trees often overtop the adjacent canopy. The crowns of these trees are dominated by much larger limbs than are found in cylindrical crowns. This spherical form of crown seems more characteristic of old-growth stands in the Coast Ranges than of those on the west side of the Cascade Range and may reflect crowns developed in a denser stand (see footnote 7).

Few old-growth Douglas-firs have vertical trunks. The lower trunk leans away from the hillside but becomes nearly vertical where it extends above the surrounding canopy. Trunks on level sites appear to slope almost at random. Even a slight inclination of a trunk results in an important differentiation of habitat on its two sides. The upper side gets almost all the moisture, both from direct precipitation and from stem flow and throughfall. Consequently, it is colonized by epiphytic plants (plants that grow on other plants) with relatively high moisture requirements, chiefly mosses. The lower side is a "desert" occupied by scattered colonies of lichens (Pike et al. 1975) that form a crust over the bark surface. The bark on the wet upper side is soft and easily eroded, sometimes appearing to be held in place by its mantle of mosses and lichens, whereas the bark on the lower side is hard and deeply furrowed, indicating that it remains in place for longer periods.

Old specimens of other tree species can play a role comparable to that of Douglas-fir to at least some degree, although none have been as thoroughly studied (fig. 13). Sitka spruce attains comparable sizes in coastal regions; irregular crown systems and heavy, epiphyte-laden branch systems are characteristic of older specimens. Noble fir and western white pine are subalpine species with some, but not all, of the distinctive characteristics of Douglas-fir, as is sugar pine in southwestern Oregon. The so-called cedars—western redcedar, Alaska-cedar, Port-Orford-cedar, and incense-cedar—are capable of attaining sizes and fulfilling roles comparable to Douglas-fir in their respective types. These species have the additional advantage of fostering improved soil conditions through their base-rich litter. The major climax species—western hemlock, Pacific silver fir, and grand fir—appear, on the other hand, to lack the ability to completely fulfill the ecological roles of these long-lived pioneers.
Table 9—Temperature regime in an old-growth Douglas-fir tree canopy as related to precipitation during the current and preceding day

<table>
<thead>
<tr>
<th>Precipitation, current and preceding day</th>
<th>Days</th>
<th>Maximum daily temperature</th>
<th>Daily temperature range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Millimeters</td>
<td>Number</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>195</td>
<td>124</td>
<td>18.8</td>
</tr>
<tr>
<td>0.1-10.0</td>
<td>81</td>
<td>111</td>
<td>11.7</td>
</tr>
<tr>
<td>10.1-20.0</td>
<td>35</td>
<td>46</td>
<td>9.5</td>
</tr>
<tr>
<td>20.1-30.0</td>
<td>18</td>
<td>34</td>
<td>8.8</td>
</tr>
<tr>
<td>30.1-100</td>
<td>26</td>
<td>48</td>
<td>7.5</td>
</tr>
</tbody>
</table>

*An increasingly wet canopy results in lower minimum temperatures and a smaller diurnal range in temperature.*

What ecological role does a live, old-growth tree fulfill? There are many, but the most important are related to: (1) provision of habitat for the distinctive epiphytic plant and animal communities found in an old-growth forest; (2) effects on carbon, nutrient, and water cycling, especially the N budget of the site; and (3) source material for the other key structural components—standing dead trees, logs on land, and logs in streams.

Epiphytic communities remove soluble mineral nutrients from water flowing over them. They also trap dust and litter fragments, including needles. This accumulation, augmented by decomposition of the epiphytes themselves, is most evident on the upper sides of large branches where it results in the formation of perched "soils."

When moist, the old-growth forest canopy is an important climatic buffer, a fact that may explain some of the special compositional and functional features of the canopy. Air temperatures in the canopy of an old-growth Douglas-fir stand in the western Cascade Range of Oregon can range as high as 104°F (40°C) during the summer and as low as 14°F (-10°C) during dry periods in the winter. When the canopy is wet, however, temperatures range from 52°F to 60°F (0°C to 15°C) (table 9). As precipitation increases, daily maximum temperatures and the daily temperature range decrease. This buffering reflects the large water-holding capacity of the canopy—about 264,000 gallons per acre (3 x 10^6 liters/ha)—equivalent to 1 1/4 inches (3 cm) of precipitation.

This environmental regime is important to survival of Lobaria oregana and may be to other canopy inhabitants. Lobaria, the dominant epiphytic lichen in old-growth stands on the west slope of the Cascade Range, is metabolically active when wet and dormant when dry. One-half to 1 inch (1 to 2 cm) of rainfall will wet the canopy sufficiently to raise the water content of the Lobaria above 70 percent. Below this moisture level, the lichen ceases to

Habitat Function. Many of the distinctive compositional features of old-growth forests—plants and animals—are related to the tree canopies. Almost every surface of an old-growth Douglas-fir is occupied by epiphytic plants; more than 100 species of mosses and lichens function as these epiphytes. The dry weight of mosses and lichens on a single old-growth tree ranges from 33 to 66 pounds (15 to 30 kg) (Pike et al. 1977), of which less than half is mosses; this excludes the ubiquitous crust-forming lichens which cannot be separated for weighing. In forests below 3,500-foot (1 000-m) elevation, about half the total weight of epiphytes is usually due to a single leafy or "foliose" lichen, Lobaria oregana, which is an active N fixer. Although lichens are found over almost all surfaces, many species are restricted to particular habitats (see table 1 in Pike et al. 1975 for an excellent illustration of this point). Lobaria oregana, for example, occurs chiefly on the upper sides of branches and twigs. Lepraria membranacea, on the other hand, prefers the lower trunk and the underside of branches. Nearly all mosses occur on the bottom half of a tree.
Lobaria oregana appears to be limited to habitats where moist conditions are always associated with cool temperatures, such as is characteristic of an old-growth canopy. When Lobaria thalli are transplanted to stands of young growth or mixed conifer-hardwood, they deteriorate rapidly, presumably because air temperatures exceed 60°F (15°C) and thalli are hydrated. Lobaria oregana usually does not occur in young Douglas-fir stands, possibly because their canopies hold insufficient moisture for adequate thermal buffering. It may be abundant on individual young trees in old-growth stands, however, where the surrounding mature trees provide an appropriate microclimate.

