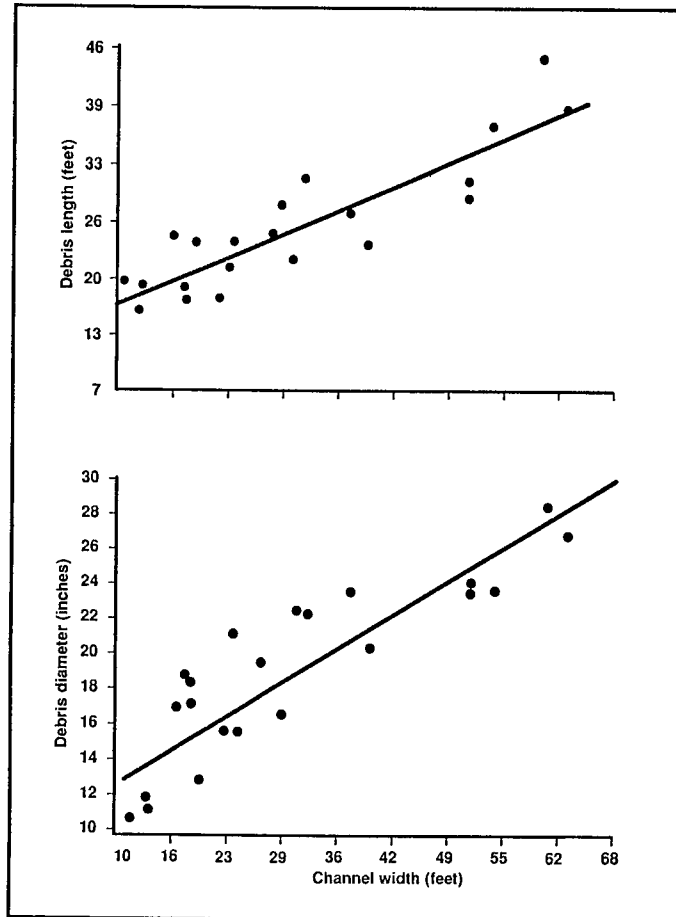


Figure 3.16—Relation between the length and diameter of stable debris and channel width. Each point represents the geometric mean length or diameter of logs not held in place by other debris at each of the western Washington study streams (adapted from Bilby (1985) and Bisson and others (1987)).

Even the largest fallen trees cannot span the bank-full channel width in large rivers. In such cases, the amount of wood and the number of fallen trees on exposed gravel bars provide constancy to wood in the river channel even though position of the material may change annually. The likelihood of fallen trees being transported back to the main channel is greatly reduced once they have formed jams at bends or outer margins of the flood plain, unless the river changes course.

Much relatively small debris enters streams after logging and is therefore more apt to move than would naturally occurring debris (Bryant 1980, Grette 1985, Lammel 1972, Swanson and Lienkaemper 1978, Toews and Moore 1982). Removing all newly added debris after logging, a requirement of many forest practices regulations, may involve bucking large debris into smaller pieces that are removed to the high water line. Such mandatory debris cleaning, however, usually takes place during low flow periods, and some of the material deposited on the upper bank may subsequently re-enter the stream at high flows. This increases the amount of shorter, less stable pieces in the channel (Bisson and Sedell 1984, Hogan 1985, Lestelle 1978, Osborn 1981).

High quality fish habitat declines as debris is exported (Bryant 1985, Scrivener and Andersen 1984). Downstream transport of small, unstable debris can lead to accumulations in debris dams that may remain in place for only a few years before moving on. Although debris dams may temporarily block fish migration, a greater long-term consequence for fish populations is the lack of large structure in the channel after debris is removed. Debris loading increases immediately after logging, then declines as accumulations gradually wash away (Bryant 1982, 1985; Toews and Moore 1982).

Processes of Wood Removal

Large floods move great quantities of wood onto the upper flood plain and downstream. Low frequency, high magnitude floods add much material to streams. The wood becomes more clumped through either flood or debris torrent forces. On small coastal streams, debris torrents may temporarily dam sections of streams draining basins larger than 6-9 square miles. When these dams fail, the resulting debris flood scours wood from the channel and deposits it high on banks or in estuaries.

Physical abrasion is the most powerful mechanism for removing stable pieces of wood from streams and rivers. Sand and gravel carried at flood velocities abrade large pieces of wood. Abrasion is greater in high gradient or sediment-rich streams than in gentle, spring-fed or low-gradient streams and rivers.

Biological decomposition is only a minor process in removing wood from streams. Water-logged wood decays slowly, but wood at the stream-terrestrial interface hosts very active microbial and invertebrate activity. Here, the biotic components respond to a gradient of temperature, moisture, and oxygen. Wetting and drying at the stream-terrestrial interface allows rapid biological decomposition of wood (Triska and Cromack 1980).

Forest management has greatly influenced the sequence of events in watersheds. The impact of natural processes that increase the rate at which woody debris disappears from stream systems is minimal compared with the impact of human activity on disappearance of wood over the last few decades.

Streams may be cleaned either immediately after logging to remove slash, or later to remove a specific blockage of fish passage (*fig. 3.17, color*). Postlogging stream cleaning is usually done by a professional crew with small equipment. Debris barriers to fish are usually removed under the supervision of a fishery biologist, who may need to use heavy equipment and explosives. Stream cleaning may damage fish habitat (Sedell and others 1985).

The State of Washington has required thorough removal of logging slash from streams for about the last 10 years. During this time, the effect of stream cleaning has been evaluated in several Pacific Northwest areas. In almost every such study, debris removal has resulted in loss of important habitat features and reduced fish populations (Bryant 1980, Dolloff 1983, Elliott and Hubartt 1978, House and Boehne 1985, Lestelle 1978, Lestelle and Cederholm 1984, Osborn 1981, Toews and Moore 1982).

Removing large, stable wood along with smaller material reduces channel stability and the quality of pools and cover. Small, easily floated wood has sometimes become temporarily abundant after stream cleaning (Meehan and others 1969, Toews and Moore 1982). Any such increases have come from new slash entering the water from debris stacked near the high water line during cleaning, or the breakup of wood in the stream before logging. In most cases, unstable debris is flushed from the cleaned reach within a few years, and channels are thus degraded.

The proportion of riffles increases and the number of pools decreases in cleaned stream channels (Bisson and Sedell 1984). The increased frequency of riffles increases the abundance of underyearling steelhead and cutthroat trout, which prefer riffle habitats; however, the abundance of coho salmon and older age classes of steelhead and cutthroat, which prefer pools, is correspondingly reduced.

State and Federal agencies annually spend more than \$6 million to remove debris jams, but the impact on habitat has had little study. In one study, fish populations in the vicinity of log jams were reduced immediately after complete removal of debris, but abundance did not decline significantly where part of the jam was allowed to remain (Baker 1979). Downstream spawning and rearing areas were damaged by large flows of sediment released when the log jams were removed. Partial removal appears to be biologically preferable to complete removal and is less expensive.

Most salvage logging in streams has been done since the great Pacific Northwest storm of 1964. Since then, Federal funds have been provided for cleaning and salvaging wood from streams after every major storm. Major timber sales on public land focus on streams of fifth-order or larger because access to established main roads is easy. A major reason for removing woody material from streams has been protection of downstream bridges and culverts to reduce property liability court cases. Even some sports clubs remove tree debris from rivers where such obstacles might impede travel (Oregonian 1986).

Use of wood-burning stoves has increased tremendously in the last 10 years (fig. 3.18). Most of the wood cut for fuel does not come from streams, but the demand for high quality wood that might otherwise reach a stream is great.

In the last 100 years, millions of trees have been cleared from rivers. County sheriffs, port commissions, and recreational boaters routinely clear fallen trees from rivers for safety and convenience. As a result, most Pacific Northwest rivers bear little resemblance to their pristine condition.

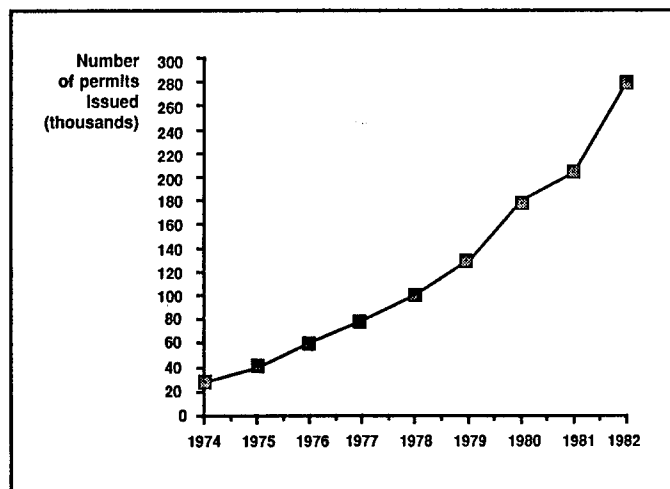


Figure 3.18—Forest Service, Pacific Northwest Region, free use wood permits.

Trends in Wood Inputs

Riparian zones in the past have supplied large trees to the stream, but most stream-banks now have smaller trees of fewer species. Most big cedars and Douglas-firs along streams in the Cascades and along most coastal streams greater than third-order have been removed or are about to be. On private land, 60-70 percent of conifer trees larger than 14 inches in d.b.h. have been harvested within 100 feet of a fish-bearing stream (table 3.5) in both the Oregon Coast Range and the Cascade Range. Fewer conifers than might be expected, larger than 12 inches in d.b.h., are growing along coastal streams (Sedell, unpublished data).

Table 3.5—Conifers larger than 14 inches in diameter harvested from 100-foot-wide leave strip

Location	Distance from stream (feet)		
	0-50	50-100	1-100
	<i>Percent</i>		
Coast Range:			
Drift Creek	0	0	0
Yaquina River	50	100	86
Siuslaw River at Pugh Creek—	44	74	65
Below North Creek	83	82	82
Above North Creek	0	13	9
Wolf Creek	53	90	68
Cascade Range:			
Santiam River	—	>57	57
Thomas Creek	57	92	76
Unnamed order 1 stream	100	100	100

— = not available.

Table 3.6—Stocking levels of large conifer trees (larger than 14 inches) in streamside areas after successive harvests

Streamside area	Pristine forest more than 70 years ago	Recently harvested stand	Leave strip stand
<i>Trees per acre</i>			
Cascade Range, both sides of unnamed order 1 stream, within 50 feet	43	24	0
Coast Range, 1 side of Yaquina River:			
Within 50 feet	16	6	3
Within 100 feet	36	22	3

The number of streamside conifers larger than 14 inches in d.b.h. has been drastically reduced from the number present 70 years ago at the first harvest (table 3.6). Conifers larger than 14 inches in d.b.h. ranged from only 0 to 19 percent of the pristine stocking level after recent logging.

Wood as Habitat in Freshwater Systems

Influences of Wood on Stream Characteristics

Woody debris influences stream channel flow and creates and maintains rearing habitat for salmonid fishes (Lisle 1982, Sullivan and others 1987). Free-swimming species, such as salmon and trout, require rearing sites where food is plentiful and little effort is needed to hold a feeding position against the current (Dill and others 1981, Fausch 1984). Such small, quiet areas are usually located behind boulders and are occupied by large, aggressive fish (Bachman 1984). Stream riffles have few such sites.

Some species, notably coho salmon, avoid riffle habitats almost entirely when competitors are present (Bisson and others 1982, Dolloff 1983, Hartman 1965); instead, they rely on pools with ample cover provided by large woody debris (Bisson and others 1985, Stein and others 1972).

Most stream fishes inhabit pools in which the current velocity is lower and the water usually deeper than in riffles. Deep pools offer fish a better chance of escaping from terrestrial predators, and also allow fish of different species or age classes to coexist in layers within the water column (Allee 1982, Fraser 1969).

Woody debris creates many of the pools in Pacific Northwest streams (Keller and Swanson 1979, Swanson and others 1976) (*fig. 3.19, color*). In small streams (up to about 3d order), single large pieces of debris or accumulations of smaller pieces anchored by a large piece often create a stepped longitudinal profile (*fig. 3.20; fig. 3.21, color*) that consists of an upstream sediment deposit, the debris structure,

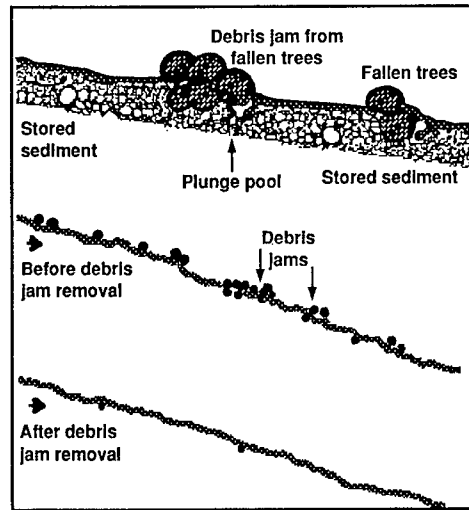


Figure 3.20—Role of woody debris in storing sediment and creating pools in streams: The "stepped profile" is characteristic of stored sediments and plunge pools created by woody debris. Removing a debris dam destroys and reduces these habitat features (adapted from Bisson and others 1987).

and a downstream plunge pool (Heede 1972, 1985). Numerous debris accumulations generally increase pool frequency (Lisle and Kelsey 1982). Numbers of pools are positively correlated with numbers of debris pieces in low-gradient streams (Grette 1985). Eighty percent of the pools in small streams of the panhandle of Idaho are caused by fallen trees larger than 10 inches in diameter (Rainville and others 1985). The frequency and volume of pools decrease in stream channels from which slash and naturally occurring debris were removed after logging (Bilby 1984, Bisson and Sedell 1984, Toews and Moore 1982).

The position of debris also influences the size and location of pools. The size of a single stem or the accumulation of stems spanning the channel affects the size of the associated pool. In an experimental flume, larger logs created longer and deeper pools, provided they were suspended above the streambed (Beschta 1983). In other studies, pool area was positively correlated with the volume of debris that anchored the pool, and the correlation improved as channel width increased in streams up to 7 feet wide (Bilby 1985, Bisson and others 1987) (fig. 3.22). Many pools, however, are created by eddies behind debris and other structures located at the channel margin rather than by the scouring action of channel flow. These backwater or eddy pools, common in all streams, are used by salmonids throughout the year for rearing (Bisson and others 1982; Bryant 1985; Bustard and Narver 1975a, 1975b; Dolloff 1983; Gibson 1981; Lister and Genoe 1979; Mundie 1969; Murphy and others 1984; Sedell and others 1982a, 1984; Stein and others 1972; Tschaplinski and Hartman 1983).

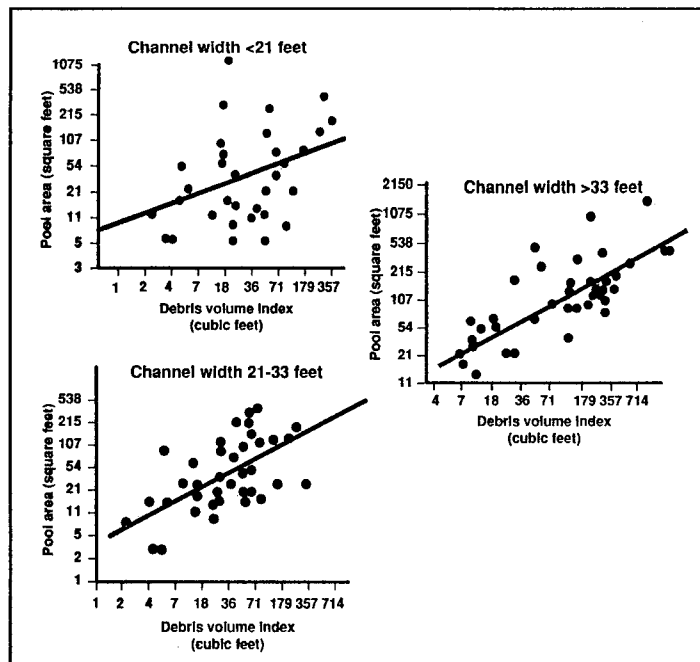


Figure 3.22—Relation between size of woody debris and pool area created for different-size streams in the Pacific Northwest. One 12-inch Douglas-fir tree contains about 72 cubic feet of wood; adapted from Bilby (1985).

Woody debris increases the complexity of stream habitats by physically obstructing waterflow. Trees extending partially across the channel deflect the current laterally, causing it to widen the streambed (Zimmerman and others 1967). Sediment stored by debris also adds to hydraulic complexity, especially in organically rich channels that are often wide and shallow and possess a high diversity of riffles and pools in low gradient streams of alluvial valley floors (Keller and Swanson 1979, Keller and Tally 1979). Even if the stream becomes so large that trees cannot span the main channel, debris accumulations along the banks cause meander cutoffs and create well-developed secondary channel systems (Keller and Swanson 1979, Swanson and Lienkaemper 1982). Debris also creates variation in channel depth by producing scour pools downstream from obstructions (Hogan 1985, Keller and Tally 1979). Wood therefore maintains a diverse physical habitat by (1) anchoring the position of pools along the direction of the stream, (2) creating backwaters along the stream margin, (3) causing lateral migration of the channel and forming secondary channel systems in alluvial valley floors, and (4) increasing depth variability.

Large, fallen trees affect live vegetation along watercourses. Trees carried by floodwaters can severely batter live plants on a flood plain, but normally only in a narrow belt along the immediate channel. Large, stabilized pieces of wood, on the other hand, protect riparian sites where alder and other species of plants can become established.



Figure 3.23—Note the large pieces of wood on the flood plain, especially in the lower right corner where stable wood has formed a protected site that has allowed the alder to grow.

Live vegetation eventually stabilizes a stream channel. Features, such as gravel bars, also become stabilized and enriched with fine sediments and organic materials as plant root systems develop and the stems resist the flow of water and reduce its velocity.

Fallen trees protect thickets of vegetation on exposed channel bars. Alders growing in channel bar areas not protected by down trees are repeatedly pruned heavily by floating woody debris and moving bedloads (Swanson and Lienkaemper 1982) (fig. 3.23). The down trees that protect the outer edge of a thicket and those in the thicket itself create local environments of quiet water where fine sediments and organic debris are deposited during high flows. This debris, coupled with leaf and woody litter from the stand, boosts soil development and vegetative growth. The large, fallen trees thus help a stand to reach a stage of structural development that allows it to better withstand floods. Fallen trees on gravel bars also provide sites where some stream-transported species of hardwoods and shrubs can reroot and grow.

Stream restabilization after major floods, debris torrents, or massive landslides is accelerated by large, woody debris along and within the channel. After wildfire, while the postfire forest is developing, an aquatic habitat may be maintained by large, woody debris supplied to the stream by the prefire forests (Swanson and Lienkaemper 1978). In many instances, however, streamside salvage logging destabilizes channel structure and, thereby, the quality of the habitat.



Sites of high biological activity and maximum habitat diversity are preferred spawning and rearing areas for salmonids. In the Pacific Northwest, many such zones of sediment and debris are located where a first-order channel debris torrent has entered a third- to fifth-order stream.

Wood as Habitat

Animal associations on woody debris in aquatic systems vary from those restricted to living on the wood to those using it only opportunistically. The sequence of colonists parallels the stage of wood decay. New wood entering a stream is used primarily as habitat, colonized by a community of algae and microbes that in turn provides food for a group of insects called grazers or collectors. This type of feeding does not significantly affect the structure of the wood, but colonization of the superficial layer by fungi softens wood enough that it may be abraded and ingested by invertebrates that scrape their food off surfaces. Most important, however, the wood becomes suitable for obligate wood grazers and the more generalized wood shredders, such as caddisflies and stoneflies, which eat fungal-infested wood. These activities result in a sculptured surface texture that provides habitat for many organisms. Decades of fungal colonization and growth soften the wood and allow oxygen to penetrate. Invertebrates that bore into the internal matrix of a fallen tree speed the decomposition process by consuming the wood and by transporting microbes into the tree. In the final phase of decay, detritivores, such as earthworms, penetrate the material; continued decomposition then resembles organic matter in soil and damp, terrestrial habitats (Anderson and others 1978, 1984; Dudley and Anderson 1982) (fig. 3.24).

Some wood that enters a small stream is already altered by fungi and other terrestrial organisms. Such preconditioning allows more rapid internal colonization by aquatic microbes and invertebrates and thereby shortens the aquatic decomposition process. Decomposition is also faster in large streams during periods of high water because physical abrasion removes softened tissue as the wood is transported or deposited in the stream. Rotting wood cannot retain enough structural integrity to provide a substrate for aquatic invertebrates during the final stages of decomposition except in small headwater streams or in backwaters of large streams.

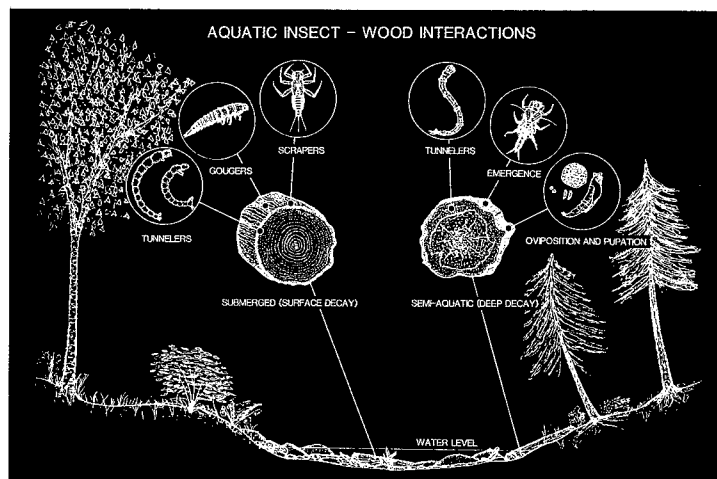


Figure 3.24—A model of wood-aquatic insect interactions in a small stream (redrawn from Anderson and others 1984, with permission).

Wood quality and texture help determine the kinds of organisms that will colonize a piece of wood. The species of wood, degree to which it is waterlogged, and decay class all affect the quality. The extent of colonization by terrestrial fungi and wood-boring insects also influences the attractiveness of the wood once it enters the water because such activity is closely associated with decay class.

The ecological role of wood-eating aquatic invertebrates is limited compared with that of terrestrial systems and marine environments. The three most important wood-processing invertebrates in Oregon streams consume about 2 percent of the available woody debris per year in small streams (Anderson and others 1978, Steedman and Anderson 1985). Wood processors are more abundant on hardwoods than on conifer wood. Microbial activity and nitrogen content are greater in decaying alder than in decaying conifer wood, a nutritional difference that helps explain the higher abundance of processors in hardwoods.

Summer populations of salmonids in western Washington streams flowing through old-growth forests have been compared with those in recently clearcut areas (Bisson and Sedell 1984). Total salmonid biomass increased after logging, but species richness declined to a population of only steelhead trout, most less than 1 year old. Coho salmon and cutthroat trout, between 1 and 3 years old, were proportionately less abundant in logged areas (Bisson and Sedell 1984). The shifts in species composition and age groups are related to habitat changes after logging of old growth and removal of large, stable, woody debris from the stream channel. Stable debris declined and unstable debris increased in the years after the 1976 Washington Forest Practices Act that mandated immediate removal of debris after logging (fig. 3.25). Pool size decreased and riffle size increased after old growth was clearcut and the stream channel cleared. Numbers of pools and riffles per unit of stream length declined after logging, which suggests that normal stairstep stream profiles had been reduced to a more even gradient (fig. 3.26).

Coho biomass in coastal Oregon streams is directly related to pool volume. Large, stable, woody debris is preferred as protective cover by young coho salmon, yearling steelhead, and older cutthroat trout, particularly in high-gradient river systems (Bisson and others 1987; Bustard and Narver 1975a, 1975b; Everest and Meehan 1981; Lister and Genoe 1979; Nickelson and others 1979; Osborn 1981; Sedell and others 1982a, 1982b, 1985).

Most salmonid species use different habitat in winter than in summer. Large, stable, woody debris is important winter habitat for coho salmon, steelhead trout, and cutthroat trout because it enhances the use of other habitats within pools. All species prefer pools during base streamflows in winter, but the level of preference is determined by pool quality and abundance of woody debris; the more woody debris, the more fish use the pool. Large, stable debris also attracts fish to pools along the stream edge rather than to those in midchannel.

During winter floods, the pool-riffle sequence or stairstep stream profile becomes a continuous, high-velocity torrent, in which there is little protection for salmonids from moving bedload sediment or swift, turbulent waters. During these brief flood periods, slack water refuges are associated almost exclusively with debris as fallen trees and standing vegetation in riparian flood plains. All three species of salmonids enter these

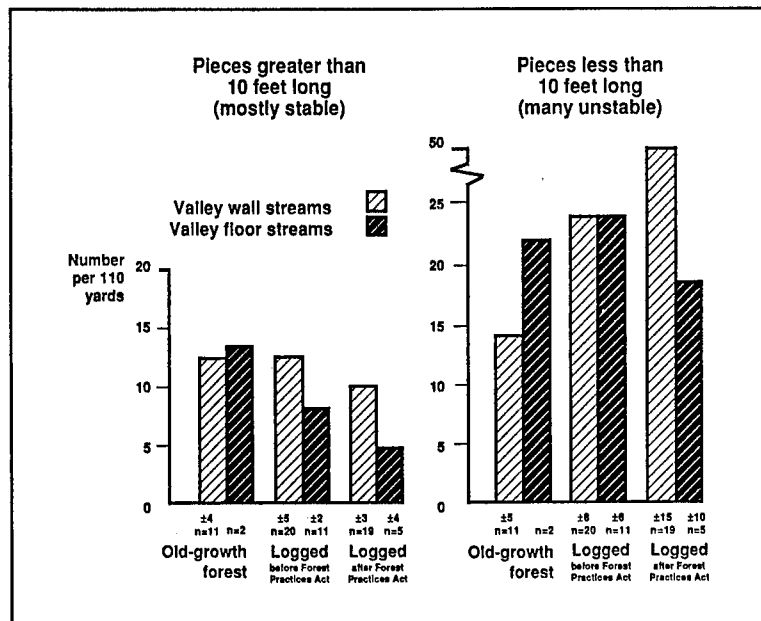


Figure 3.25—Effects of stream cleaning on the relative abundance of stable and unstable debris in steep valley wall streams and low-gradient valley floor streams in southwestern Washington; after implementation of the Washington Forest Practices Act; adapted from Bisson and Sedell (1984). Number of sample sizes is indicated on each bar.

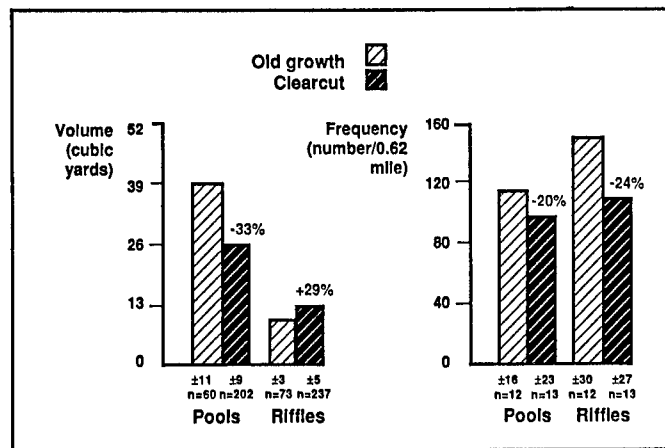


Figure 3.26—Comparison of volumes and frequencies of pools and riffles in streams in old-growth forests with streams in recently clearcut areas; 95-percent confidence limits and sample sizes are indicated on each bar.

debris-enhanced refuges until streamflows subside. Large, woody debris may also expand the feeding space by creating or enhancing areas of slow-moving or standing water in organic-rich flood plains, even along the smallest streams (Bustard and Narver 1975a, 1975b; Koski and others 1985; Murphy and others 1984).

Table 3.7—Juvenile chinook and coho salmon densities from different woody habitat types in the main channels of the Chickamin River, southeast Alaska, March-April 1984

Woody habitat type	Number of sample sites	Average number of salmon	
		Chinook	Coho
No woody habitat, slack water along edges	3	5	8
Rootwads without boles, stumps	12	56	50
Single downed trees, rootwad and stem	14	87	90
Log jam, several downed trees	7	292	195

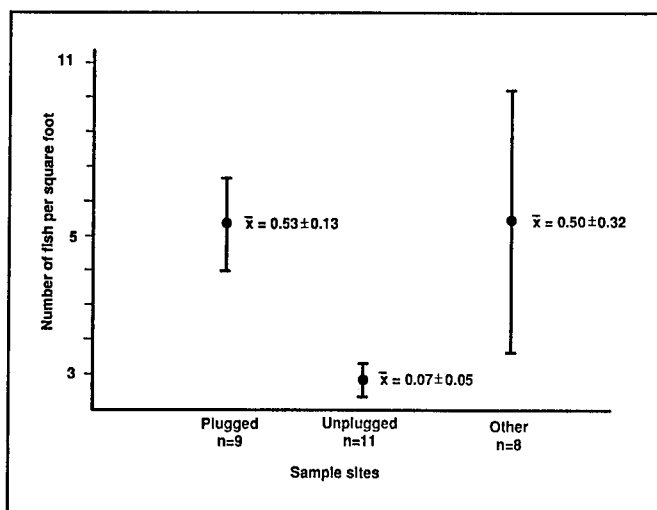


Figure 3.27—Densities of coho salmon in Upper Queets River side-channels, which are capped or plugged at the head by cobble and organic debris. Plugged side-channel areas represent 58 percent of total side-channel habitat; unplugged side-channels, 31 percent; and intermediate side-channels, 11 percent. Bars represent 95-percent confidence intervals.

Almost all juvenile anadromous fish in large rivers are reared on stream edges in a wood-rich environment (table 3.7 and fig. 3.27). Whole fallen trees or debris jams offer more productive, more diverse habitat than that around rootwad or stump habitats (Canadian Fisheries and Marine Service and The International Pacific Salmon Fisheries Commission 1979; Cornelius and Siedelman 1984; Sedell and others

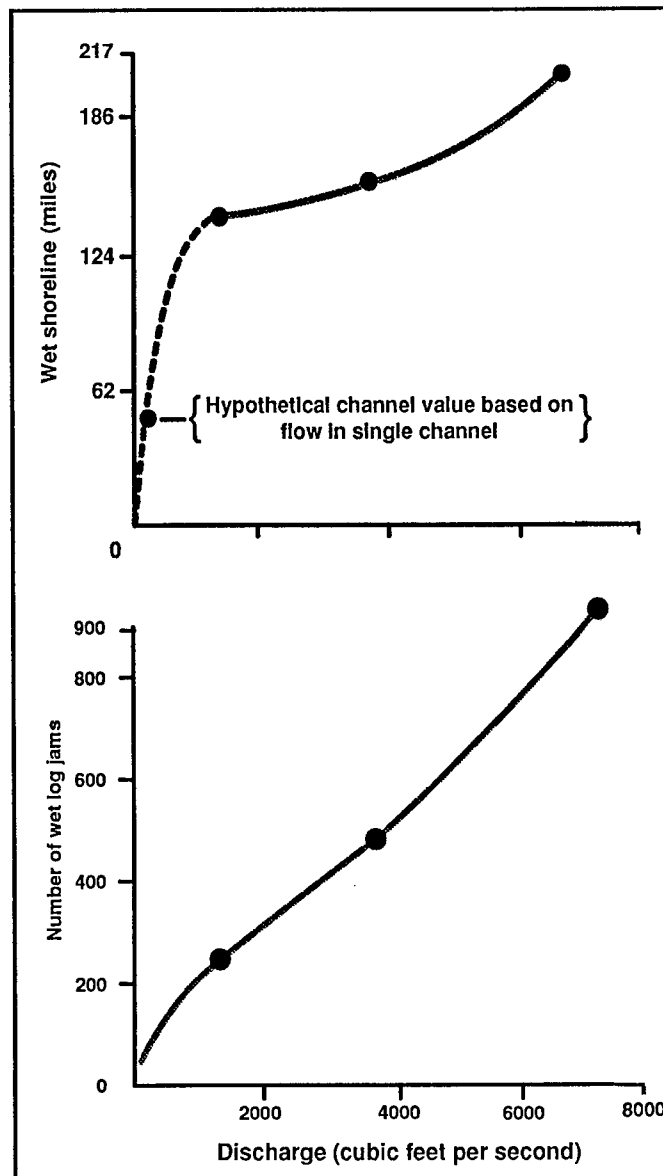


Figure 3.28—Relation between discharge and selected rearing indices in the Morice River.

1982a, 1984). Essentially, the hydraulic forces around any rough element such as fallen trees or stumps mainly determine the quality of fish habitat. Relations between discharge and wet debris jams can be quickly constructed to determine changes in fish habitat quality caused by salvage operations or water diversions (fig. 3.28).

Decomposition and Nutrient Cycling

Trees falling in streams decompose at different rates and in different patterns than those that fall to the ground. Wood decomposes more slowly in water than on land; waterlogging prevents deep penetration of oxygen into the wood. The fungi and invertebrates that cause the most rapid decomposition of fallen trees on land are also strongly aerobic (Triska and Cromack 1980). Waterlogged parts of fallen trees decompose in thin (0.25 inch) surface layers. As the decomposed surface is grazed or abraded, oxygen penetrates farther into the wood, and that area becomes food for the decomposers. If only part of a fallen tree is constantly in contact with water, that part decomposes slowly, but the exposed part may decompose rapidly because neither low oxygen nor extremes of moisture limit decomposer activity. Trees that fall in very small streams may contact water only during the rainy season when streamflow is highest. Low stream level and air drying the rest of the year may speed wood decomposition.

The concentration of essential nutrient elements increases as large pieces of wood decompose. Nitrogen increases primarily through biotic use of the carbon and through nitrogen-fixing micro-organisms. Nitrogen fixation on fallen trees in streams accounts for 5 to 10 percent of the annual nitrogen supply to the stream (Triska and others 1982). Although bark decays more slowly than wood, the tannins in Douglas-fir bark do not affect nitrogen fixation (Baker and others 1983).