The canopy of an old-growth Douglas-fir forest harbors large numbers of invertebrates of many species. A single stand may have more than 1,500 species. A minority of species spend their entire cycle in the canopy: Araneida, Acarina, Homoptera, Collembola, Neuroptera, Thysanoptera, and Psocoptera. Other species of Lepidoptera, Hymenoptera, Diptera, and Coleoptera occur as eggs, larvae, and pupae in the canopy; but the adults can and do move out of the canopy. The majority of species encountered in the canopy are adults that spend their immature stages on the forest floor or in streams. In their canopy studies, Drs. George Carroll (University of Oregon) and William Denison (Oregon State University) discovered overwintering caddisfly adults in Douglas-fir canopies. Many adults of species of Mycetophilidae (fungus gnats) trapped in the canopy occur as larvae in the abundant mushroom rooms on the floor.

Figure 14. Relationship between canopy temperature, lichen (Lobaria oregana) thallus water content, and precipitation in the preceding 48 hours. Several thresholds are indicated: 0°C which is the lower thermal limit for nitrogen fixation; 70-percent thallus water content which is the lower moisture limit for nitrogen fixation; and 16°C which is the upper thermal limit (tolerance) for a saturated Lobaria thallus.
Although primary consumers (insects—such as sawflies, scales, or aphids—which feed on foliage or beetles which feed on wood) do occur in the canopy, they are not abundant. The most abundant arthropods are predaceous spiders, which belong to families such as Salticidae and Thomisidae. The large numbers of flies found in the canopy probably provide food for the spiders. Other arthropods feed on debris or on bacteria and fungi on surfaces of the canopy or are predators of other invertebrates. During one sampling period, invertebrates washed from foliage samples included:

<table>
<thead>
<tr>
<th>Food source</th>
<th>Invertebrates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Needles</td>
<td>1 species of scale</td>
</tr>
<tr>
<td></td>
<td>1 species of mealy bug</td>
</tr>
<tr>
<td></td>
<td>1 species of Lepidoptera</td>
</tr>
<tr>
<td>Bacteria and fungi</td>
<td>6 species of mites</td>
</tr>
<tr>
<td>living on needles</td>
<td>4 species of flies (as larvae)</td>
</tr>
<tr>
<td></td>
<td>5 species of Collembola</td>
</tr>
<tr>
<td>Other invertebrates</td>
<td>2 species of mites</td>
</tr>
<tr>
<td></td>
<td>2 species of spiders</td>
</tr>
</tbody>
</table>

The canopy of an old-growth forest provides several insect habitats, both vertically and horizontally. Some species are found in the upper canopy, others in the lower; some species occur on major limbs and others among twigs and foliage.

Several vertebrates depend heavily on the old-growth canopy as sites for nesting, feeding, and protection. Well-known examples are the northern spotted owl, northern flying squirrel, and red tree vole. The vole may live for many generations in the same tree. The role that the large branch systems and organic accumulations play in providing suitable habitat should not be overlooked.

**Cycling Function.** Old-growth trees are one of the primary sites for photosynthesis, or production of the food base, on which the rest of the system depends. In this sense, they are the same as younger trees, except that each tree represents a large accumulation of organic material and nutrients (a "sink" in the short run and a "storehouse" in the long run) as well as a large photosynthetic factory. A single old-growth tree can have over 60 million individual needles with a cumulative weight of 440 pounds (200 kg) and a surface area of 30,000 square feet (2 800 m²) (Pike et al. 1977). Total leaf areas in old-growth stands are probably not much different from those in younger stands, but the leaves are concentrated on fewer individuals. Variations in production and live biomass strongly reflect mortality of these large dominant trees, which are both factory and storehouse, and the rate at which other trees occupy the vacated space.

A distinctive and unusual functional role of an old-growth tree is its contribution to the nitrogen economy of low-elevation to midelevation sites. Lichens that inhabit the canopy fix significant amounts of N which ultimately become available to the whole forest through leaching, litter fall, and decomposition. Estimates of fixed N range from 2.5 to 4.5 pounds per acre (3 to 5 kg/ha) per year. Most of the fixation is accomplished by Lobaria oregana, although several other large foliose lichens, such as L. pulmonaria, Pseudocyphellaria rainierensis, and Peltigera aphthosa, are also azotodesmic and, therefore, capable of fixing atmospheric N. Lobaria oregana accounts for half the total epiphytic biomass in the western Oregon Douglas-fir stands that have been studied. Lobaria and most N-fixing epiphytes are not common in young-growth stands, and this may be related to the microclimate of the old-growth forest canopy. Significant epiphytic inputs of N are, therefore, largely confined to old growth. Nitrogen-fixing bacteria on Douglas-fir foliage have not been found in the Pacific Northwest, even though they have been reported in Europe.

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8 Azotodesmic lichens contain a blue-green alga, either as a primary plant symbiont or a secondary one, and therefore are capable of fixing N. Nonazotodesmic lichens contain a green alga as the sole algal symbiont and are not capable of fixing N.
Standing Dead Trees or Snags. In any old-growth stand there are substantial numbers of standing dead trees or snags (fig. 15). Indeed, snags were the first dead component of natural forests of which foresters were made aware—initially because of the fire and safety hazard they represent and, more recently, because of their value to wildlife (Bull and Meslow 1977, Bull 1978, Thomas et al. 1979a, Mannan et al. 1980). Some representative data for old-growth stands are provided in table 10. The only comprehensive study on dynamics of snags is by Cline et al. (1980), who studied 30 stands from 5 to 440 years old in the Coast and Cascade Ranges. Densities of snags decrease with stand age, but mean d.b.h. of snags increases from 5 to 29 inches (13 to 72 cm) between stand ages 35 and 200; larger snags survive longer. Cline et al. (1980) report mean densities of snags over 3.6-inch (9-cm) d.b.h. at 13.8 per acre (34.6/ha) and 7.3 per acre (18.3/ha) in stands 120 and 200 years old, respectively. These values, as well as a life table (model) estimate of 9.2 snags per acre (23/ha) for a 200-year-old stand, are substantially below the densities in table 10; all six of the old-growth stands of Cline et al. (1980) are located in the Coast Ranges.