Although rates of biotic wood processing differ in stream systems from headwaters to mouth (terrestrial to marine) (table 3.8), the slow decomposition of wood in freshwater streams maximizes the influence of wood on stream stability and as habitat. As we understand better the critical function of large organic material in streams and rivers, we realize that productivity of aquatic habitats depends on the biological diversity provided by a continuous supply of coarse woody debris.

Table 3.8—Processing rate of large woody debris in the forest floor, in streams, and in estuarine habitats^{a b}

Organism	Forest floor (fast)	Stream (slow)	Estuary (fast)
Microbes	Rot fungi diverse and abundant	Aquatic hyphomycetes (rot fungi, virtually absent)	Fungi minor or absent
Invertebrates: Insects	Diverse and abundant, including gallery-forming social insects	Few species (for example, <i>Lara</i> , <i>Brilla</i> (Tipulidae), no social insects)	Absent
Others	Oligochaeta important in later forms	Absent	Annelida, Mollusca, and Crustacea diverse (some boring forms with cellulase)
Vertebrates	Gallery or destroy wood in search of invertebrate food	Absent	Absent
Environmental controls	Temperature, moisture, and oxygen ^c	Temperature and oxygen ^c	Temperature and oxygen ^c

^a Adapted from Cummins and others (1984).

^b Hardwoods decompose faster than conifers.

^c Lignin little decomposed anaerobically.



Figure 3.8—Most trees that enter stream channels in young-growth sites are red alder, which has a shallow root system and low resistance to undercutting.



Figure 3.17—A terminus of a debris torrent that would have been a candidate for stream cleanup in the 1960's and 1970's because of the slash.



Figure 3.19—Woody debris creates many of the pools in Pacific Northwest streams.



Figure 3.21—Accumulations of small debris behind one large piece of debris often create a longitudinal, stepped profile.



Chapter 4. What We Know About Large Trees in Estuaries, in the Sea, and on Coastal Beaches

Jefferson J. Gonor, James R. Sedell, and Patricia A. Benner

Summary

Coarse woody debris is an important part of estuarine and oceanic habitats, from upper tidewater of coastal rivers to the open ocean surface and the deep sea floor.

Introduction

An estuary is a body of water at the coastal end of a river system, in which fresh-water mixes with saltwater before it enters the ocean. An appreciably wider shallow basin or embayment with extensive tidelands is in the estuarine section of most Pacific Northwest river systems. In some systems with large flows and narrow, deep channels, such as the Rogue River in Oregon, the truly estuarine region is confined to a short reach upstream of the river mouth. Fallen trees in streams or within reach of flood or tidal waters move downstream to enter estuarine and marine systems.

The estuarine portion of the ecosystem supports important environments and habitats including those of people, most of whom live around the lower ends of river systems. The ecologic and economic role of woody debris in these ecologically complex, productive systems is not well known.

Origin and History of Pacific Northwest Estuaries

During the late Pleistocene, eustatic sea level was about 325 feet lower than it is today. Pacific Northwest coasts were not glaciated, and rivers excavated deep valleys in the flat, exposed coastal plain. Sea levels rose after the close of the Pleistocene, and the coastal plain was submerged to form the present Continental Shelf. The seaward ends of many of these river valleys became flooded, and sediments accumulated in former meanders in the rivers' old flood plains. The main channels of these drowned rivers remain as the central, deeper channels of modern estuaries that retain the elongate, sinuous topography of a river in its flood plain valley. Channels are relatively shallow for most of their length.

The position and configuration of estuaries, no older than 10,000 to 15,000 years, remain dynamic, but the physiography has changed. Estuaries have long existed on the continental border of the Pacific Northwest, and they have moved across the Continental Shelf and present coastal plain in response to fluctuations in sea level changes.

Today's estuary continues to accumulate sediments in the former channels and on the flood plains, usually river-derived silts and muds in the upper reaches and increasingly sandy material near the mouth. Estuarine tidal flats and marshes occupy the former flood plain areas along the drowned river valleys that are now estuarine embayments (fig. 4.1).



Figure 4.1—An Oregon estuary: Coquille River marsh at Bandon, 1985 (photo, courtesy of Tony Howell).



Figure 4.2—Lower estuary, Tillamook, Oregon, 1871 (photo, courtesy of the Oregon Historical Society, negative ORH 52608).

History of Wood in Northwest Estuaries and Coastal Beaches

U.S. Government reports and early visitors' journals of the Pacific Northwest documented great amounts of large wood in the estuaries and on the beaches at river mouths. These mid-1800 accounts describe the quantities and size of the drift trees, also called "snags," that significantly exceeded present amounts of woody debris in the lower portions of river systems and beaches (fig. 4.2).

Coast survey reports in the 1850's recorded that many of the drift trees in the lower Columbia River were as large as 150 feet long by 13 to 18 feet in circumference; the largest was 267 feet long (Secretary of the Treasury 1859). Swan (1971) also reported drift trees as large as 250 feet long by 8 feet at the base, with a root span of some 20 feet, on the beach near the mouth of the Quillayute River in the Washington territory.

ENTRANCE TO COQUILLE RIVER. OREGON.

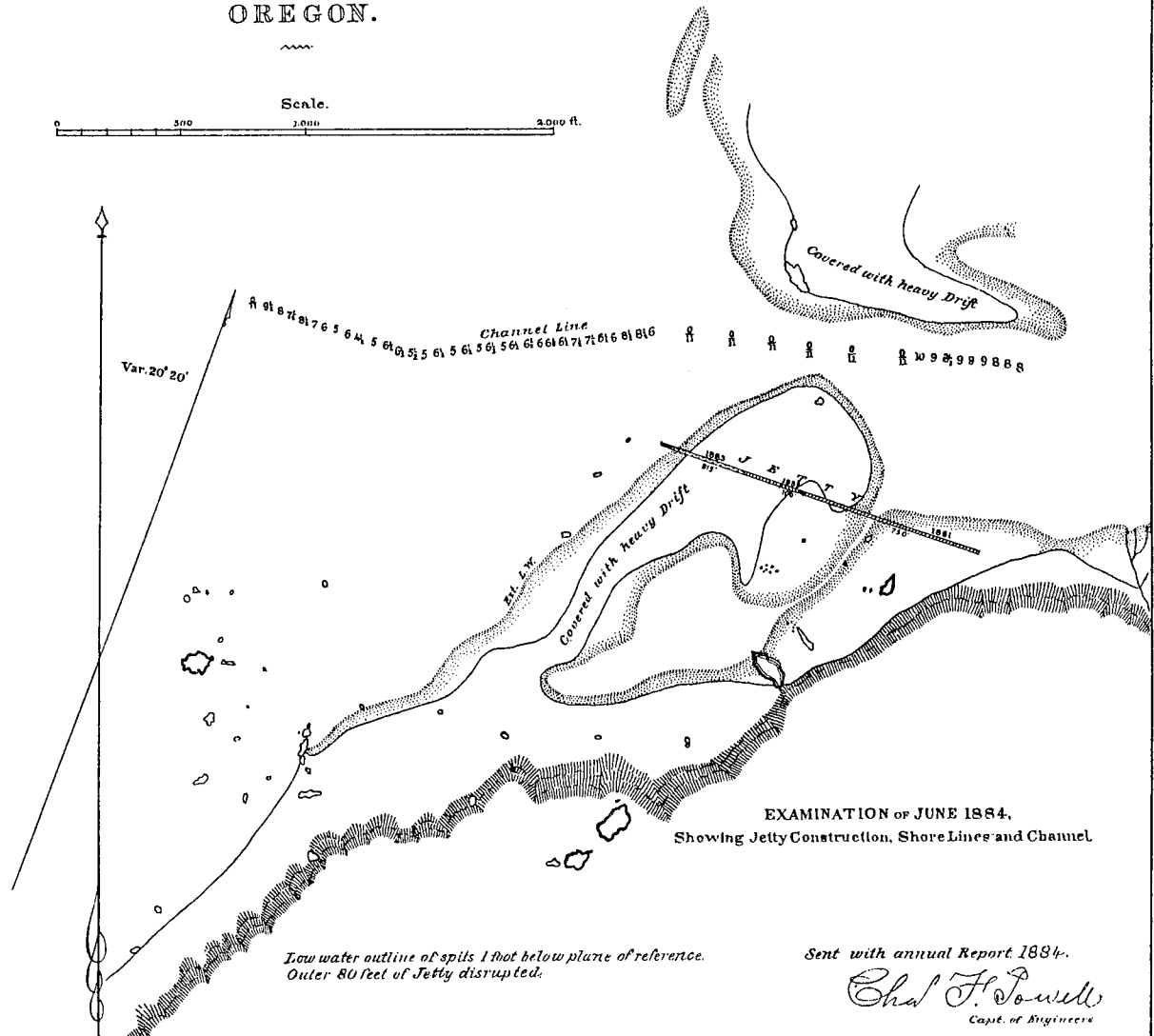


Figure 4.3—Driftwood at the mouth of the Coquille River; adapted from U.S. Army Corps of Engineers historical map (Report of the Secretary of War 1884).

The U.S. Army Corps of Engineers reported that Northwest estuarine shorelines and river-mouth beaches had often been covered with driftwood in the 1870's, as was the mouth of the Coquille River in the 1880's (fig. 4.3).

For several years after the coastal areas were settled in the 1850's and 1860's, roads were limited and land travel was impractical, especially in the winter. The coastal rivers were under the influence of tides for 12 to 40 miles from their mouths and had a low-gradient, deep channel along which commercial boats and log rafts could travel. Slowing currents and stormwind patterns, however, created zones of wood deposition in the estuaries. Many snags and sunken driftwood presented major obstacles for river traffic. The Corps' responsibility on many rivers during the late 1800's was to improve and maintain the navigability of the portions of the rivers deemed to be economically important (table 4.1).

Table 4.1—Snags removed from rivers by the U.S. Army Corps of Engineers, 1891-1917^a

River	Number of snags removed	Related activities
Tillamook River, 12 river miles	9,829+	86+ overhanging trees cut
Coos River, 22 river miles	8,591+	1,751 boulders blasted
Coquille River, 40 river miles	6,407+	81 scow loads of drift (1891-93)

^a Reports of the Secretary of War (1891-1921).

The wood-removal operations by the Corps represented only a portion of the total wood pulled from the lower river systems. Gill-net fishers formed teams to remove wood that threatened to tear fishing nets. Local landowners and later, port authorities, also worked to maintain channel navigability.

Sources of Wood For Estuaries and Beaches

Driftwood is found throughout an estuary, both in the channel and on mudflats and higher vegetated areas. Currently, the greatest concentration of woody debris is found along the shoreline of an estuary out of reach of tidal water. The most stationary wood is in the marshes, or at least partly buried in the channel.

Driftwood deposited in marshy areas between the main channel and the shoreline in the lower Nehalem estuary is estimated to have 50 percent fewer pieces and 60 percent less volume than in 1939. Stranded wood in the marsh in 1939 probably included many escaped lumber company logs that had been floated downriver or held in booms.

Another human-related source of wood is the many pilings and associated wood structures. Port authorities estimated that nine estuaries in Oregon in 1986 had at least 15,000 maintained pilings and thousands more wood structures—old stubs from abandoned log pens and channel projects, old mill pilings, and remnant docks. This wood can be considered a partial substitute for the snags that naturally occurred before the late 1800's.

Streams and rivers have long supplied estuaries and beaches with wood, and most of the material was transported downstream during higher flows. A captain in the U.S. Army Corps of Engineers in 1897 noted of the Coquille estuary, "It has always been difficult to keep this portion of the river open. The drainage area is densely wooded, and every freshet brings down many stumps, logs and trees; these lodge and arrest sediment, forming shoals." (Report of the Secretary of War 1894-95).

Flow Regimes in Pacific Northwest Coastal Estuaries

Watersheds annually replenished wood in the lower portions of the river basin and often floated wood into the ocean, from which it washed up onto the beaches. The lower river and estuary banks (riparian corridor) probably were the most common sources of the largest driftwood in the bays. In the 1860's, the banks of the upper half of the Coquille estuary were lined with mature hardwoods that made travel on the Coquille like walking "dim aisles in ancient cathedrals" (Dodge 1898). In the Tillamook River system in 1904, the U.S. Army Corps of Engineers cut down all overhanging trees along the banks of the estuary in an attempt to alleviate the woody debris problem (Report of the Secretary of War 1904-5).

The woody vegetation along many river corridors was cut in the 1800's to clear land and for a local source of wood. Upstream, the riverside forests were among the first to be commercially harvested because the logs could be floated down the river to the ports at a time when no other transportation was available (Sedell and Duval 1985). Major sources of large wood for estuaries and beaches along the Northwest coast were exhausted by 1920.

The ocean is another source of driftwood in estuaries and on beaches. Winter storms blow ocean-transported wood into river mouths and onto coastal beaches, generally north of the debris' origin. Some of the woody debris may be buried for long periods by river-bottom sediments in the estuaries or in sandy spits on the coast, but much of the wood probably remains fairly mobile. Other driftwood is deposited on the marshes and along the higher ground of the estuary boundaries, where it remains until it decomposes.

Estuarine tidal exchange and streamflow features govern the transport and retention time of woody debris and create salinity gradients. This physical regime in turn affects the distribution of marine wood-boring animals and their degradation of wood in these estuaries.

Tide affects river level much farther upstream than the penetration of even the most dilute seawater at the highest tides. This hydraulic effect causes river levels to rise and fall and can even reverse the direction of flow in the reach referred to as the "tidal river." Its farthest upstream extent is the "head of tide." This effect, present throughout the year, increases the rate of transport of floating woody debris faster than might be expected and increases the chance that wood stranded on the shoreline by freshets will be reached by subsequently higher tides and be returned to the downstream flow. Tidal reaches for Oregon rivers vary; the two longest tidally influenced river sections are those of the Columbia (140 miles) and the Coquille (40 miles) (table 4.2).

The most distinctive environmental features of estuaries along their length are the horizontally created gradients of salinity and temperature caused by the mixing of fresh river water with ocean saltwater; such gradients are vertical at times, going from fresh to saline conditions as depth increases. The salinity gradient along the length of an estuary varies greatly over time because of the twice-daily ebb and flow of the tides and the seasonal changes, such as winter floods' moving the freshwater seaward. These variations are greatest in the middle of the estuary where salinity conditions are intermediate between the upper freshwater and lower saltwater.

Table 4.2—Tidally influenced reaches of major coastal Oregon rivers^a

River and estuary	Head of tide (river mile)
Alesea	16
Columbia	140
Coos	27 (both Millicoma and South Fork Coos Rivers)
Coquille	40
Necanicum	3 (Necanicum River) and 4 (Neawanna Creek)
Nehalem	9
Nestucca	7
Rogue	5
Siletz	22
Siuslaw	25 (Siuslaw River); and 7 (North Fork Siuslaw River)
Tillamook	7 (Tillamook River); 4 (Trask River); 2 (Wilson River); 1 (Kilchis River)
Umpqua	27
Yaquina	26

^a Adapted from Percy and others (1974).

Seasonal Stratification and Flushing

The density differences between freshwater from streamflow entering an estuary and seawater entering from the mouth can result in vertical stratification of the estuarine water mass. In a density-stratified estuary, a low salinity, low density, mixed surface layer flows toward the sea, and the denser, more saline, seawater originating at the mouth flows upstream near the bottom. This bottom flow replaces the seawater that is entrained and mixed upward, along the length of the estuary, into the surface outflow. This upward mixing continually increases both the volume and salinity of the upper layer as it flows down the estuary.

The presence and extent of vertical-density stratification vary seasonally in Pacific Northwest estuaries, mainly during the rainy winter season when streamflow dominates estuarine hydrography. Winter floods may produce vertical stratification even in the lower segment of the estuary near the mouth; at this season, the upstream flow of saline, ocean water is strong near the bottom and the downstream flow of dilute, mostly riverine water is strong at the surface. The near-bottom flow of marine water weakens gradually in the upstream direction and finally ceases at some point upstream. Flows in the upper estuary above this point are downstream near both the bottom and the surface.

The "null point" in the system in short-term subsurface transport of water and suspended materials, including woody debris, is in the midestuarine region where near-bottom flow is not appreciable either upstream or downstream. Its exact position varies with the volume of river discharge. Below this null point, water and sediment may be transported upstream along the estuary bottom. At and above it is a region of increased turbidity and sedimentation as suspended riverine sediments enter a region of decreased velocity and flocculation. Woody debris may be incorporated into sediments in the estuarine channels of this zone, to be periodically remobilized and flushed farther down the estuary during periodic winter floods when increased

riverflow moves the null point downstream. In summer, floating wood might be retained in the upper estuary, moving downstream only during tidal cycles with the greatest vertical range. In winter, the hydrographic regime favors downstream transport along the entire estuary.

Water in Pacific Northwest estuaries is not strongly density stratified in summer when seasonal rainfall and resulting streamflow are at a minimum and tidal exchange dominates the estuarine hydrographic regime. The relatively great tidal range of the region results in enough volumes and energy to mix the estuary vertically through most of its length. In summer, difference between surface and bottom water at any point is much less than in winter.

Pacific Northwest estuaries typically have a large proportion of tidelands-to-subtidal area that results in a high exchange ratio (Johnson and Gonor 1982). This is the ratio of the tidal prism (intertidal volume) to the total high tide volume of the estuary and is proportional to flushing time if flow is not restricted. Many of the known flushing times are fewer than 10 days in summer. Because of the length of the estuaries compared with the cross section of the mouth, however, these estuaries are "choked." The lower well-mixed sections flush rapidly in the larger estuaries, but the upper regions may take two to four times as long to flush. Successive upstream segments of the estuary take longer to flush, and at one point in the upper estuary the water present at high tide cannot reach the estuary mouth and exit during a single ebbing tide. Most of this water from the upper reaches is returned on the succeeding floodtide to the region of its previous position. This is a seasonal null point. Above this point, the water mass is only gradually replaced by streamflow and tidal mixing, so that it attains a characteristically high salinity in summer and an elevated temperature in shallow areas from warming by the sun.

Both floating and suspended woody debris are retained longer in upper estuarine regions with the longest flushing times, whereas floating wood in the lower segments exits more rapidly. Marine wood borers adapted to the annual salinity and temperature regime of the upper reaches grow and reproduce rapidly at the warm temperatures reached above the summer null point. Decreased flushing also increases the chance that the dispersion stages of wood borers will be retained longer in the upper estuary and thus increases their chance of encountering new wood that is also retained longer in the upper estuary.

Velocity of ebb tide current may be high at the mouth of Northwest estuaries (Bourke and others 1971). Maximum ebb currents may be 6 knots per hour at the mouth of the Columbia River, as much as 7 knots at Coos Bay, and 5 knots at the entrance to Grays Harbor—sufficient to move floating wood rapidly away from the immediate coast and into the coastal current system.

A tidally related, clockwise rotating eddy has been identified just off the mouth of the Columbia River (Barnes and others 1971). The eddy is strongest at ebb tide and brings floating material onshore just north of the river mouth. Large rafts of drift trees off the mouth of the Columbia River, noted in the historic record of early explorations, may have been related to this eddy. Such an eddy would have collected trees washed out of the Columbia and retained them in the near-shore ocean.

Marine, Wood-Degrading Organisms

Much of the water leaving the lower estuary on the ebb tide mixes with outside ocean water and is moved away from the mouth by the longshore current (Johnson and Gonor 1982). The water re-entering the lower estuary on the incoming tide is thus mostly oceanic in temperature and salinity. Outside ocean water is thoroughly mixed with water within the estuary during every tidal cycle below the summer null point. The summer and, to a lesser degree, the winter environmental regime of the lower parts of Pacific Northwest estuaries closely resembles that of the cold near-shore ocean. The marine wood borers of this lower estuarine region cannot tolerate upstream conditions in summer, where the water is warmer, less saline, and more characteristic of southern waters. Because of longer water retention times in the upper estuary, the colonization and survival of warm-temperate wood-boring species are favored once they are introduced.

The fate of trees entering estuarine and marine portions of the ecosystem is mainly determined by organisms that degrade the wood and recycle its nutrients and energy. The kinds of organisms involved and their relative roles in marine and terrestrial environments vary widely. Marine organisms known to degrade wood entering the sea belong to taxonomic groups different than those dominating this process in terrestrial and freshwater environments. They are not as diverse as those in terrestrial environments, and the relative roles of micro-organisms and animals in initial attack on cellulosic materials differ. Marine fungi and bacteria appear to play minor roles in the initial invasion and degradation of wood in the sea. The major roles in degradation of marine wood are played by a few genera of wood-boring crustacea and a larger number of bivalve mollusks (table 4.3). In contrast to the fate of fallen trees in terrestrial environments, wood in estuarine and marine environments is rapidly attacked by animals, long before significant soft rot takes place; the animals disperse it before, not after, microbial decomposition of its constituents.

Isopods

Wood-boring isopod crustacea (gribbles) of the genus *Limnoria* are major reducers of wood in estuarine and marine waters of the Pacific Northwest. Only two species are involved, *L. lignorum*, the endemic northern species, and *L. tripunctata*, the introduced species that is predominantly southern in distribution but is also found in the upper reaches of Pacific Northwest embayments and estuaries. *Limnoria lignorum* is a coldwater species that occurs in embayments and the lower reaches of estuaries. It can reproduce in the cold outer coastal waters where *L. tripunctata* can survive as adults but can rarely reproduce or establish new colonies.

Both species are typical isopods in appearance, resembling small, elongate pill bugs of terrestrial environments. *Limnoria lignorum* is large; individuals average 0.012 to 0.016 inch long and 0.004 inch wide. Adult *L. tripunctata* are smaller, typically about 0.012 inch long and 0.004 inch wide. Although both gribble species are small animals, they are major wood-deteriorating organisms in the sea because (1) they live in dense colonies in interconnecting burrows in the surface layers of sound submerged wood, and (2) they are abundant and widely distributed. They do not attack rotted wood, but bore actively and continuously by removing small pieces of fresh wood from the blind ends of their burrows and consuming them. All wood removed by gribbles during burrowing is ingested. About 45 percent by weight is used and the rest is voided as fecal pellets (Ray 1959a, 1959b). These small, flattened, cylindrical pellets are composed of finely ground wood fibers lightly bound together by a thin membrane of chitin secreted by the hind gut. Fecal pellets are continually washed from the gribble burrow systems by respiratory ventilating

Table 4.3—Wood degraders in estuaries

Classification	Organism	Relation with wood	Life History
Arthropoda; class, Crustacea: <i>Limnoria lignorum</i> <i>Limnoria tripunctata</i> (introduced)	Isopods (gribbles, or wood borers)	Burrow and live in wood in inland marine waters Ingest all wood excavated during borrowing 65 percent by weight of wood is voided as fecal pellets	Live in dense colonies in wood; as many as 30 organisms per 0.4 square inch of wood surface 1- to 2-year lifespan Burrow 0.4-0.8 inch per year in the Pacific Northwest Weak swimmers as adults; no free-swimming larval stage; juveniles or recently matured individuals swarm from colony and are dispersed by currents to other wood; long-distance dispersal may be by floating wood containing colonies
Mollusca; class, Bivalvia: Family, Teredinidae— <i>Bankia setacea</i> <i>Teredo navalis</i> (introduced)	Shipworms (wood- boring mollusks)	Bore and live in wood located in coastal and saline estuary waters Line burrows with calcium carbonate walls Consume some of the wood that is bored	Live in dense colonies in wood in shallow marine waters <i>Bankia</i> : lays eggs in water; pelagic larval stage lasts 3-4 weeks at 12-15 °C and is dispersed by currents; 7-month lifespan <i>Teredo</i> : 10-week lifespan broods developing eggs
Family Pholadidae— <i>Xylophaga</i> species <i>Xylophaga</i> <i>washingtona</i>	Xylophagid borers	Deeper, oceanic wood borers: Burrow and live in sunken wood on ocean floor Ingest wood as food source and process it for other marine benthic organisms	Long-lived larval stage; high reproductive rate; early maturity and rapid growth; characteristics suitable for effective use of an unpredictable and transient food source

currents created by the animals. The nonbuoyant pellets sink rapidly in still water. They are light enough, however, to be easily dispersed by the typical wind-driven turbulence and currents of estuarine and coastal shallow waters. Gribbles convert wood in one step from the original massive, intact form to microscopic, nonbuoyant particles freely dispersed in the environment and deposited in surficial sediments. As individuals of a colony burrow deeper, the outer, riddled region of the wood with the older galleries becomes waterlogged and softened by micro-organisms. Consequently, it is fragile and easily broken into small pieces by abrasion and wave action that gradually removes the outer layers no longer occupied by the gribble colony.

Gribble population density in wood is high, as many as 30 animals per 0.4 square inch of wood surface. Long-distance dispersion along the coast or between embayments is mainly by colonies in wood that floats from one location to another.

Chemical reduction of wood by isopods.--Although gribbles remove a significant fraction of the total weight of wood by passing it through the digestive tract, they do not use all the major polysaccharide components with equal efficiency; and there is no evidence that they can alter lignin (Ray 1959a, 1959b).

Both species of gribbles in waters of the Pacific Northwest are predominantly intertidal or subtidal animals that principally attack wood located in the lower, saline intertidal zone or the portions of large upright pieces, such as pilings, below midtide depth. Gribbles are intolerant of sediment in their burrow system. When colonized logs are rolled by waves across mudflats or sand beaches, the burrow systems become clogged and the colony is reduced or killed. Such wood is readily reinvaded if it is refloated by subsequent tides.

Wood-Boring Mollusks

Other than gribbles, the only shallow-water, wood-boring animals in the Pacific Northwest are two species of shipworms. These are the most important reducers of wood in estuarine and shallow marine waters of the region. The most common species of shipworm is *Bankia setacea*, a coldwater native to the North Pacific found in the open coastal ocean as well as in embayments and the lower parts of estuaries. Because of its abundance, large size, and rapid growth, *B. setacea* is the major marine, wood-destroying animal in these waters. The other species is *Teredo navalis*, a smaller, introduced warmwater species of restricted distribution in the Pacific Northwest.

Shipworms are specialized bivalved mollusks that inhabit shallow water (maximum 650 feet) and coastal areas. They have elongated bodies and use toothed ridges on their specialized shell valves for mechanically rasping their way into wood. As shipworms bore into wood, they secrete a calcium carbonate lining to their burrows. *Bankia* larvae first attach to wood by a byssal thread and penetrate the wood within 48 hours. Cutting teeth develop on the larval shell after attachment, and the metamorphosed larva begins to bore into the wood, burying itself completely within 24 hours.

These infestations, often so dense that their burrows nearly touch, can rapidly attack and convert the interior of large, solid trees into finely divided wood powder that is dispersed into the estuarine environment. The role of shipworms as agents of wood conversion and dispersion in the carbon and energy cycles of Pacific Northwest coastal waters has not been studied. *Bankia setacea* is a highly opportunistic species with rapid growth, a relatively short adult lifespan, a high reproductive output, and widely dispersed, long-lived pelagic larvae capable of rapidly colonizing new wood as it arrives in the coastal waters. In Pacific Northwest coastal waters, infestations of wood by *Bankia* are intense.

Bankia uses the cellulose fraction of the wood with about the same efficiency as gribbles. Lignins and the remaining cellulosic material are not digested but are voided as finely divided detrital particles in fecal pellets. Shipworms must bore to grow, so much of the bored wood is not ingested but is flushed directly out of the burrow as it is ground into a fine powder. Shipworm fecal pellets are lightly bound with mucus and easily break apart. The fine wood particles they contain are not buoyant but are easily suspended. Shipworm wood borings thus become microdetritus, like those from gribbles, and directly enter the detritus web.

Xylophagid Borers

Deep-sea wood-boring bivalves (xylophagid borers) are found off the Pacific Northwest coast. These borers quickly invade wood in the deep sea and grow rapidly. Their boring activity converts the wood into fecal pellets that settle to the sediment surface and attract other deep-sea benthic animals. Their conversion of wood into a readily available detritus source supports the development of a complex benthic community.

Like the shipworms of shallow water, the deep-sea xylophagids are opportunistic species. They quickly colonize wood that, having been carried offshore, becomes waterlogged and sinks to the deep-sea floor. In the North Atlantic, test boards on the floor of the sea (5,948 feet) became infested with a dense population of two species of xylophagids within 104 days (Turner 1977). These deep-sea wood borers have a high reproductive rate, an early maturity, a high population density, and rapid growth—characteristics suitable for effectively using wood that is an unpredictable and transient habitat and food resource in the deep sea. Because adults die as the wood is consumed and disintegrates, dispersion must be through an abundantly produced, efficient, and long-lived larval stage that searches for wood at the sediment-water interface.

Like shipworms, xylophagids use wood for both habitat and food. They are probably the most important deep-sea organisms for converting wood into a finely divided detrital source of food for other deep-sea benthic organisms. They also provide locally abundant prey to deep-sea benthic predators.

Fungi

Marine fungi degrade cellulosic materials, but their ability to rapidly or extensively degrade large pieces of wood appears to be much less than that of terrestrial fungi. Cellulolytic activity has been demonstrated, however, in some taxonomically diverse marine species of Fungi Imperfecti and Ascomycetes. These same organisms have been associated with soft rot attack and weight loss in experimental blocks of wood placed in the sea (Jones and others 1976). Virtually nothing seems to be known about their ecological roles in wood degradation and energy or nitrogen flow in marine detrital systems. Marine fungi are not requisite for the initial attack on wood by the primary marine wood-deteriorating organisms in Pacific Northwest waters. Most of the fungi that break down lignin attack only the wood surface, no deeper than one-eighth inch. Species of the fungal genus *Luworthia*, however, penetrate deeply into wood and are more like terrestrial wood-decaying fungi.

Bacteria

The role of cellulose-degrading bacteria in the sea is obscure, but many species of marine bacteria have been identified as active degraders of cellulose (Kodata 1958). Cellulose-decomposing aerobic bacteria are abundant in seawater and bottom sediments and are widely distributed in the sea and estuaries. These organisms play an important role as remineralizers of cellulose-containing organic matter, but their exact role in marine and estuarine carbon cycles is not known. Some cause rapid deterioration of cotton nets in the sea, and some colonize and attack submerged wood. Cellulolytic bacteria in the digestive tract of the shipworm *Teredo navalis* are probably responsible for the breakdown of ingested cellulose. Previous or concurrent direct attack on wood by bacteria, however, is not a prerequisite to marine borer activity. Bacteria seem to be important in the breakdown of finely divided wood particles, but the intermediate ecological roles of cellulolytic bacteria in the degradation of cellulosic detritus produced by marine wood borers have not been evaluated.

Fallen Trees in the Tidally Influenced River

High water, especially winter storm floods, brings large trees into the tidally influenced region of coastal stream systems. Tides influence water level even in the extreme upper region of the estuary where the salinity is too low for marine wood-boring animals to survive. Surface salinity is virtually zero, but bottom water may contain some salt in summer. The ecological functions of fallen trees in the tidal river water are much the same as those upstream, but many of the fish and other animals are different from those upstream. Fallen trees and logs are present in channels and on intertidal banks, including any freshwater marshes in the reach under tidal but not salt influence (Secretary of the Treasury 1859) (fig. 4.4).

A large drift tree whose roots embrace a mass of hard clay or stones...may very readily be carried outward by the strong effluent current of the Columbia, and especially in the season of freshets; but when the current slacked the root of the tree would remain upon the bottom, sink into the sands, and continue stationary whilst the remaining movement of the current would be able to shift the loose sand and deposit it around the roots.

Fallen trees influence the estuarine portion of the ecosystem, mainly through their physical properties as large masses; they form heavy, solid objects and firm substrates in an environment where the bottom consists mainly of fine sediment. Fallen trees in the tidal river segment of coastal stream systems create riffles and provide shelter from predators for upper reach fishes. Examples of common fishes in this section of Pacific Northwest estuaries are stickleback, sturgeon, starry flounder, and juvenile and adult salmonids. Fallen trees can also affect local waterflow patterns by creating turbulence and thereby affecting the sedimentation pattern and the formation of bars or mudbanks. Emergent parts of fallen trees stranded in the channel or partly or wholly on tidally exposed banks are used by water birds as refuge perches during daily rest cycles, or by predatory birds, such as herons and eagles, as hunting perches.



Figure 4.4—Rootwads help anchor driftwood (photo, courtesy of the Oregon Historical Society, negative ORH 45285).

Fallen Trees in the Tidal River

Biological decay in the uppermost estuary (freshwater, but tidally influenced river section) is slow, on the order of many decades, especially for trees partly embedded or buried in typically anaerobic upper estuarine muddy sediments where attack would be only from cellulolytic fungi. Unlike the saline lower estuary, there are no animal groups to act as rapid degraders. Battering by trees rafted downstream on floods or uplifted and carried by tides is probably the major force breaking trees into smaller components. Rolling breaks branches, and trees are typically caught on tideflats by stubs of broken branches.

Fallen Trees in the Upper Estuary

Fallen trees are further transported by floods and tides from the tidal river into the upper estuary system, that brackish, tidally influenced region above the summer null point. Salinity in summer at both surface and bottom can be appreciable but less than in the more marine lower reaches. Salinity in winter is very low, and most marine animals not adapted to prolonged lower salinity cannot survive. Because of lower streamflow and limited tidal flushing in summer, water temperatures in the upper estuary are significantly higher than those in the lower reaches, so marine wood borers are not present.

The gribble *Limnoria tripunctata* is found in marine waters from inland British Columbia through the Puget Sound region and in all the major estuaries of the Douglas-fir biome. The introduced shipworm *Teredo navalis* is established on the Pacific coast in San Francisco Bay and in the inner parts of a few embayments on outer Vancouver Island. It is more resistant to periods of lower salinity and higher temperature than the native shipworm *Bankia setacea* and consequently can establish populations in upper estuarine areas where *Bankia* cannot colonize. Trees and logs caught in the channels, or stranded, or embedded in the banks and tideflats of the upper estuary are soon attacked by the gribble *L. tripunctata*.