Figure 15. Large numbers of standing dead trees or snags are characteristic of old-growth forests. A. The volume and numbers of standing dead trees may not be apparent to the casual observer in this 250-year-old Douglas-fir stand in the Bagby Research Natural Area, Mount Hood National Forest; dead stems are marked with an X. B. Heavily decomposed snags in old-growth Douglas-fir-western hemlock stand.
The large standing dead stems in excess of 20-inch (50 cm) d.b.h. and 65-foot (20-m) height are most valuable to wildlife (Scott 1976). Mannan et al. (1980) found hole-nesting birds usually used snags over 24-inch (60-cm) d.b.h. and 50 feet (15 m) tall in western Oregon. Density and diversity of species of hole-nesting birds were significantly related to mean diameter of snags. Smaller snags apparently do not provide suitable habitat for some animal species, and some tree species are preferred by hole-nesters (McClelland et al. 1979).

Under natural conditions, large snags are not strictly a unique attribute of old-growth stands. Young-growth forests developing after wildfires have large residual snags from the original stand for various lengths of time. Cline et al. (1980) found residual or remnant snags in young-growth forest up to the oldest (110-year) age class they studied. Our experience is that large Douglas-fir snags typically persist for 50 to 75 years before being reduced to stubs less than 35 feet (10 m) in height; snags of western redcedar may remain essentially whole and standing for 75 to 125 years.

Large snags result from large trees; so they are a special product of old-growth forests. Managed young stands lack the residual snags of postwildfire stands unless snags are specifically planned. Natural stands appear to require about 150 years to develop snags 20 inches (50 cm) in diameter (Cline et al. 1980). Cline et al. (1980) suggest a life table approach for predicting densities and sizes of snags and recommend retention of large, defective trees for future snags in second-growth forests.

Various classifications, based on external features, have been developed for snags (Cline 1977, Cline et al. 1980, Thomas et al. 1979a); in general, these describe a time sequence in decomposition and disintegration of a dead tree (fig. 16). It is important to differentiate the stages of a snag since these are associated with changing values for wildlife. Both the path (stages) and the rate of disintegration of snags vary widely, however, depending on such factors as tree species, incidence and extent of decay at time of death, and environmental conditions. Douglas-fir snags typically disintegrate from the top down, losing the top and bark first. The trunk finally breaks off in large chunks, leaving a short snag or stub. Western redcedar and western white pine, on the other hand, often form bark-free, gray “buckskin” snags and remain essentially entire until they rot away at ground level and fall.

Table 10—Numbers of standing dead trees >13 feet (>4 m) in height and mean d.b.h. in age sequence of old-growth Douglas-fir-western hemlock stands in the Cascade Range

<table>
<thead>
<tr>
<th>Forest age sampled</th>
<th>13-31 feet (4-9 m)</th>
<th>32-64 feet (10-19 m)</th>
<th>&gt;65 feet (&gt;20 m)</th>
<th>All</th>
<th>Mean d.b.h.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Years</td>
<td>Number obscured</td>
<td>Number/acre (number/ha)</td>
<td>Number/acre (number/ha)</td>
<td>Inches (centimeters)</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>2</td>
<td>10 (26)</td>
<td>9 (22)</td>
<td>5 (12)</td>
<td>24 (60)</td>
</tr>
<tr>
<td>450</td>
<td>6</td>
<td>6 (16)</td>
<td>4 (10)</td>
<td>2 (6)</td>
<td>13 (32)</td>
</tr>
<tr>
<td>850+</td>
<td>3</td>
<td>7 (17)</td>
<td>5 (12)</td>
<td>2 (4)</td>
<td>13 (33)</td>
</tr>
</tbody>
</table>

1 Short snags or stubs (<13 ft or <4 m in height) average about 61 per acre (152/ha) in 7 old-growth stands ranging from 250 to 1,000 years old; there is no apparent trend in numbers with age of stand in this small sample.
Habitat Function. A primary role of standing dead trees is the provision of habitat for wildlife. This has been discussed by Thomas et al. (1979a) for the Blue Mountains of Oregon and Washington. Snags in that area are the primary location for cavities that are used by 63 species of vertebrates—39 birds and 24 mammals. Uses include sites for nesting and overwintering, locations for courtship rituals, and food sources.

Thomas et al. (1979a) indicate a direct correlation between numbers of snags and related populations since suitable nesting sites are generally thought to limit populations; Mannan et al. (1980) confirm this for hole-nesting birds in western Oregon. The large, hard snags required by primary excavators, such as the pileated woodpecker (Dryocopus pileatus), are especially important. Such snags will be hard to perpetuate in managed stands (because of smaller trees and programs for salvaging wood and reducing fire and safety hazards), yet such snags are also suited to other wildlife species and will produce soft snags through the process of deterioration. Snags representing a variety of decay classes are needed in a stand to meet the differing requirements of vertebrates since not all use the same material. One special attribute of old-growth and large (natural), second-growth stands is that they provide the necessary array of snags with varying levels of decay, whereas young stands on cutover areas do not.

Cycling Function. Most of the functional roles (in energy and nutrient cycling, including sites for microbial nitrogen fixation) of standing dead trees are the same as those of logs and will be considered in the discussion of logs.
Figure 17. Large masses of logs can be a dominant feature of old-growth forests, as illustrated in these stands with near-maximal accumulations: A. Midelevation stand of old-growth Douglas-fir in the western Cascade Range of Oregon. B. Old-growth stand of noble fir near Mount St. Helens, Washington.
Logs on Land. Logs, also describable as down dead trees or coarse woody debris, are nearly as conspicuous as the large, live trees. Large masses of logs can be the dominant feature of old-growth forests (fig. 17), and, in numbers, volume, and weight of organic matter, they constitute an important component. From 38 to 85 tons per acre (85 to 190 tonnes/ha) are typical values that have been reported. Down logs averaged 85 tons per acre over a 25-acre (10-ha) watershed covered with old-growth Douglas-fir-western hemlock forest (Grier and Logan 1977). Amounts within the watershed ranged widely— the lightest weights (24 tons/acre or 55 tonnes/ha) on a dry ridgetop and the heaviest (259 tons/acre or 581 tonnes/ha) on a lower slope, streamside area. Losses by downslope transfer had occurred on the ridgetop, and substantial amounts of debris had accumulated on the lower slope. In a 10-acre (4-ha) midelevation stand of Douglas-fir, western hemlock, and true firs, there were 82 tons of debris per acre (182 tonnes/ha), 55 percent as recently fallen trees. Logs occupied 29 percent of the forest floor in this stand (fig. 18).

The average weight of down logs in seven old-growth stands, from 250 to over 900 years old, was 53 tons per acre (118 tonnes/ha), the range was 38 to 70 tons per acre (85 to 156 tonnes/ha). The largest accumulation of down wood recorded for a stand thus far is in the Carbon River Valley at Mount Rainier National Park, a hectare plot contains 188 tons per acre (418 tonnes/ha) of logs that covered 23 percent of the plot.

Logs are also major pools of important nutrients, such as N and phosphorus (P). In the old-growth watershed, the log component contained 192 pounds per acre (215 kg/ha) of N and 6.0 pounds per acre (6.7 kg/ha) of P (Grier and Logan 1977). In the midelevation stand, coarse woody debris contained 485 pounds per acre (544 kg/ha) of N (see footnote 9). Logs are also major pools of important nutrients, such as N and phosphorus (P). In the old-growth watershed, the log component contained 192 pounds per acre (215 kg/ha) of N and 6.0 pounds per acre (6.7 kg/ha) of P (Grier and Logan 1977). In the midelevation stand, coarse woody debris contained 485 pounds per acre (544 kg/ha) of N (see footnote 9).

6 Unpublished data on file at Forestry Sciences Laboratory, Corvallis, Oreg.

8 Weights of down logs and stand age are only loosely correlated. Natural young Douglas-fir stands (about 100 years old), surveyed at the same time as the old growth, had masses of logs as large as some found in old-growth stands—primarily material carried over from previous stands as snags and logs. Large volumes of coarse woody debris are apparently characteristic of our natural forest ecosystems, adding credence to the concept of coarse woody debris as a mechanism to provide continuity of habitat from one forest generation to another (Maser et al. 1979) and for conserving large masses of organic matter and nutrients in major disturbances. It also suggests that the long-term ecological effects of nearly complete removal of woody debris in cutover stands and the prevention of new accumulations in intensively managed stands should be carefully examined.

Figure 18. Down logs in midelevation stand of old growth in the H. J. Andrews Experimental Forest. Logs occupied 29 percent of the forest floor in this stand.
Table 11—A 5-class scheme for rating decomposition of Douglas-fir logs¹

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bark</td>
<td>intact</td>
<td>mostly</td>
<td>partially</td>
<td>absent</td>
<td>absent</td>
</tr>
<tr>
<td></td>
<td>intact</td>
<td>intact to</td>
<td>intact to</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>sloughing</td>
<td>sloughing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twigs, 1.2-inch (3-cm)</td>
<td>present</td>
<td>absent</td>
<td>absent</td>
<td>absent</td>
<td>absent</td>
</tr>
<tr>
<td>Large branches</td>
<td>present</td>
<td>present</td>
<td>present</td>
<td>present</td>
<td>absent</td>
</tr>
<tr>
<td>Exposed wood texture</td>
<td>intact</td>
<td>intact to</td>
<td>large, hard</td>
<td>small, soft,</td>
<td>soft and powdery</td>
</tr>
<tr>
<td></td>
<td></td>
<td>partly soft</td>
<td>pieces</td>
<td>blocky pieces</td>
<td>(when dry)</td>
</tr>
<tr>
<td>Portion of log on ground</td>
<td>support</td>
<td>support</td>
<td>log is</td>
<td>all</td>
<td>all</td>
</tr>
<tr>
<td></td>
<td>points</td>
<td>points and slightly sagging</td>
<td>sagging</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exposed wood color</td>
<td>original</td>
<td>original</td>
<td>original to</td>
<td>light brown to reddish</td>
<td>red-brown to dark brown</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>red-brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epiphytes</td>
<td>none</td>
<td>none</td>
<td>conifer seedlings (≤3 years old)</td>
<td>moss and hemlock seedlings</td>
<td>moss and hemlock seedlings</td>
</tr>
<tr>
<td>Log shape</td>
<td>round</td>
<td>round</td>
<td>round</td>
<td>round</td>
<td>oval</td>
</tr>
<tr>
<td>Invading roots</td>
<td>none</td>
<td>none</td>
<td>conifer seedlings</td>
<td>in sapwood only</td>
<td>in sapwood and heartwood</td>
</tr>
</tbody>
</table>

Characteristics not used that also apply:

Fungal fruiting bodies: none

- Cyathus, Tremella, Mycena, Collybia, Polyergus, Cortinarius, Mycena, Cortinarius
- Polyporellus, Pseudohydnum, Fomitopsis
- Mycena, Mersamius
- Collybia, Cantharellus

Mycorrhizae: none

- none in sapwood
- in sapwood and heartwood

¹ Adapted from Fogel et al. (1972).
Like standing dead trees, logs go through recognizable stages of disintegration. One system for classifying the stage of decay of down logs is a five-class scheme based on easily recognized physical characteristics (table 11); some classes are shown in figure 19. As indicated in figure 10, standing dead trees may directly enter any of the first four log decay classes, depending on their condition when they fall. For example, a live tree, uprooted or broken off in a windstorm, becomes a decay class 1 log, whereas a very rotten snag might collapse into a decay class 3 or 4 log.

Figure 19. These logs are representative of several stages of decay or "decay classes."