Attack by gribbles provides continuous and rapid physical breakdown of the wood surface that reduces the radius as much as an inch a year and produces large quantities of fecal pellets. The easily suspended fecal pellets are a carbon source of the sediment surface and the midwater pelagic system. Gribbles transfer fine wood particles to the carbon pool of the benthic sediment system by enormously increasing the surface area of wood and effectively converting trees directly into nonbuoyant wood powder. Further microbial degradation of gribble fecal pellets by cellulolytic bacteria in the surface sediments may channel this carbon source into the benthic detrital food web. The role of wood transferred to benthic and pelagic detrital systems in the form of fecal pellets from marine wood borers has not been examined. Organic detritus is the principal energy source for food webs in estuarine and shallow marine benthic portions of the ecosystem; the principal source of this detrital carbon is debris from macrophytes in the system. Some of the pelagic food web is also based on detritus, and fecal pellets from gribbles are an appropriate size for direct ingestion by zooplankton. Attack by marine borers dramatically increases the rate at which the wood becomes waterlogged and sinks. The role of such wood as large, solid, in-place objects is similar to its role already described for the upper estuary.

Sediment lodges in the extensive spaces of abandoned outer burrow systems of gribble colonies, and some sediment fauna are found in the old, riddled wood. As the surface area of the hardened wood increases, the older portions are invaded by bacteria and marine lignicolous fungi that attack the remaining wood.

Recently arrived, buoyant trees and logs in the upper estuary are transported by river floods and winter high tides to the extreme edge of the highest reach of winter high waters, the highest of the year. This usually results in a dramatic strandline of large trees and logs, sometimes in continuous rafts, in the upper or high salt marsh that is the community type characteristically present at this tide level within the upper estuary. Trees and logs function here as agents of disturbance in an otherwise very dense, productive, and uniform plant community, the consequences of which we discuss later (fig. 4.5, color).

Fallen Trees in the Lower Estuary

The lower estuary, from below the null point to the mouth, is dominated by marine influence. Its salinity and temperature range are nearer to those of the open coast than to those of the upper estuary. Trees and logs here are degraded to smaller detritus but have the same physical role as in the upper reaches of the estuary.

Trees and logs transported into the lower region of Pacific Northwest estuaries enter a habitat too cold in summer for reproduction by *L. tripunctata*. Lower estuarine salinity regimes, however, are sufficient for occupation and survival by the two indigenous species of marine wood borers, *L. lignorum* and *B. setacea*. Both can colonize wood for most of the year, and *Bankia*, in particular, has a high growth rate and can significantly degrade large pieces of wood within 1 year. Between the two, any stationary wood in the lower estuary is rapidly destroyed. The result, again, is reduction of large masses of wood to a fine, nonbuoyant wood powder, most of which is introduced into detritus-based food webs of the estuary. Both the mass and the physical properties of trees are altered; waterlogging increases, and the surface of the trees is converted into a friable mass of riddled wood rapidly abraded into macrodetritus by waves and battering. Shipworm wood borings and fecal pellets become microdetritus and directly enter the detritus web.

Fallen Trees in Salt Marshes

Salt marshes are densely vegetated, low coastal wetlands at elevations within the annual vertical range of regular tidal fluctuations. Plants of the salt marsh community are capable of growing in saturated estuarine sediments and withstanding stresses from salinity and tidal inundation. The requisite conditions of lower salinity, extensive areas of soft sediments at high tide levels, and low wave energy are virtually restricted to estuaries in the Pacific Northwest.

There are no true open coast salt marshes in the Pacific Northwest. Estuarine marshlands have built relatively rapidly toward the sea by deposition of sediments influenced mainly by modern economic activities. Extensive areas have been removed from estuarine systems through diking for agriculture, pastures, roadbuilding, and construction. Logging, road construction, and cultivation—all of which disrupt watershed stability—increase sediment loads in rivers and streams and result in increased sediment accumulation rates in estuaries.

Salt marshes are important parts of estuarine systems in the Pacific Northwest. Salt marshes have very high annual plant production rates, a significant fraction of which is exported to the rest of the estuarine portion of the ecosystem as plant detritus. They also function as hydraulic buffers to flood and storm surges because of their extensive area. Migratory waterfowl and juvenile fishes, especially salmonids, use tidal drainage creeks in the marsh at high tide.



Eilers (1975) examined the role of trees in salt marshes of the Nehalem estuary in Oregon through the use of historic charts and aerial photographs and by direct observation. Information indicated that trees have long been important in salt marshes. The upper margins of the high salt marsh were clearly delimited in 1939 aerial photographs by extensive and continuous piles of large drifted trees. Trees, many of them large, were abundant enough to obstruct the channel in the period around 1900. An island, which first appeared in the Nehalem estuary between 1875 and 1914, was covered with live trees and fallen trees associated with other changes in topography. The island today stands 6 feet above tide level, illustrating the sediment trapping ability of piles of down trees and associated vegetation.

Eilers (1975) found that circular-to-oblong depressions, 1.8 to 6.8 feet in diameter and 0.8 to 1.6 feet deep, common in the high marsh at tidal elevations between 9 and 10 feet above mean low water were former resting places of large drifted trees that had been moved about by extreme high tides. When drift trees remain in place in marshes for long periods, the general elevation around them increases from siltation and accumulation of organic matter. When these trees refloat during unusually high tides, floods, or storm surges, the shallow depressions that remain in the marsh increase habitat diversity; at low tide, these depressions are filled with juvenile fishes. Refloated trees are an important source of disturbance that also influences the distribution of marsh plant communities and plant succession (*fig. 4.6, color*).

The relative mobility of large drift trees and logs in different parts of the high marsh influence successional processes in opposite ways. A spruce/alder/willow wetland forest community dominates the highest portions (9.4 to 9.8 feet mean lower low water) of the salt marsh, slowly invading it as the progradation characteristic of marshes in this region proceeds (Eilers 1975, Johannessen 1964). This forest advances in some places by active colonization of stable piles of drift trees and logs left on the high marsh by past storms. Large drifted trees embedded in the marsh are colonized by terrestrial plant species unable to grow directly on the marsh soil because of salinity. Most of the spruce in the high marsh were growing on nurse trees, and few of the spruce roots extended into the marsh soil (*fig. 4.7*). In other parts of the marsh exposed to winter storm waves, the forest edge was in retreat, mainly because accumulations of drifted trees battered against the trees and upper marsh shore at abnormally high tides (Eilers 1975).

Drifted trees in the upper marsh are exposed to a wet, predominantly freshwater environment and resemble decaying fallen trees in terrestrial environments rather than trees elsewhere in the estuary. If these trees remain in place, they are attacked by wood-decaying fungi and show the typical sequence of internal rotting. Their relation to nitrogen cycles in the upper marsh and to small mammals inhabiting this environment is not known.



Figure 4.7—Sitka spruce grow on nurse logs in Oregon coastal marshes.

Use of Drift Trees in Estuaries by Birds and Seals

Much of the following information about birds' use of emergent portions of drifted trees and logs in estuaries is from Bayer's (1978, 1983) extensive studies of birds' use of estuarine resources in Yaquina Bay, Oregon.

Bald eagles use trees and logs away from shore on tideflats and on sides of estuary channels; they avoid perching directly on soft mud surfaces. Because eagles forage from a central place, use of perches near shore rather than more distant, taller trees conserves the birds' energy. They perch in places that provide good visibility of open channel water and of tideflats where they watch for opportunities to capture aquatic birds or steal prey caught by gulls and herons in the shallows on the tideflats (Stalmaster and others 1985). Drift trees on flats are more centrally placed in relation to potential food resources for eagles, so flight time to and from a foraging area is less (fig. 4.8).

Green herons, great blue herons, and great egrets are predators that prefer to stand and wait for prey, principally fish, to pass by. They can wade in the intertidal flats only when the water is no more than 8 inches deep. Herons and egrets use drifted trees that remain partly out of water at times of high tide, as well as floating logs, log rafts, and booms as perches for resting and foraging. Great blue herons defend feeding territories on log rafts when they are available, virtually confining their feeding activity to these territories. They conserve energy by using emergent wood near or surrounded by water to combine two necessary daily activities—perching and foraging. Herons thus have more time for foraging than they would hunting for fish when the tide is low enough for them to wade in the shallows. When perches on tideflats or in the channels are not available, herons must alternate between perching in distant trees to rest and wading at low tide to forage, with flights necessary between perching and foraging locations. Herons in upper Yaquina Bay have established territories on log rafts floating along channel margins. These herons can avoid long foraging flights and require smaller feeding territories because the rafts are over deeper water than they could wade in; thus they can also catch larger fish found in deeper water than they could by wading on the flats where smaller fish usually occur.



Figure 4.8—Bald eagles choose to perch on mudflat objects, such as driftwood, rather than on the tidal substrate (photo, courtesy of Range Bayer).

Cormorants and brown pelicans also require perches for rest between periods of foraging, and they prefer perches surrounded by water and away from the shoreline—wooden structures, such as piling, and stranded logs and trees. Small shorebirds that feed on tideflats at low tide and require perches for resting at high tide use any available emergent wood.

Natural, old, drifted trees are more abundant in Siletz and Nestucca Bays than in some of the other Oregon estuaries; birds can nest in young trees growing on drifted trees and logs stranded in the intertidal area. Purple martins, which require rotting wood for cavity nesting, use tree butts sticking out of the flats at Siletz Bay. Because rotting trees on land near water have become scarce, suitable stranded trees become important resources for these birds.

Gull-nesting areas within estuaries are uncommon today because of limited suitable nesting habitat. Pilings, humanmade structures that resemble formerly more abundant stranded trees, are used by gulls for nesting (Bayer 1983).

Natural drifted trees in estuaries and the use of herring spawn by marine birds in Oregon estuaries are indirectly related. Herring that enter estuaries to spawn require solid substrates in the intertidal area for egg (spawn) attachment. In estuaries where the intertidal area and shore are predominantly soft muddy sediments, solid surfaces are limited. Masses of herring spawn are attached to red algae, rockweed (*Fucus*), eelgrass, rock, shells, and pebbles on the flats and on any available wood, such as logs and drift trees, especially branches of trees stranded in estuaries. Using herrings' preference for finely divided spawning substrate, Pacific Northwest Indians once placed brush and cut branches in the estuaries during the herring spawning season to collect spawn to eat. At present, suitable intertidal spawning substrate is limited in Oregon estuaries, and herring spawn becomes overlaid and crowded on the substrate. Crowding greatly reduces hatching success by creating oxygen deficiencies in the mass of spawn. Masses of excess spawn break free and are



rolled across the tidflats by waves to accumulate on beaches. Both this beached spawn and the spawn remaining attached in place are eaten by birds, including nonaquatic species, such as crows. Gulls feeding alone can consume most of the spawn on a beach at low tide. During the herring spawning period in Yaquina Bay, the total resident bird population increases from about 1,000 to 2,000 birds of each species to a total of about 10,000 birds (Bayer 1980). To the extent that suitable intertidal substrate, such as stranded tree branches, limits herrings' spawning in estuaries, the availability of herring spawn as food to birds associated with estuaries is limited.

Rafted and stranded trees and logs away from the shoreline and undisturbed by people are potentially important to harbor seals, which require haul-out areas for resting out of the water. These seals now haul out on log booms and log rafts in the channels of estuaries. The availability of log booms during the day increases the time that suitable haul-out space is available to harbor seals. Without this type of resource, seals can haul out on shore only at night when people are not present. Natural rafts and drifted trees stranded on tidflats very likely were once also used for haul-out by harbor seals and may have been one of the limiting resource for seal populations in Pacific Northwest estuaries (Bayer 1981, 1985; Calambokidis and others 1978).

Fallen Trees Rafted Out of Estuaries

Aboard a seagoing vessel off the Northwest coast in heavy seas during a storm in November 1852, James Swan (1857) reported:

The next morning we found ourselves about thirty miles to the westward of the Columbia River, from which a huge volume of water was running, carrying in its course great quantities of drift logs, boards, chips, and saw dust, with which the whole water around us was covered.

How much wood was historically transported to the ocean is not known, though it must have been substantial at a time when most of the riparian zones along the river corridors and in the watersheds were dominated by large conifers. Hundreds of millions of board feet of logs and downed trees have come down into Puget Sound in Washington and Georgia Strait in British Columbia from the rivers that drain the Washington Cascade Range and the British Columbia coastal mountains. These large quantities were joined by significant numbers of logs that were separated from rafts in estuarine log storage areas or from towed rafts (fig. 4.9). More than 10 billion board feet of logs are annually stored or travel in estuaries and lower rivers of the Pacific Northwest from Alaska to California, including British Columbia (Sedell and Duval 1985). A 1-percent-escape rate would allow more than 100 million board feet to enter the ocean from this source alone.

More than 2 billion board feet of wood is estimated to be annually transported to the North Pacific ocean, an estimate believed to be conservative because large regional storms were excluded from the calculation, and pieces of wood less than 10 feet long were not considered (Sedell and Hansen, unpubl. data). Two billion board feet per year is a small amount for the entire northeastern Pacific from San Francisco Bay to Nome, Alaska. This is testimony to the retentive nature of rivers and estuaries, as well as to the substantial reduction in volume and size of wood now entering western streams.

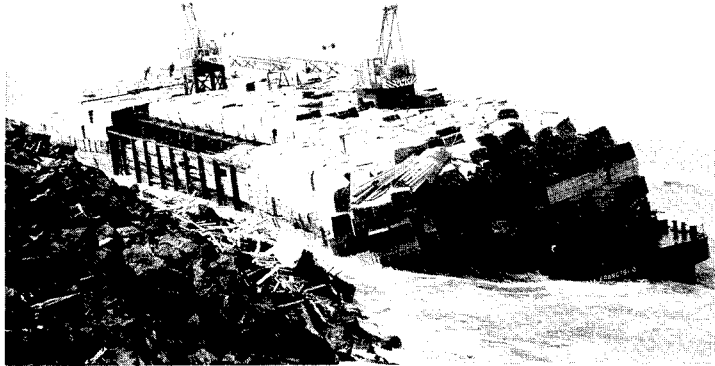


Figure 4.9—Logs and other escaped wood added to driftwood in estuaries and on beaches (photo, courtesy of Jack's Photo Service, Coos Bay, Oregon).

Amounts of wood in rivers and estuaries in the past were high compared with today's supply. In the past, sources of large, long trees were abundant; a large amount of wood was stored on beaches, in estuaries, and in rivers; and there were no dams on the rivers (fig. 4.10). A vast array of organisms have adapted to the use of this material. Some may find substitute habitats, but others—obligate feeders of wood in the ocean environment—cannot.

Today, only 7 of the 17 coastal port authorities in Oregon are directly involved in snag, stump, and debris removal in their estuaries. The sources of drift have been greatly reduced since the 1850's, and the opportunities for wood to be retained in the lower estuary have also been reduced through diking, marsh filling, and channelization. Pilings create retention sites, but these sites are likely to be cleared of debris.

Ocean Transport of Woody Debris

The transport and fate of floating or sunken woody debris discharged from estuaries into the ocean is determined by regimes of coastal wind and current. Along the Oregon and Washington coasts, these regimes differ in direction and intensity with season, so that the direction of wood transported from the same estuary varies greatly. The California current flows south along the coast all year, a broad and slow, surface flow of about 0.2 knot per hour. During the winter, a second coastal flow known as the Davidson current forms and flows northward over the Continental Shelf, pushing the California current somewhat offshore. Its mean velocity is 0.35 knot per hour and results from strong northerly atmospheric circulation.

Prevailing coastal winds shift north-south direction seasonally, with short transitional periods of weak winds. Strong winds blow predominantly out of the southwest from October through April (Barnes and others 1971) (fig. 4.11A). Occasional periods of onshore winds during the summer move a shallow layer of surface water northward along the coast and toward the shore. Storm winds often beach large trees floated out of estuaries and northward along the coast. Redwood stumps from northern California are stranded on Oregon beaches when high tides and storm surges combine to cause unusually high water.



Figure 4.10—Beached wood in the late 1800's often included cut logs as well as drifted trees (photo, courtesy of the Oregon Historical Society, negative ORH 26616).

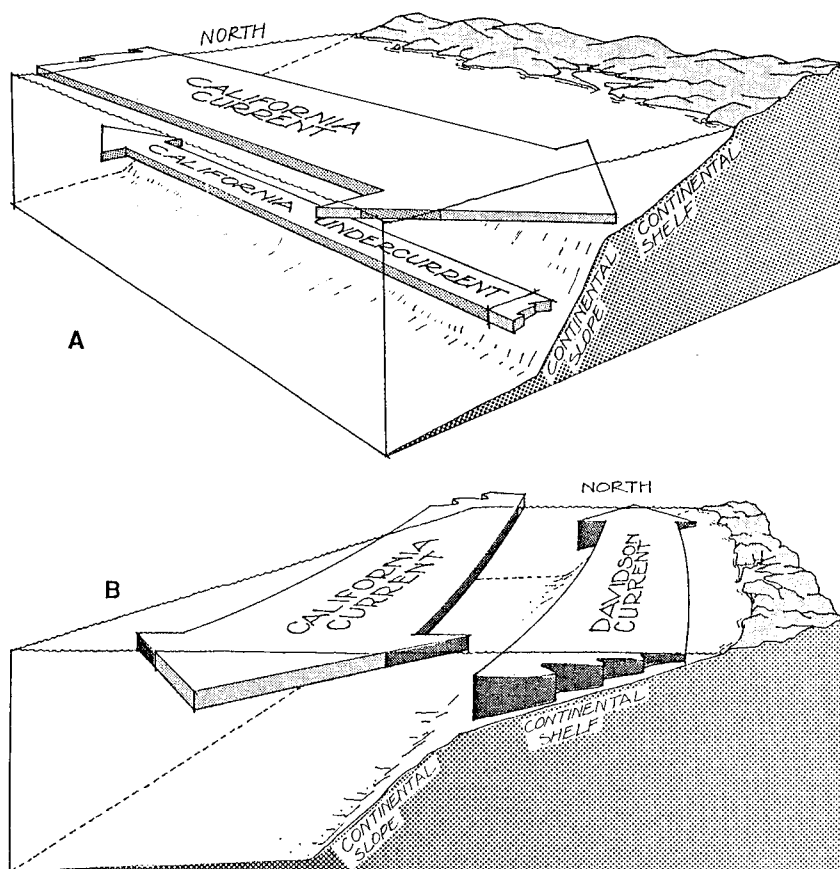


Figure 4.11—Nearshore currents transport wood north along Oregon coastal beaches (after Parmenter and others 1985): A. Summer circulation off Oregon. The California current, a broad, shallow surface current, drifts slowly southward over the Continental Shelf and slope during the summer. The California undercurrent is a narrow, fast-moving current flowing northward at depths greater than 650 feet over the Continental Slope. B. Winter circulation off Oregon. The fast-moving, relatively narrow Davidson current flows northward at all depths over the Continental Shelf. The California current, flowing slowly southward on the surface, is pushed offshore by the Davidson current.

Fallen Trees Along the Shore

Weaker coastal winds that are more constant in direction blow from the north-northwest from May to September and create a nearshore current that flows south and offshore (fig. 4.11B). In contrast, when floods bring large quantities of wood downstream into the coastal system, wind and currents keep floating wood inshore and do not allow it to circulate in the open ocean. In summer, offshore movement of water from the nearshore zone is balanced by upwelling of deep water in a zone 5 to 10 miles from the shore. Complex shoreward movements associated with these upwelling fronts may also entrain wood and retain it in the coastal region.

Driftwood deposits of the Pacific Northwest differ in both kind and quantity from those observed along other coasts. More important even than the great size of individual trees or logs is the massiveness of the overall deposits, each of which may cover many acres of beach to a depth exceeding 10 feet (fig. 4.12, color). The total accumulation of driftwood between Cape Mendocino in California and Puget Sound in Washington is estimated to be several million cubic yards or a few billion board feet (Stembridge 1979).

Trees are driven ashore on sand beaches by wind and waves along most of the Pacific Northwest coast. These trees form large piles of driftwood, once characteristic of Pacific Northwest shores, until removed by extremely high water. They act as barriers to wind-transported sand and can form the nucleus for at least a temporary accumulation of sand. Drifted trees are often found deep in the base of large dunes and spits when another cycle of waves erodes the sands.

Drifted trees play an important role in natural cycles of erosion and deposition of beaches and foredunes along the Oregon coast. These cycles were examined by use of a series of aerial photographs beginning in 1939 to study long-term changes in the Siletz spit (Komar 1983, Komar and Rea 1976). There, erosional and accretional episodes occur along segments of the shore 325 to 1,950 feet long. The following sequence of events was identified:

1. Rip-currents begin to erode embayments in the foreshore. During periods of high tides and high waves, the deepened embayments permit waves to reach the back-shore area and the seaward edge of the foredunes, eroding a vertical scarp into them.
2. Subsequent high tides deposit drifted trees and logs in the embayment at the base of the scarp.
3. Lower energy waves build a broad, high "summer" berm in the embayment.
4. The criss-crossed mass of trees and logs behind the berm effectively trap sand washed in by waves or blown onto the upper beach at low tide by the predominantly onshore winds.
5. Windblown sand continues to accumulate around the trees and logs, reestablishing the foredune, which becomes colonized by dune grass. The foredune often becomes reestablished in 10 to 15 years.
6. Dune reformation is eventually followed by another episode of erosion, repeating the cycle and exposing trees and logs previously embedded in the dunes.

More evidence of the influence of driftwood on shoreline stability and accretion comes from a study of the Alsea spit in Oregon (Stembridge 1974, 1979) and from studies of the beaches of northern Puget Sound in Washington (Terich and Milne 1977). Recent changes were charted along Oregon's 300-mile ocean shoreline, and 110 miles of stable sandy shore and 40 miles of prograding sandy shore were identified (Stembridge 1976). Much of the stability and accretion was attributed to changes in land-use during the 20th century that resulted in an increase in the coastal sediment supply, in the deposition of saw-log driftwood, and in the introduction of European beach grass.

Drifted trees may thus act as passive, stabilizing objects along coastal dune fronts. Because trees shelter or shade some sand, colonizing plants often grow in the moister sand at the base of stranded trees. Other plants, such as Sitka spruce, grow on drifted nurse logs on the backshore. Driftwood not only provides beach stability but contributes moisture and nutrients that appear to be necessary for the establishment of woody vegetation (Stembridge 1979). The role of driftwood in the maritime dune fringe community has not been well studied. Burrows of mice and insects can be found around the highest, oldest, driftwood trees embedded in dunes behind sandy beaches, particularly on shores in a prograding phase.

Trees beached on rocky shores undergo quite different processes. Winter storm waves batter and pile up large quantities of driftwood against the sides of rocky points and headlands. Such trees are highly abraded and roughly splintered, and winter shores abound in the freshly broken fragments of these trees. Most of this splintered and shattered material is partly waterlogged, and much of it is not buoyant. It appears to undergo further direct grinding on rocks into coarse woody debris, some of which lodges among and below rocks, whereas the greater part is washed into deeper water by the waves. Rocky shores are thus another site of direct and rapid degradation of large trees into small fragments capable of entering a detritus-based system through physical rather than biological agents.

Trees have an important ecological role in rocky shore intertidal community structure. Sessile plants and animals in this community compete for the major limiting resource—attachment space. In the absence of other influences, the more successful or dominant competitors gradually exclude others and occupy all surface space, which results in decreased community diversity. Battering by trees at high tide during winter storms is a significant force in opening up patches of unoccupied space, which thereby contributes to the maintenance of a mosaic community of higher diversity (Dayton 1971). Patches of attached organisms or those cleared by tree abrasion produce a mosaic of different phases of colonization and thus prevent complete occupation of all space by the competitive dominants, with concomitant reduction in community species diversity. Disturbances of both physical (waves and trees) and biological (grazing and predation) origin were the major forces that produced structure and order in the space-limited intertidal community of rocky shores (Dayton 1971).



Figure 4.13—Driftwood Beach State Park, San Juan Island, shows that some beaches are still (1986) covered with wood.

As much as 50 percent of the trees along the rocky shores of San Juan Island showed saw-cut ends and were obviously from logging operations (fig. 4.13). About 15 percent of the trees had intact root systems, indicating they originated from erosion of shores and streambanks. The remaining 35 percent of trees on these rocky shores were too worn to determine their origin. By contrast, at an open coast site on the Olympic Peninsula, less than 1 percent of drift trees were saw cut, indicating that most of the large accumulations of such wood in this relatively remote location were of natural origin (Dayton 1971). Even today, naturally derived trees play an important role in community processes on some rocky shores. This role is obviously proportional to their abundance and size, which once were greater than they are now.

Present-Day Look at Wood on Coastal Beaches and in Estuaries

Wood volume on coastal beaches varies between locations and fluctuates between seasons. In winter, storms transport wood downriver into the ocean, then deposit it on the beaches. In other seasons, there may be a net loss of wood from the beaches back to the ocean.

Seventy percent of the volume of woody debris longer than 1.6 feet was lost from river-mouth beaches from 1970 to 1984 (Benner and Sedell, in press).

Gone are the mature stands of trees that were the source of large driftwood before the late 1800's. Wood is being used for fuel in home wood stoves, and the number of Forest Service free-use wood permits (*fig. 4.14, color*) issued by the Pacific Northwest Region for cutting cords of firewood have increased by more than 800 percent from 1970 to the present (*fig. 4.15*). Forest practices regulations that directed the cleaning of wood from stream channels during logging operations in the 1970's in the Northwest also reduced the source of woody material for estuaries and beaches. Fewer logs now escape from lumber operations and other human-related sources (*fig. 4.16*).

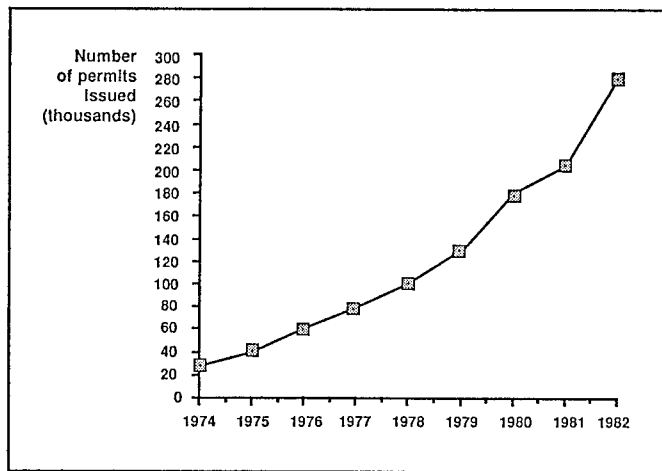


Figure 4.15—Increase in Forest Service free-use permits for firewood, 1974-82.



Figure 4.16—Log boom stores logs in an Oregon slough in the late 1800's. Some logs escaped to the beaches (photo, courtesy of the Oregon Historical Society).

Drifted Trees in the Open Sea

Floating trees can travel long distances and are quickly colonized by shipworms, gibbles, and barnacles. When this moving wood sinks to the bottom of the ocean, it forms the primary energy base in a diverse community of invertebrates and functions as an island of productivity in an otherwise stable, low diversity, low productivity environment. Schools of small fish are also attracted to floating objects, including drifting trees and slow-traveling boats. The schools in turn can attract predator fish, such as tuna, and an ecological community becomes associated with the floating forms.

Transport and Fates

Drifting trees that escape the inshore tidal currents enter the open sea. In winter, nearshore currents along the Pacific Northwest coast transport trees northward. Unless these trees are moved farther offshore, they will eventually be beached by stormwinds. The direction of transport in the California current system is southerly inshore in summer and offshore all year. If trees escape onshore transport and enter the current, they are carried into the open sea where they may enter the westward transport of the North Pacific gyre.

An inventory of driftwood along some beaches on the Hawaiian Islands showed that most of the trees were from the west coast of North America (Strong and Skolmen 1963). The other trees were native to the Philippines, Japan, or Malaya. Even if attacked by marine borers, large trees remain afloat for long times and, if they are carried into the central gyre system of the North Pacific, may be transported for long distances across the Pacific, to beach in such places as the Hawaiian Islands. Ancient Hawaiian civilizations prized and preferred the huge Douglas-fir trees that washed up on their shores. Local chiefs made double canoes from the large stems, which were described by explorers and missionaries in the early 1800's (Heyerdahl 1952, Strong and Skolmen 1963). The anthropological records show an integrating of large, floated Douglas-fir and redwood trees into the customs and rituals of Oceania cultures.

Biological Role of Floating Trees

Large trees capable of remaining afloat for long periods of time are natural agents in the dispersion of marine wood borers and attached, sessile plants and animals, as well as of nonswimming mobile animals associated with these encrusting or "fouling" species. Trees at sea are usually heavily laden with growths of such epifauna and flora, including both attached species from the open sea and nearshore species acquired in transit to the open sea. In addition, the water strider, the only insect to have invaded the open sea and become pelagic, lives and lays eggs on driftwood.

Many pelagic fish species of commercial and recreational importance associate with floating objects in the open ocean. Tunas in particular aggregate around trees and logs and other flotsam. Both Japanese and American fishers routinely seek such objects while fishing for skipjack tuna and yellowfin tuna in the eastern and western Pacific (Inone and others 1963, 1968; Kimura 1954; McNeely 1961; Uda 1952), and their success rate for tuna was well over 4:1 in favor of seines set around drifting trees and logs (Pacific Tuna Development Foundation 1979).

Several hypotheses have been suggested to explain this association. One is that shadows cast by floating objects make zooplankton more visible to predators (Damant 1921) or that pelagic fish simply seek shade from the floating material (Suyehiro 1952). Floating trees and logs serve as egg and algal attachment sites, as invertebrate food and habitat, and as cleaning sites where external parasites on pelagic fish are removed (Gooding and Magnuson 1967). Communities of organisms may form food webs in association with drift logs (Brock 1985). Small fish initially accompany a drift tree, feeding on small planktonic organisms in its vicinity. With time, larger predators arrive, taking advantage of accumulated prey. Prey respond by using the floating tree as a shelter. Within 5 weeks from the time of initial object or tree placement, the forms of predators (tunas and dolphin-fish) in the vicinity of the object may vary as much as 100 tons. Predators rapidly deplete the available prey, albeit prey continuously recruit to the object. In their search for food, predators move away from the object to return later, apparently using it as a focal or reference point.

Based on underwater and surface observations, dolphin-fish may range from 0.3 to 2.5 miles from a floating tree and return 15 minutes to 1 hour later. Yellowfin and bigeye tuna have been ultrasonically tagged and tracked in Hawaiian waters and found to travel 6 to 12 miles from a floating tree, then to return 10 to 20 hours later (Brill and others 1984).

Size of floating debris has an effect on the attraction of fish to it. Objects with greater dimensions have experimentally been found to attract larger numbers of fish (Hunter and Mitchell 1968). A lower size limit of effectiveness of an object appears to be about 1 square foot. Drifting trees with limbs and roots vertically oriented in the water attract fish better than do trees or logs with horizontal orientation (Yabe and Mori 1950).

Wood in the deep sea not only serves as a source of energy in an energy-scarce environment but also contributes to environmental diversity and associated community complexity in the deep sea. Wood, along with other remnants of land plants, was often present in dredges from the deep-sea floor, even from deep-sea trenches (Bruun 1957). A sunken tree is a focus of abundant deep-sea life for a long time (Bruun 1957, Turner 1977). Wood is more common on the deep-sea floor off the mouths of rivers and wooded coastlines, and deep-sea hauls rich in land-plant debris had a large number and high diversity of deep-sea animals (Bruun 1959; Knudsen 1961, 1970).

Trees escaping into the nearshore system are usually infested with gribbles and shipworms or become invaded while near shore. Such trees gradually become waterlogged and sink slowly if they are not driven ashore by winds. Trees that are attacked by marine borers and sink over the Continental Shelf or in the deep sea represent a direct entry of terrestrially fixed carbon into the oceanic benthic system. The sources, forms, and routes of supply of organic material to the energy-poor deep sea are little known. Woody debris containing deep-sea species of molluscos wood borers of the genus *Xylophaga* have also been recovered from deep ocean areas. It has been experimentally demonstrated that these deep-sea molluscos wood borers quickly attack wood samples placed on the floor of the sea.

These pelagic teridas have large populations, high reproductive rates, rapid growth, and short lifespans, making them the first known case of an opportunistic species in the deep sea. Like their shallow-water shipworm relatives, they produce large amounts of finely ground wood fragments. Piles of fecal pellets produced by borers may attract more than 40 species of epibenthic, deep-sea invertebrates known to use detrital sources (Turner 1981). The enrichment of the bottom, a result of the disintegration of the wood and the accumulation of fecal pellets, contributes to the development of a rich fauna.

Wood also appears to be the normal habitat of some species of small deep-sea mytilid bivalves that attach themselves to crevices in burrows of wood borers. Terrestrially derived plant material in the deep sea contributes to niche specialization in groups other than mollusca. Deep-sea species known to be associated with terrestrial plant material include echinoderms that feed on this material, bilaterally symmetrical hermit crabs that live in hollowed plant stems, and gammared amphipods that live in or feed on wood. Chiton, small putilliform gastropods, and sepunculids as well as nematodes and polychete worms are often found on wood or in old burrows of wood borers (Turner 1981). How this wood-dependent deep-sea community finds new wood is still unknown.

Woody debris from decomposition of large pieces of wood on land enters the bedload of streams and is transported downstream to join similar nonbuoyant debris produced in coastal waters and estuaries. This material enters the ocean in large quantities (Hedges and others 1982), to be transported by bottom currents. Near the shore, as far as 1.25 miles from the beach, bottom currents in water less than 130 feet deep result from wave motion and are predominantly a shoreward flow that returns material to the wave zone. Offshore, where water is deeper than 130 feet and thus below the effect of waves, bottom and near-bottom currents on the Continental Shelf flow northward, parallel to the coast.

Vascular plant debris is one-third of the total organic matter in bottom sediments in the Columbia River system (Hedges and others 1982). The major types of plant debris are derived from nonwoody angiosperm tissue and gymnosperm (conifer) wood. The transport of woody plant debris to the sea introduces it into marine food webs as a terrestrially derived organic carbon energy source. The proportions and fluxes of terrestrial plant material into sediments on the Washington continental shelf have been described (Hedges and Mann 1979). The fine sand sediment on the inner continental shelf has a low organic carbon content, mostly derived from marine phytoplankton. On the midshelf, between 12.5 and 25 miles offshore, the sediment is a finer organically enriched silt, as is nearshore sediment around the Columbia River mouth, where the sediment content of terrestrial plant debris would be expected to be high. Ninety-five percent of the organic matter in the sediment off the Columbia mouth is of terrestrial origin, that of nearshore sand is about 20 percent, and the midshelf silts 22 to 25 miles offshore contain 46 to 61 percent terrestrial organic carbon (Hedges and Mann 1979).