Important physical and chemical changes are associated with the progression of decomposition (fig. 20). Logs increase in moisture content at a very early stage in decomposition and retain significant quantities of water thereafter. This is an important factor in their suitability as wildlife habitat and as sites for establishment of tree seedlings and for N fixation. Nitrogen becomes concentrated in logs as decay progresses; over threefold increases occur between class 1 and 5 stages of decay. The concentrations of phosphorus and calcium show patterns similar to N.

Figure 20. Important physical and chemical changes are associated with the progression of decomposition in logs. A. Changes in percent of water and volume of water per unit of wood with time; note the rapid increase in percent water early in decomposition. B. Changes in content of nitrogen (N) and phosphorus (P) with time. C. Changes in density of wood with time.
Large logs disappear slowly. In one old-growth Douglas-fir stand at mid-elevation, for example, a class 5 log had charcoal on surfaces in contact with mineral soil, suggesting that it had fallen at the time of the wildfire that initiated the present stand 470 years ago! Decomposition rates can be expressed as decreases in log density (fig. 20c). Logs lose only about 40 percent of their original density after 150 to 200 years. Based on decomposition models, 480 to 580 years are estimated for a 30-inch (80-cm) diameter Douglas-fir log to become 90 percent decayed.12

Habitat Function. Logs provide essential habitat for a variety of invertebrates (Deyrup 1975) and vertebrates (Maser et al. 1979). They are used as sites for lookouts, feeding and reproduction, protection and cover, sources and storage of food, and bedding. The high moisture content of logs makes them particularly important as habitat for amphibians.

Maser et al. (1979) reported that 178 vertebrates use logs in the Blue Mountains—14 amphibians and reptiles, 115 birds, and 49 mammals; they tabulated use by log decay classes for each species. Logs are considered important in early successional stages as well as in old-growth forests. The persistence of large logs has special importance in providing wildlife with habitat continuity over long periods and through major disturbances.

Logs may contribute significantly to reestablishment of animal populations by providing pathways along which small mammals can venture into clearcuts and other bare areas. This has relevance to the reestablishment of tree seedlings on bare areas since survival and growth of new trees depend on development of appropriate mycorrhizal associations. Surprisingly, fungal symbionts apparently disappear from cutover areas shortly after their host trees are removed (Harvey et al. 1978a), and the sites must be reinoculated with their spores. Many myc symbionts have underground fruiting bodies and completely depend on animals for dissemination of spores. Small mammals are the vectors. They consume the fungus and carry spores to new areas, thereby inoculating tree seedlings (Maser et al. 1978a, 1978b; Trappe and Maser 1978).

Logs also serve as sites for reproduction of tree species, especially western hemlock (fig. 21). This is clearly an important function in natural stands since these seedlings and saplings supply replacements as openings appear in the overstory canopy. In one old-growth stand at mid-elevation in the Cascade Range, over 64 percent of the western hemlock and 4 percent of the Pacific silver fir reproduction were rooted in rotten wood.13 The phenomenon of nurse logs is widespread in the forest types of the Pacific Northwest. Minore (1972) found that seedlings of both Sitka spruce and western hemlock were more numerous and taller on rotten logs than on the adjacent forest floor at Cascade Head Experimental Forest in the Sitka Spruce Zone (Franklin and Dyrness 1973) on the Oregon coast. In the South Fork Hoh River Valley of Olympic National Park, also in the Sitka Spruce Zone, reproduction of spruce and hemlock is essentially confined to rotten wood substrates;14 different species of logs also vary in their suitability as nurse logs as evidenced by differences in densities of seedlings. In subalpine environments, such as the Pacific Silver Fir Zone, successful reproduction of western hemlock is inevitably associated with rotten logs which are also heavily colonized by Pacific silver fir (Thornburgh 1989, Franklin 1988). Rotten logs as seedbeds or "nurseries" may have practical significance in a variety of situations; for example, as sites for natural reproduction after shelterwood or selective cuttings or for planting in cutover areas. Wood substrates appear to have particular silvicultural importance in coastal environments and where reproduction of western hemlock is desired. Rotten logs can also be of key significance in perpetuating campgrounds in old-growth forests in the Cascade and the Coast Ranges by providing seedbeds for tree reproduction.15


13 Means, Joseph E. Personal communication. USDA Forest Service, Forestry Sciences Laboratory, Corvallis, Oreg.


Rotten wood is also critical as substrate for ectomycorrhizal formation. In one coniferous forest stand, over 95 percent of all active mycorrhizae were in organic matter—of which 21 percent were in decayed wood (Harvey et al. 1976b). In another study in the northern Rocky Mountains, decayed wood in soil was important in moist, mesic, and arid habitat types (Harvey et al. 1979); it was the most frequent substrate for active ectomycorrhizae on the dry site, probably because of high moisture levels in the wood. Mycorrhizal fungi can colonize logs, presumably using them as sources of water and nutrients (Harvey et al. 1978). The mycorrhizal relationships may be important factors in establishment of seedlings on nurse logs; they are also important to mature trees.

Just as quality and special properties of wood products vary by tree species, the natural ecological characteristics of logs also vary by species. Average size of logs and slow rates of decay make some species, such as Douglas-fir and redcedar, more persistent. Differences in value of species as nurse logs may relate to physical and chemical properties of the log or the type of wood rot infesting it; the inferior performance of western hemlock in the role of nurse log is one example.
Cycling Function. Based on current knowledge, the most important cycling functions of logs are as sinks or storage compartments for energy and nutrients and as sites for N fixation. In addition, logs may provide physical stability, protecting the site from surface erosion.

The accumulations of carbon and nutrients represented by logs can be very large. In the short-term view, this material is a sink since it is made available so slowly. On the other hand, it is a significant source of stored energy and nutrients and one that can “bridge” major disturbances (can be continuous from an old-growth forest through a wildfire to a young-growth stand). Trunks of live trees, snags, and logs are structures in which N is retained through a wildfire; whereas in more easily burned organic components (leaves, forest floor) substantial N is volatilized and lost from the system.