Thus, an appreciable quantity of lignin-containing particles derived from coniferous wood is transported across the Pacific Northwest continental shelf, at least 49 miles offshore, and is deposited in the midshelf sediments where it constitutes at least half the total sediment organic carbon content. The role of intact wood in marine pelagic and benthic food webs remains unknown, as does the potential role of offshore marine wood borers in initial reduction of this wood. The significant amount of coniferous wood products on the floor of the midshelf, however, suggests a potentially valuable research area that could shed light on the interactive link between the forests of the Pacific Northwest and the ocean portion of the ecosystem.

Current Management of Wood on Beaches and Estuaries

When logs do reach the shore or beach, should they be removed or allowed to remain (fig. 4.17)? The thinking developed in this chapter argues that abundant drift logs help stabilize beaches by capturing land and shielding the shore from wave action. The States of Oregon and Washington differ in their policy about removing logs. Oregon has the following policy for removal of logs from its beaches:

To assure continuation of scenic and recreational values for public enjoyment at the ocean shore and to protect marine life and intertidal resources, beach logging, as a general practice, shall be prohibited unless such removal can be shown a significant public benefit.

Washington State's policy on log removal appears to contrast markedly with Oregon's. The Department of Natural Resources (DNR) has an established procedure for licensing individuals who wish to retrieve drift logs, either from the Puget Sound or the Columbia River below Grand Coulee Dam. Certain restrictions are imposed on the license holders, but the department cooperates by administering the sale of unbranded drift or salvage logs retrieved by the licensee. If the log is just floating in the Sound, there is little question about a permit holder's being able to latch onto it. But if the log is lying on a beach in front of a house, who does it belong to? The DNR's answer is as follows:

Log patrolmen, brand owners, and their agents all have the right to enter peaceably any tideland, marsh, beach, etc., for the purpose of salvaging logs. Likewise, beach owners have rights also; where one right ends and the other begins is hard to define. Generally speaking, the removing of logs from the water side by boat does not infringe upon the rights of the beach owner. A beach owner does not have any legitimate claim to a log that washes upon his beach, and to exercise any appreciable claim over this log could result in criminal action.

But if the beach-front owner believes the logs should be left to protect the beach from wave erosion, the stage is set for argument. The matter is not trivial as more than 9 million board feet were salvaged in 1974 by log patrolmen. The policies of Oregon and Washington apply only to coastal beaches and tidal portions of rivers; neither policy applies to estuaries. The difference is that the beaches in Oregon are public, whereas those in Washington are private.

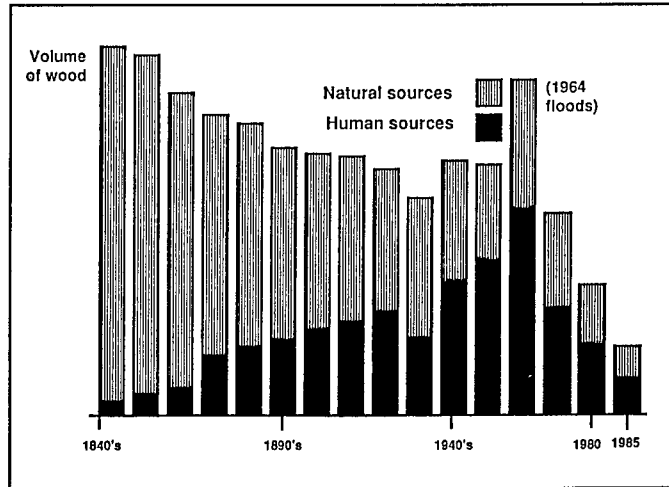


Figure 4.17—Estimates of wood inputs to beaches and estuaries in Oregon from 1840 through 1985.

The other major regulatory arena in estuaries centers on wetlands and mitigation policy and involves the provisions in section 404 of the Clean Water Act of 1972. When wetland or marshes are removed, filled, or dredged, wetlands in another area within the estuary must be created, restored, or enhanced. In Oregon, large woody debris is not currently an issue in the mitigation process. The Division of State Lands and the Department of Environmental Quality, which administer wetland and marsh alteration permits, do not consider woody debris to be an issue in Oregon tidal marshes. They do not encourage removal of wood. There is no mitigation credit for removing wood. Also, in the enhancement and restoration process, wood is *not* considered. In effect, the Division of State Lands and the Department of Environmental Quality take a neutral stand about wood. They do not encourage removal, and wood is not considered in wetland management. The hope is that the management of the estuary linked to the forest through large woody debris can become a part of the creative mitigation process and can become consistent with the way nature has linked the two.



Figure 4.5—Driftwood deposited by storms in the high marsh can serve as nurse logs to the forest surrounding the estuary.

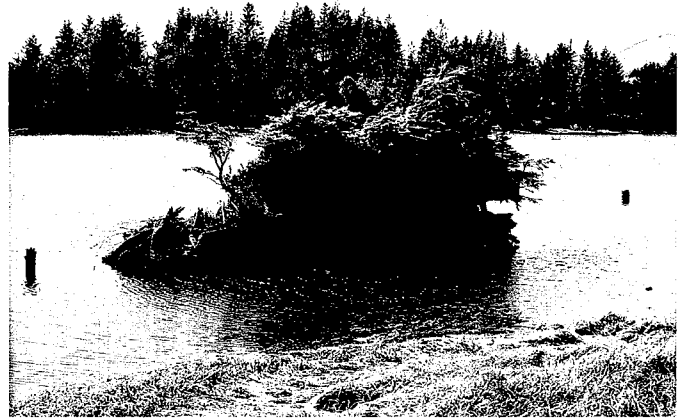


Figure 4.6—Sitka spruce and huckleberry on nurse log in Nehalem Bay, Oregon.



Figure 4.12—Beachwood along the Washington coast.



Figure 4.14—Collecting firewood reduces the amount of driftwood in Oregon estuaries and on beaches.

Chapter 5. Looking Ahead: Some Options for Public Lands

Jerry F. Franklin and Chris Maser

Summary

Intensive and diversified forest management are compared. These approaches represent opposing ends of a continuum of philosophies and of techniques available to the forest manager.

Introduction

Most public forest lands in the Pacific Northwest are and will be used to produce commodities and amenities. We must maintain biological diversity on these lands if we are to achieve multiple-use management objectives that require a healthy ecosystem. The key to a healthy ecosystem is structural and functional diversity across forested landscapes (Franklin and Forman 1987).

We use coarse woody debris as a good example of biological diversity that may be either retained or lost by management decision; each decision will affect forests, streams, rivers, estuaries, and oceans.

We know too little about complex ecosystems (Society of American Foresters 1984b), so we need constantly to re-evaluate management philosophy in light of new information. We conclude this chapter with recommendations for research needed to better understand and maintain biological diversity.

Intensive Forest Management

Intensive forest management is the use of artificial means to produce wood fiber in the shortest time possible. The economic advantage of such management is the continuation of industrial production after the old-growth forest is removed. But biological disadvantages cause concern about the long-term economics of intensive management.

The current approach to intensive forest management maximizes timber output by simplifying forest biology and subsidizing it with energy inputs. This approach homogenizes the forest, thus reducing ecological diversity.

Biological simplification is a serious issue, both ecologically and economically (Old-Growth Definition Task Group 1986). Simplification occurs at many levels, such as genetic, structural, and so forth. Simplification is often carried out when it is not essential to management objectives or is even economically disadvantageous.

Genetic simplification takes many forms, including eliminating or excluding some species and reducing variability in others. Local elimination and subsequent exclusion of a species usually results from accident rather than by design. Exclusion of a species from a significant amount of the landscape can result in extinction, as has been hypothesized for the northern spotted owl (Gutiérrez and Carey 1985). Local extinctions in the aggregate cause global simplification through loss of species. Intra-specific genetic variability is often reduced by design in genetic manipulation of Douglas-fir or, even more drastically, in cloning it. Other forest activities, such as artificial regeneration of trees from wild seed, can also result in substantial, unplanned modification of the natural genetic variability.

Structural simplification of stands includes eliminating snags and fallen trees, reducing the range of tree sizes and growth forms, and geometrically spacing trees. Long before intensive forest management was applied, foresters removed deadwood because of concerns about wildfire. Intensive forest management seeks uniformity in tree size and form by concentrating on one or two species. Trees are regularly spaced to optimize stand growth and to provide access for mechanical equipment.

Unmanaged landscapes in the Douglas-fir region are dominated by a wide mix in size of patches, from small to very large, and with a high degree of heterogeneity or structural variability within patches. Patch boundaries often merge gradually or are feathered at their edges. Wildfire and windstorms created most of these patches. Management has increased the number of patches in forested landscapes, particularly with the dispersed clearcutting system used on Federal lands. The patches are much more uniform in size, however, and very homogeneous. The boundaries or edges between patches have also been drastically increased, sharpened, and straightened under intensive management. Management may have increased the number of patches in forested landscapes, but numerous small patches of Douglas-fir less than 100 years of age may not be desirable ecologically or economically (Franklin and Forman 1987, Thomas and others 1979).

The temporal or successional simplification from intensive management affects both early and late successional stages. Rapid establishment of a fully stocked, closed-canopy conifer forest is a major economic objective; planting and elimination of competing vegetation contribute to this objective. Intensive timber management aims to eliminate three successional stages: grass-forb, mature, and old-growth. In coastal Douglas-fir forests of the Pacific Northwest, grass-forb is the earliest stage; the mature stage usually begins at 80 to 100 years of age (culmination of mean annual increment) and persists for about 100 years, during which time substantial growth continues and biomass accumulates. Old-growth conditions develop gradually and begin when the trees are 175 to 200 years old (Old-Growth Definition Task Group 1986). The concept of successional simplification becomes clear when rotations under intensive management are compared with those under unmanaged conditions (fig. 5.1).



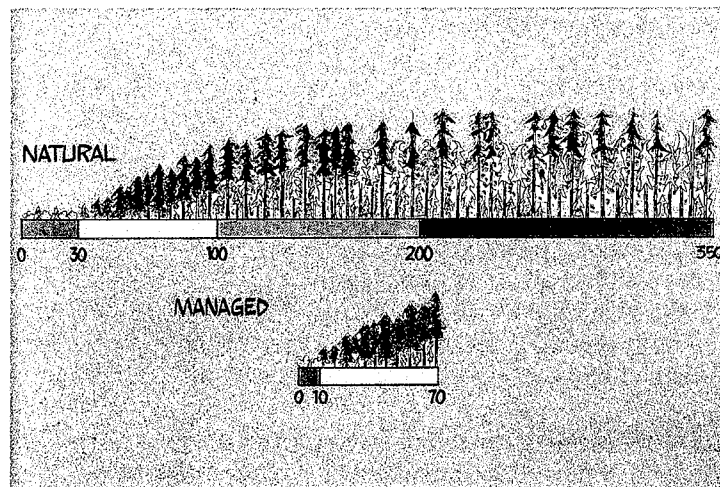


Figure 5.1—Contrast in duration of successional stages under natural and human disturbance regimes. Typical frequency for fire return under natural conditions is 350 to 450 years in northern Oregon and Washington. Normal rotation for managed stands is 70 to 90 years. Managed rotations eliminate the mature and old-growth stages of stand development and abbreviate the open, preforest canopy stage.

Diversified Forest Management

Diversified forest management emphasizes maintaining long-term site productivity through ecological diversity in the forest portion of the ecosystem. This method includes rotations longer than 80 years, reinvesting organic matter and nutrients in the site in the form of large snags and down stems, and producing diversified forest products.

The biological advantage of diversified forest management is that forest health is maintained indefinitely. But the social and economic disadvantage is disruption of industrial and community stability during the transition period to diversified management. Essentially, the choice is between short-term or long-term effects.

Maintaining Options

Maintaining options is the basis of diversified forest management. A manager retains the ability to respond to changes in product needs, in environmental conditions, and in knowledge about how forests function. Economic conditions and markets have changed drastically in the last two decades. Is there any reason to expect greater stability in the future? Climatic changes and increasing pollutant loads can be expected. Do our tree-breeding programs take these changes into account?

Diversified management accommodates change and recognizes our limited knowledge of how forests function. The amount of fundamental information, such as that concerning the dynamics of the belowground forest component, is growing rapidly. Only about 20 percent of the biomass is belowground, but turnover of fine roots and mycorrhizae may be so high that most of the photosynthate is needed for their maintenance. Other examples of recent scientific findings are: (1) the importance of photosynthesis that occurs outside the normal growing season—including such sites as the productive coastal Sitka spruce-western hemlock forests (Franklin and Waring 1980); (2) the significance of tree canopies as sites for condensing and precipitating water,

nutrients, and pollutants—producing, on some sites, 25 percent or more of the water input (Harr 1982); and (3) the many locations at which nitrogen fixation occurs in forests—in canopy lichens (Carroll 1980), in fine litter (Silvester and others 1982), in rotting wood (Harmon and others 1986), through small mammals (Li and others 1986), and in the rhizosphere (Li and Castellano 1987). The importance of coarse woody debris has been recognized only since the late 1970's.

Maintaining Forest Productivity

Compared with an intensively managed forest, a diversified forest provides a greater array of timber products and biological organisms and much greater inputs of soil organic matter and nutrients. Safeguarding the genetic diversity of a forest contributes to sustained productivity because the potential for loss of trees to pathogens, climatic change, or pollutants is less.

A diversified forest contributes significantly to the stability of streams, rivers, and estuaries; it provides coarse woody debris, essential to the stability, diversity, and productivity of the tributary aquatic portion of the ecosystem. Intact riparian zones help maintain high water quality and provide large pieces of organic material.

Accommodating Early and Late Successional Species

Intensive forest management shortens the early stage in succession that precedes tree canopy closure and eliminates the late successional stages. In contrast, diversified management accommodates all successional stages.

Many organisms use early successional stages. The herb and shrub stage has the highest diversity (number of species) of any stage in forest succession. This is also the stage of succession during which nitrogen-fixing plants, such as alder, ceanothus, and lupine, carry on most of their activity; the largest single input of nitrogen occurs during this successional stage.

The young, closed-canopy forest, by contrast, is the least diverse stage of succession; here also, the trees mobilize all resources of the site. The relation between species diversity and successional stage is exemplified by mammals (fig. 5.2). Other groups of organisms, including higher plants and terrestrial and aquatic invertebrates, show similar relations.

The time of full canopy closure can be delayed by using wide spacings, which also might reduce planting and thinning costs (Oliver 1986). Results of spacing trials suggest that such stands produce lower total yields but produce trees with much larger diameters (Reukema 1970).

Maintaining mature and old-growth stands can be facilitated by reserving existing stands and creating new stands with long rotations. Management regimes can be designed to generate old-growth characteristics earlier than would occur under natural conditions (Old-Growth Definition Task Group 1986). Harris (1984) suggests a scheme that combines old-growth islands with much larger, long-rotation buffer areas.



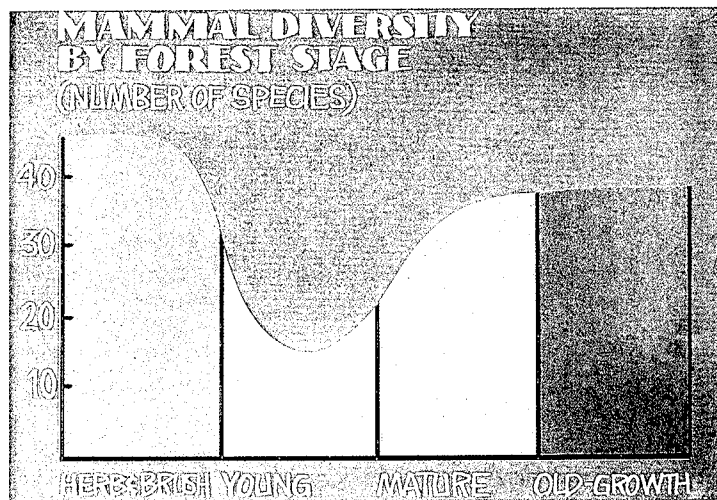


Figure 5.2—Relation between successional stage and number of mammal species using each stage as primary habitat (data based on Harris 1984).

Reservation and creation approaches are both needed because some reserved mature and old-growth stands will be lost to catastrophe as reserved forest patches in highly fragmented landscapes are lost now (Franklin and Forman 1987, Ruediger 1985). Loss of old-growth stands to natural successional processes does not appear to be a serious problem because changes are slow and stands appear stable for many centuries.

Natural old growth is a finite resource from which we must learn to simulate the old-growth condition in the managed forest. Our ability to successfully implement long rotations is unproved, even with the current knowledge of old-growth forest characteristics. Ecological theory suggests that reserved old-growth islands will have greater diversity than old-growth islands created from managed forests (Harris 1984).