The discovery of significant bacterial N fixation in coarse woody debris is recent; it occurred almost simultaneously in the forests of the Northeastern, Southeastern, and Northwestern United States. The most thorough study reported to date is Roskoski’s (1977) in northeastern hardwood forests. Greater decay and higher moisture contents were associated with a higher incidence of N fixation in woody debris. Fixation occurred in an average of 25 percent of the wood samples >0.4 inch (1 cm) in diameter. Larger woody debris was probably more favorable for N fixation because of better moisture conditions (and consequent low oxygen levels) and because larger pieces last longer, disintegrate more slowly, and, therefore, provide greater opportunity for inoculation by the appropriate bacteria. Larsen et al. (1978) and Roskoski (1977) found higher rates of N fixation in logs at advanced stages of decay and higher moisture content.

Roskoski (1977) estimated total N fixation in hardwood stands of different ages. The largest amounts were in the youngest (14 years old-1.25 ± 1.80 kg/ha per year) and oldest (200 years old-0.96 ± 0.77 kg/ha per year) stands. The amounts of N fixed were directly related to the weight of coarse woody debris which was 17 tons per acre (38 tonnes/ha)-all from the previous old-growth forest-and 15 tons per acre (34 tonnes/ha) in the 4- and 200-year-old stands, respectively.

Amounts of N fixation have not yet been estimated for old-growth coniferous forests in the Pacific Northwest, although N fixation has been detected. Substantially greater amounts are expected than those estimated for eastern hardwood forests, based on the large tonnage of woody debris present (5 to 15 times that reported by Roskoski 1977), and the much larger average size of material in the Douglas-fir region. We estimate approximately 4 pounds per acre (4.4 kg/ha) per year of N fixed in an average old-growth stand; a daily rate from Larsen et al. (1978) of 2.0 x 10^-9 moles per gram of logs is assumed in all decay classes throughout the year in the more moderate year-round climate on the west coast.

Our typical old-growth stand has 65 tons per acre (145 tonnes/ha) of logs and 20 tons per acre (45 tonnes/ha) of snags.

Decaying logs and decayed wood in soil are also of overwhelming importance as sites for nonsymbiotic N fixation in forests in the northern Rocky Mountains (Harvey et al. 1978); this is especially true of dry sites and during dry periods. Nitrogen fixation may occur in standing dead trees, even with their wider fluctuations in moisture content and aeration, but the amounts are unknown. Fixation is also associated with development of heart rots in live trees (Aho et al. 1974). Harvey et al. (1978) provide examples of both situations-N fixation associated with *Fomes pinicola* (a saprophytic fungus) in dead Douglas-fir and with *Echinodontium tinctorium* (a heart rot) in live western hemlock.

Logs have numerous important roles in cycling nutrients and maintaining site productivity. Complete removal of wood residues by harvesting and broadcast burning eliminates logs as reservoirs of nutrients and water and as entities whose physical effects may have a positive influence on the quality of a site (Jurgenson et al. 1977). Increased commercial use of wood residues or complete yarding of unmerchantable residues reduces the amount of sound or partially decayed logs. Since the products of decay and fire (humus, decayed wood, and charcoal) are important to quality and function of forest soils (Harvey et al. 1978, Jenny 1980), future forest management must consider logs as “parent material” for soil organic matter.
Logs in Streams. Large, woody debris in streams is a dominant element in aquatic ecosystems of old-growth forests. Debris largely controls the distribution of aquatic habitats, stability of streambeds and streambanks, and routing of sediments and water through the stream system.

Large, organic debris enters streams by a variety of mechanisms, some of which are interrelated and occur as a chain reaction. Principal mechanisms of input are blowdown, slides, avalanches, deep-seated mass movements from adjacent slopes, and undercutting of streambanks. Large debris is exported from sections of streams by flotation at high streamflow; in massive debris torrents involving the rapid down-channel movement of a slurry of soil, alluvium, and large organic debris; and by movement of fine particulates and dissolved material produced by biological and physical breakdown of logs.

The general character of large debris in small (first to second order) and intermediate-size (third to fourth order) streams in old-growth Douglas-fir is shown in figures 22 and 23. The first-order stream (fig. 22) is choked with debris, located essentially where it fell. The third-order stream (fig. 23) is large enough to float and redistribute some of the debris, forming accumulations along the channel. The third-order stream is still narrow relative to the length of individual pieces of debris, so accumulations of debris affect the width of the entire channel. In fifth-order and larger rivers, debris from old-growth forests accumulates high on streambanks at high flow, and, therefore, plays only a minor direct role in the physical and biological character of the river (Keller and Swanson 1979).

Figure 22. Small, first-order streams in old-growth forests are often choked with coarse woody debris as in these mapped sections of a stream in the H. J. Andrews Experimental Forest, western Oregon Cascade Range.

Figure 23. Third-order streams are large enough to float and redistribute much of the woody debris, forming distinct accumulations as in this section of Mack Creek in the H. J. Andrews Experimental Forest, western Oregon Cascade Range.
Table 12—Loading of coarse (>4-inch or 10-cm diameter) debris in sections of 5 streams flowing through old-growth Douglas-fir forests in the McKenzie River system, western Oregon

<table>
<thead>
<tr>
<th>Stream</th>
<th>Loading of coarse debris</th>
<th>Length of sample area</th>
<th>Width of channel</th>
<th>Gradient of channel</th>
<th>Stream order</th>
<th>Watershed area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pounds per square foot</td>
<td>Kilograms per square meter</td>
<td>Feet</td>
<td>Meters</td>
<td>Feet</td>
<td>Meters</td>
</tr>
<tr>
<td>Devilsclub Creek</td>
<td>8.7</td>
<td>43.5</td>
<td>297</td>
<td>90</td>
<td>3.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Watershed 2 Creek</td>
<td>7.6</td>
<td>38.0</td>
<td>445</td>
<td>135</td>
<td>8.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Mack Creek</td>
<td>5.7</td>
<td>28.5</td>
<td>990</td>
<td>300</td>
<td>40</td>
<td>12</td>
</tr>
<tr>
<td>Lookout Creek</td>
<td>2.3</td>
<td>11.6</td>
<td>990</td>
<td>300</td>
<td>79</td>
<td>24</td>
</tr>
<tr>
<td>McKenzie River (Rainbow)</td>
<td>.1</td>
<td>.5</td>
<td>2,540</td>
<td>800</td>
<td>130</td>
<td>40</td>
</tr>
</tbody>
</table>

* Specific gravity of wood is assumed to be 0.50 gram per cubic centimeter.

The relationship between size of debris and size of stream controls the arrangement and concentration of large debris at different points in a river system. In a downstream sequence, conditions change from (1) abundant, randomly distributed debris to (2) moderate loading of debris in a clumped distribution, and finally, to (3) a low concentration of widely distributed debris. The general decrease in loading of coarse debris downstream is exemplified in the McKenzie River system where headwater tributaries may have nearly 10 pounds per square foot (50 kg/m²) of coarse woody debris, whereas the mainstream McKenzie River at Rainbow has only 0.1 pound per square foot (0.5 kg/m²) (Table 12).

Quantities of large debris in streams flowing through old-growth forest are large and variable. Froehlich (1973) measured large organic debris (>10-cm or 4-inch diameter and >0.3 m or 1-foot length) in 10 relatively undisturbed streams draining from 6 to 120 acres (2.4 to 49 ha). Values ranged from 7.1 to 24.8 tons per 100 feet (21 to 73.9 tonnes/100 m); mean was 13.8 tons per 100 feet (41.1 tonnes/100 m) and standard deviation, 6.6 (19.7). In five streams draining 282 to 1,593 acres (114 to 645 ha), loadings of large debris were 5.7 to 14.2 tons per 100 feet (17 to 43 tonnes/100 m); mean was 10.3 tons per 100 feet (30.7 tonnes/m) and standard deviation, 3.6 (10.7).

Expressed on an area basis, concentration of large debris averaged 10.1 pounds per square foot (50.6 kg/m²) in the small streams draining less than 120 acres (48 ha) of old growth. In contrast, large debris in four natural, second-growth stands initiated by wildfire 75 to 135 years ago averaged only 3.8 pounds per square foot (19.1 kg/m²). Furthermore, 75 percent of the coarse debris loading in these streams was made up of large diameter, decomposed pieces derived from the prefire, old-growth stand. Structural elements inherited from preexisting old-growth stands may persist in a stream through much of the development of second growth. Swanson and Lienkaemper (1978) hypothesized that streams flowing through managed, short-rotation forests will have very low loadings of coarse debris because management activities, such as harvesting and thinning, remove the source of large debris.
Loading of debris may be abruptly reduced by debris torrents, or “sluice-outs.” Debris torrents are rare occurrences in old-growth ecosystems; the return period of torrents in a 25-acre (10-ha), old-growth watershed in the H. J. Andrews Experimental Forest has been estimated to be from 500 to 600 years. Torrents may reduce loading of debris to less than 1.0 ton per 100 feet (3.0 tonnes/100 m) of stream. As torrents move past forested streamside areas, however, banks are undercut, destabilizing trees and leading to a several-decade post-torrent period of relatively high inputs of coarse debris and reestablishment of stable debris dams and associated stream habitat. Where streamside stands are very young (less than 30 or 40 years), pieces of debris after a torrent may not be large enough to form stable accumulations and associated habitat.

The history of large debris in streams has been examined by dendrochronological methods (Swanson et al. 1976, Swanson and Lienkaemper 1976). Large pieces of debris commonly have been in streams for 25 to more than 100 years and have, therefore, weathered extreme events, such as the December 1964 flood in the Pacific Northwest. Western redcedar is particularly long lasting, followed, in order of increasing rate of breakdown, by Douglas-fir, western hemlock, and riparian hardwoods. This long residence time results from both the characteristic predominance of slowly decomposing Douglas-fir and western redcedar and the large debris provided by old-growth stands.

Large debris in streams strongly influences morphology of the channel and routing of sediment and water. In first-order through about third-order streams, debris helps to form a stepped longitudinal stream profile. Much of the energy of a stream is dissipated at falls or cascades created by debris. This pattern of dissipation in a small proportion of total stream length results in less energy available for erosion of bed and banks, more storage of sediment in the channel, slower routing of organic detritus, and greater diversity of habitat than in straight, even-gradient channels.

In small and intermediate streams in the Pacific Northwest, large debris may be the principal factor determining the characteristics of aquatic habitats. The important role of debris in creating habitat for fish has been reviewed by Narver (1971), Hall and Baker (1975), and others. The wood itself is a habitat or substrate for much biological activity by microbial, invertebrate, and vertebrate organisms.

The general influence of woody debris on aquatic habitat has been measured in several streams in the H. J. Andrews Experimental Forest (Swanson and Lienkaemper 1976). In an 800-foot (240-m) section of Mack Creek, which flows through old growth, 11 percent of the stream area is woody debris, 16 percent is wood-created habitat (primarily depositions of sediments behind woody debris), and 73 percent is nonwoody habitat—mainly cascades dominated by boulders. This section occurs in a third-order stream channel draining about 1,500 acres (600 ha). Woody debris occupies 25 percent and wood-created habitat another 21 percent of the stream area of Devilsclub Creek, a first-order tributary of Mack Creek draining 25 acres (10 ha). Much of the biological activity in the processing of detritus and other consumer organisms is concentrated in the wood and wood-created habitats.

Over half the inputs of N are associated with woody debris, including N fixation on wood. Quantitatively, woody debris is also the major energy input.

Distinctions between stream ecosystems in old-growth and second-growth stands are less clear than those between stream orders. Large organic debris plays the dominant role in streams in old-growth forests and clearly does not in managed second-growth forests. Natural, second-growth stands have residual debris dams as well as residual large stems for new dams that help span the period until the young stand begins producing larger diameter woody debris. Analysis of the overall response of aquatic communities to long-term changes in structure and nutrient sources, such as those resulting from reduced concentrations of large, organic debris, is an important research problem.