Mixed Stands

Soil improvement is a major objective of growing mixed-species stands. The classic example is using alders in mixture with conifers because of alder's nitrogen-fixing capabilities; other species also have favorable nutrient benefits. Cedars and related species (Cupressaceae and Taxodiaceae) are calcium accumulators (Kiilsgaard and others, in press; Zinke and Crocker 1962). Cedar litter contributes to development of soils comparatively rich in bases, low in acidity, and more favorable to biological productivity (Alban 1967, Turner and Franz 1985). Many hardwoods also produce a base-rich litter.

Hardwoods mixed into coniferous stands may be appropriate for a variety of non-timber objectives besides their effects on soil nutrients. Deciduous hardwoods result in an open canopy for part of the year and thus influence conditions on and in the forest floor. Some invertebrate and vertebrate populations respond favorably to increased sunlight. Hardwood trees themselves provide a very different habitat for epiphytes, invertebrates, and some kinds of predators. Bigleaf maple, for example, is an outstanding substrate for epiphytic plants.

Mixed-structure stands could be created to provide truly uneven-aged stands with the classic, inverted-J, size-class distribution, which means that the large number of small trees decreases as the size of individual trees increases. This is often interpreted as indicative of a stable population. A single-tree selection system could be used to manage such a stand for continuous yields. Consequences of such a harvest system on specific species will vary from site to site and will depend on the mix of shade-tolerant and shade-intolerant species. A much simpler and broadly relevant example of a mixed-structure stand is the development of a two-layered forest, consisting of two distinct age classes. One approach being tested is the creation of shelterwoods in which the leave trees are left through the entire next rotation. This could create greater canopy diversity (perhaps for wildlife habitat or moisture condensation), provide a source of large deadwood structures, or produce higher quality wood.

Protecting Riparian and Wetland Habitats

Healthy riparian habitat is an important goal of diversified management. Coarse woody debris provides much of the basic structure for the smaller streams. Litter from streamside vegetation provides the primary energy base of the aquatic community.

Riparian management should conserve as much structural and compositional diversity as possible. A mixture of herb, shrub, and tree species is desirable for perpetuating litter and wood inputs that vary in timing and quality. Maintaining multiple-canopy layers contributes significantly to structure and composition, as well as to a more varied physical environment in which canopies include both deciduous and evergreen components.

Streamsides may be protected by maintaining vegetated corridors, especially along large streams. Prescriptions for managing riparian zones must include methods for maintaining needed structure, composition, and windfirmness over a long period in harmony with treatments on adjacent lands.

Maintaining Coarse Woody Debris in the Ecosystem

Providing coarse woody debris to the terrestrial and aquatic portions of the ecosystem is a major challenge in land management because of the linkages involved. These include a continuous flow from (1) producing large trees to (2) creating and maintaining large snags to (3) creating and maintaining downed stems and, finally, to (4) producing and transferring wood from the terrestrial to the aquatic environment.

Snags and downed stems are transitory structures, so they must be produced continuously. Snags are especially short lived in the Douglas-fir region, rarely persisting (in forms useful to cavity dwellers) beyond 60 or 70 years. To fulfill all functions, snags must also be renewed in sizes greater than 24 inches in d.b.h.

The practice of removing unmerchantable material is ecologically undesirable when all large woody material is removed from a site. Such practices need to be modified or eliminated.



Some live trees can be retained as sources of future snags. Saving trees with crown and upper stem defects, such as top rot, broken top, or fork, is desirable because they are likely to contain some decay that produces desirable snags for cavity dwellers. Lower stem, butt, or root defects should be avoided because they may be susceptible to windthrow that would reduce their longevity as snags. Live trees may also be converted to snags by fire or girdling. One strategy may be to kill trees at intervals to provide a continuing source of snags through the next rotation.

Need for a Landscape Perspective

The size, shape, and location of individual forest patches or stands have profound effects on landscape stability and productivity (Franklin and Forman 1987). The spatial arrangement in the landscape of management activities, stand types, stream habitats, and so forth is also critical to diversified management. In some cases, the importance of spatial arrangement is well known, such as the juxtaposition of feeding and hiding habitat for wildlife. But many other relations, such as those between forests and streams, are poorly understood. One of the most difficult spatial issues is the movement and changing roles of wood in a river drainage, from headwater to estuary. Aggregates of wood in aquatic ecosystems have great significance for productivity and biological diversity.

Size, shape, distribution, and context (degree of contrast with the surrounding landscape) of diverse patches are important landscape considerations. Shape and location of clearcuts have dramatic effects on windthrow in adjacent forest stands (Gratkowski 1956, Ruth and Yoder 1953), and the amount of recently cutover forest can significantly influence hydrologic regimes (Christner and Harr 1982, Geppert and others 1984).

The staggered-setting system of clearcutting, used widely on Federal lands in the Douglas-fir region, intersperses 25- to 40-acre clearcuttings with live timber and results in a patchwork that maximizes the amount of high-contrast edge within a landscape. Such landscapes are particularly vulnerable to catastrophic windthrow or other disturbances once 20 to 30 percent of the landscape is cut over. Forest patches large enough to provide an environment suitable for species that inhabit the forest interior generally disappear by the time half the landscape is cut over. Furthermore, creating small management areas and dispersing management operations over the landscape is economically inefficient. Many effects of management could be reduced by aggregating rather than dispersing cuttings, although cumulative effects on hydrologic regimes would need to be carefully considered. Evaluating specific ecological, economic, and social implications of staggered-setting clearcutting and alternative approaches of managed landscapes is badly needed (Franklin and Forman 1987); however, the general importance of a landscape perspective in management decisions is already clear.

Information Needed for Developing Improved Management Regimes

Little biological research was done in Pacific Northwest forests before about 1950. Then research facilities were expanded to allow some scientific focus on the more obvious and practical issues of that time, such as growth and yield of forest stands, methods for tree regeneration, and control of various tree-damaging agents. We have only recently begun to identify critical ecological questions. Quantifying many of the relations, such as those between levels of coarse woody debris or habitat for specific

organisms, is demanding and expensive. Much research is still needed to convert the qualitative information to management prescriptions and to confirm hypotheses about the role of woody structures in the world ecosystem.

Needed research appears to fall into three major categories: (1) long-term site productivity, (2) roles of coarse woody debris, and (3) dynamics of coarse woody debris.

Long-Term Site Productivity

No more important forestry issue exists than that of the sustainability of commercial forest-land productivity. This requires more than simply insuring that soils are not compacted or eroded or that some critical level of soil nitrogen is maintained. But, unfortunately, our knowledge does not go much beyond this simple perspective. We must have more insightful information; at the least, we need to determine what is required for sustaining forest production.

One major component of needed research is quantifying the effects of coarse woody debris on site productivity, including the contribution of coarse woody debris to the physical, chemical, and microbiological properties of the soil. What role do decay-resistant components of wood play in soil structure? How important are pockets of woody material in a soil matrix in the functioning of specific belowground components, such as mycorrhizae, at specific times of year and in different forest types? What role do dead roots play in maintaining soil structure and providing belowground energy and nutrient sources?

The relation between woody debris and long-term productivity is critical for freshwater, estuarine, and marine portions of the ecosystem just as it is for the terrestrial portion. Developing information for aquatic communities may be more difficult because the supply and dynamics of wood in rivers must be considered over an entire drainage.

We must synthesize existing and new information. Computer models can now address some questions of long-term site productivity (Kimmins and Scoullar 1979, Shugart 1984). Such models are valuable tools in synthesizing and identifying information needs. Models are also the only way we can explore the effects of various management activities as they might develop over decades or even centuries; thus, refining old models and developing new ones are high priority. Such models are as much management tools as research tools.

Quantifying the Roles of Coarse Woody Debris

We know that snags and downed stems are important in terrestrial and aquatic environments, but we do not know how much of this material is needed in what sizes, decay states, or spatial arrangements. These questions must be primary research objectives because management costs associated with creating and maintaining coarse woody debris are considerable.

Quantifying needs for coarse woody debris to achieve both game and nongame wildlife objectives is a pressing management issue. We know that coarse woody debris is an essential resource for animals, but we do not have detailed information on how much is needed. Important variables include snag and down stem densities, tree species, decay state, and size. The spatial arrangement of downed stems on cutover areas is also important. How much continuity is required from the standpoint of animal movement into and across cutover areas?

A long-term experiment at the H.J. Andrews Experimental Forest in western Oregon will examine the effects of several management treatments on site productivity. Coarse woody debris is one major variable in the experimental design that has the specific objective of quantifying the effects of downed stem density and spatial arrangement on mammals' movements into and across clearcuts. Studies of this type are expensive but essential for getting quantitative information needed for long-term management decisions.

Research also needs to be conducted on the roles of coarse woody debris in geomorphic processes and in aquatic environments from headwater streams to deep ocean habitats. How do stem size, density, and spatial arrangement (parallel or at right angles to the slope) affect surface erosion? How are the quantitative relations between stem or log-jam numbers related to aquatic productivity? What densities and sizes of stems are necessary for essential structural diversity and substrate in estuarine environments?

Dynamics of Coarse Woody Debris

Snags and downed stems are transient structures, so knowledge of their dynamics is essential. Much useful information has already been generated from various ecosystem and wildlife-oriented research programs. Among other things, this information has created an understanding of the highly variable nature of coarse woody debris and its decomposition.

The factors that affect patterns and rates of disappearance of snags and downed stems are important variables for which information is inadequate. These variables include tree species, cause of death, size of piece, wood quality as reflected in growth rate and proportions of heart and sapwood, and patterns of decomposition along major environmental gradients. Some contrasts are already apparent between mixed-conifer and ponderosa pine forests east of the Cascade crest and the Douglas-fir—western hemlock forests to the west, but information is fragmentary. Patterns of decomposition relative to moisture and temperature need to be learned. Other variables that need to be investigated are comparisons of wood decay in clearcuts and forests and comparisons of decay of burned (charred) vs. unburned material of comparable type.

Similar wood decay variables require investigation in aquatic environments. There are additional important dimensions, such as how does mechanical battering affect fragmentation of large wood in streams and the ocean? How does transport and aggregation of woody debris in aquatic environments differ from that on land?

A long-term study of wood-decay processes at the H.J. Andrews Experimental Forest (*fig. 5.3, color*) is designed to examine the effects of tree species (Douglas-fir, western hemlock, western redcedar, and Pacific silver fir), wood size, and early insect colonizers on pattern and rate of decay. Nearly 500 logs about 24 inches in diameter and 19.5 feet long have been placed in a replicated design that should allow sampling to continue for about two centuries. This study has already provided some surprising results, especially on the effects of invertebrate populations. A related study of decomposition in aquatic environments has been established in a third-order stream with smaller logs of Douglas-fir, red alder, and western hemlock.

Synthesis of information on the dynamics of snags and downed stems should take the form of simulation models. Only one model deals with the dynamics of woody debris over long periods (Graham 1982); such models need much greater emphasis. Simulators are needed that can provide managers with information on the yield of coarse woody debris for different environments and under different management regimes—yield models for dead material instead of live trees!

Conclusion

The challenge to managers of public forest lands is to maintain ecological diversity in perpetuity. We must understand and accept biological complexity. We must follow the basic principle of maintaining or restoring genetic, structural, and spatial complexity.



Figure 5.3—An experimental study of log decomposition planned to span a 200-year period has been installed at the H.J. Andrews Experimental Forest in the central Oregon Cascade Range; major variables include species, size, and presence or absence (log enclosed in insect-proof tent) of invertebrates during early stages of decomposition.

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Appendix

Nomenclature

Common name	Scientific name
Fungi: ¹	
Red ring rot	<i>Phellinus pini</i> (Thore ex Fr.) A. Ames
Yellow laminated rot	<i>Phellinus weirii</i> (Murr.) Gilbn.
Plants: ²	
Alder	<i>Alnus</i> sp.
Bigleaf maple	<i>Acer macrophyllum</i> Pursh
Blueblossom	<i>Ceanothus thyrsiflorus</i> Esch.
California laurel	<i>Umbellularia californica</i> (Hook. & Arn.) Nutt.
Coast redwood	<i>Sequoia sempervirens</i> (D. Don) Endl.
Douglas-fir	<i>Pseudotsuga menziesii</i> (Mirb.) Franco
Eelgrass	
European beachgrass	<i>Ammophila arenaria</i> (L.) Link
Grand fir	<i>Abies grandis</i> (Dougl.) Lindl.
Huckleberry	<i>Vaccinium</i> spp.
Jeffrey pine	<i>Pinus jeffreyi</i> Grev. & Balf.
Lodgepole pine	<i>Pinus contorta</i> Dougl. ex Loud.
Mountain hemlock	<i>Tsuga mertensiana</i> (Bong.) Carr.
Pacific silver fir	<i>Abies amabilis</i> (Dougl.) Forbes
Port-Orford-cedar	<i>Chamaecyparis lawsoniana</i> (A. Murr.) Parl.
Red alder	<i>Alnus rubra</i> Bong.
Red algae	<i>Fucus</i> spp.
Red oak	<i>Quercus borealis</i> (L.)
Rockweed	<i>Fucus</i> spp.
Salal	<i>Gaultheria shallon</i> Pursh
Salmonberry	<i>Rubus spectabilis</i> Pursh
Sitka spruce	<i>Picea sitchensis</i> (Bong.) Carr.
Snowbush	<i>Ceanothus velutinus</i> Dougl. ex Hook.
Sugar pine	<i>Pinus lambertiana</i> Dougl.
Tanoak	<i>Lithocarpus densiflorus</i> (Hook. & Arn.) Rehd.
Western azalea	<i>Rhododendron occidentale</i> (T. & G.) Gray
Western hemlock	<i>Tsuga heterophylla</i> (Raf.) Sarg.

¹ After Aho (1982).

² After Franklin and Dyrness (1973), Simon and Schuster (1978).

Western redcedar	<i>Thuja plicata</i> Donn
Western yew	<i>Taxus brevifolia</i> Nutt.
White fir	<i>Abies concolor</i> (Gord. & Glend.) Lindl.
Willow	<i>Salix</i> spp.

Insects:³

Douglas-fir bark beetle	<i>Dendroctonus pseudotsugae</i> Hopkins
Net-spinning caddisfly	<i>Hydroptila</i> spp.
Water strider	<i>Gerris</i> spp.

Fish:⁴

Bigeye tuna	<i>Thunnus obesus</i> (L.)
Chinook salmon	<i>Oncorhynchus tshawytscha</i> (Walbaum)
Coho salmon	<i>Oncorhynchus kisutch</i> (Walbaum)
Cutthroat trout	<i>Salmo clarki</i> Richardson
Dolphin fish (mahimahi)	<i>Coryphaena hippurus</i> (L.)
Herring	<i>Clupea</i> spp.
Skipjack tuna	<i>Katuwouvs pelamis</i> (L.)
Starry flounder	<i>Platichthys stellatus</i> (L.)
Steelhead trout	<i>Salmo gairdneri</i> Richardson
Stickelback	<i>Gasterosteus aculeatus</i> L.
Sturgeon	<i>Acipenser</i> spp.
Yellowfin tuna	<i>Thunnus albacares</i> (Bonnaterre)

Birds:⁵

Acorn woodpecker	<i>Melanerpes formicivorus</i> (Swainson)
Bald eagle	<i>Haliaeetus leucocephalus</i> (L.)
Brown creeper	<i>Certhia americana</i> Bonaparte
Brown pelican	<i>Pelecanus occidentalis</i> L.
Cormorant	<i>Phalacrocorax</i> spp.
Crow	<i>Corvus</i> spp.
Downy woodpecker	<i>Picoides pubescens</i> (L.)
Great blue heron	<i>Ardea herodias</i> L.
Great egret	<i>Casmerodius albus</i> (L.)

³ After Borror and DeLong (1964).

⁴ After Brown (1985), Gooding and Magnuson (1967).

⁵ After Robbins and others (1983).

Green heron	<i>Butorides striatus</i> (L.)
Gull	<i>Larus</i> spp.
Hairy woodpecker	<i>Picoides villosus</i> (L.)
Lewis woodpecker	<i>Melanerpes lewis</i> (Gray)
Northern flicker	<i>Colaptes auratus</i> (L.)
Osprey	<i>Pandion haliaetus</i> (L.)
Pileated woodpecker	<i>Dryocopus pileatus</i> (L.)
Purple martin	<i>Progne subis</i> (L.)
Red-breasted sapsucker	<i>Sphyrapicus ruber</i> (Gmelin)
Turkey vulture	<i>Cathartes aura</i> (L.)

Mammals.⁶

Black bear	<i>Ursus americanus</i> Pallas
Harbor seal	<i>Phoca vitulina</i> L.
Racoon	<i>Procyon lotor</i> (L.)

⁶ After Hall (1981).



Maser, Chris; Tarrant, Robert F.; Trappe, James M.; Franklin, Jerry F., tech. eds. 1988. From the forest to the sea: a story of fallen trees. Gen. Tech. Rep. PNW-GTR-229. 153 p.

Large, fallen trees in various stages of decay contribute much-needed diversity of ecological processes to terrestrial, aquatic, estuarine, coastal beach, and open ocean habitats in the Pacific Northwest. Intensive utilization and management can deprive these habitats of large, fallen trees. This publication presents sound information for managers making resource management decisions on the impact of this loss on habitat diversity and on ecological processes that have an impact on long-term ecosystem productivity.

Keywords: Decomposition, fallen trees, habitat diversity, ecosystem function, land, water, sea.

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