In summary, coarse woody debris is extremely important to streams in old-growth coniferous forests. Debris dams and associated plunge pools and trapped sediments, such as gravel bars, provide a great diversity of habitats for organisms. The resulting stepped stream profiles provide for greater physical and biological stability by dissipating energy otherwise used in cutting channels and moving sediment. Debris dams also slow the routing of other organic inputs, allowing organisms time to more fully process these materials before they are exported downstream. Finally, the woody debris is itself a major source of energy and nutrients for the stream ecosystem.
Old-growth forests provide highly specialized habitats and are neither decadent, unproductive ecosystems nor biological deserts. In this paper, we have contrasted the compositional, functional, and structural features of old growth with those of young-growth forests wherever data permit. It is clear that there are major contrasts between old-growth and managed, young-growth stands; structures, species, and patterns and rates of material (carbon and nutrient) flows and cycles characteristic of old growth will be absent from managed lands unless specifically provided for in silvicultural prescriptions. Differences between old-growth stands and natural, second-growth stands often appear to be one of degree; however, this is often because of material carried over from the old to the new stand, such as large snags and logs, which provide woody debris and animal habitat and serve other functions.

Alternatives for managing old-growth forest ecosystems or attributes include management to: (1) perpetuate existing old-growth stands, (2) recreate ecosystems with old-growth characteristics by long rotations, and (3) provide for individual features of old-growth forests. The first two alternatives involve a relatively small percentage of the commercial forest land in the Pacific Northwest; various acreages have been proposed in Federal land-use planning exercises, including spotted owl management plans, generally totaling 5 percent or less of the land base. Perpetuation of existing stands is the surest course since the old-growth conditions exist and can be expected to persist for several additional centuries. This assumes viable sites (appropriate size and shape with boundaries that can be protected) are selected and catastrophic fire and windthrow are avoided. Recreation of old-growth conditions through long rotations is theoretically possible but clearly unproved at this time. Site selection is important, though perhaps not as critical as it is where perpetuation of an existing old-growth forest is the objective.

The third alternative—providing for individual features—involves applying the information from this report to the main body of commercial forest land in the Pacific Northwest, not simply to the small enclaves managed for old growth. Our knowledge of old-growth forests and how they work can be used to advantage in managing millions of acres of forest for timber production by improving their ability to provide additional ecological benefits. Some of the most important ecological features of old-growth forests, and, indeed, the entire natural forest sere, can be duplicated on these lands with relatively small sacrifice of production of timber. Knowledge of old growth, such as that about snags and coarse woody debris, is widely applicable to forest management.

If the forest manager decides to retain, maintain, or recreate some forest ecosystems with old-growth characteristics several questions require attention. How should the old-growth allocation be distributed over the landscape? Which management practices should be followed in areas selected for retention of old growth and on areas to be managed on long rotations? Size and shape of old-growth enclaves are, distributional concerns. Structural features are the management key in either perpetuating or recreating old-growth stands.

**Distribution of Old-Growth Management Areas.** Having decided to maintain a certain percentage of a management unit as old-growth forest, a land manager must decide how it is most effectively distributed. Should a small stand be maintained in each drainage or compartment or fewer large tracts reserved? Where are boundaries best located? The history of natural wildfires is somewhat instructive, at least in indicating the landscape patterns in which existing old-growth stands originated. Stands were typically established in blocks of hundreds of acres. Boundaries most often were along topographic features, such as ridges or streams. “Feathering” of boundaries, resulting in large areas of mixed stands (residual old growth scattered through a young stand), was common. Fires often skipped large patches of trees, particularly on lower slopes and stream bottoms, or stands protected by natural barriers.

How large a drainage unit or stand is essential for a viable old-growth ecosystem is a difficult question. Generally, an area of 300 to 500 acres (120 to 200 ha) is sufficient for most plants and animals. This size has been suggested as essential to a pair of breeding northern spotted owls, for example, one of the most wide-ranging species dependent on old growth. McClelland et al. (1979)
suggest 50 to 100 acres (20 to 40 ha) for the nesting and feeding areas of cavity-dwelling birds. Generally, 500 to 1,000 acres (200 to 400 ha) are needed for a third-order stream drainage. Areas much smaller than 500 acres (200 ha) can, on the other hand, preserve many attributes of old-growth forests, particularly if the boundaries chosen for the area prevent rapid deterioration of the stand.

Entire drainage basins, even for small first- or second-order streams, are ecologically the most desirable units for old-growth forest management. Such drainages have natural topographic boundaries that often provide superior protection from windthrow and other external influences for the reserved stand. A variety of ecological conditions are present, along with a stream system in which natural land-water interactions (for example, woody debris inputs to the stream) can continue. Plant and animal diversity will also be higher in a drainage basin than in an isolated upland forest stand of the same size.

Another useful location for old-growth management areas is along streams. Streamside strips (buffer zones) were originally conceived for shading streams and minimizing increases in water temperatures; a more valuable function in streams up through at least third order is in providing essential energy, structural inputs (for debris dams), and stability of banks. Debris dams must be continually created to replace broken dams; this is particularly important after infrequent debris torrents that remove all, or most, pieces of large debris. Streamside strips of old-growth forest will provide for continued physical and biological stability of the aquatic ecosystem.

Streamside and roadside strips of old growth have the additional advantage of providing migration routes for organisms dependent on mature forests. The strips skirt managed stands and provide continuity between otherwise isolated pockets of natural and old-growth forest. Such migration routes may be important for avoiding loss of species as "islands" of habitat suited to a species become more limited and isolated MacClintock et al. 1977). The protected travel routes provided by these strips allow organisms to migrate in response to shifts in location of suitable habitat.

Reserve strips must be in appropriate locations and of sufficient size to survive normal windstorms. Streamside strips have often been narrow (since shading the stream was the primary objective) and sharp edged; consequently, they are extremely susceptible to blowdown. The wetter soils on lower slopes and streamside do not make retention of strips any easier, and up slope harvesting often intensifies this problem. Regular programs to salvage logs on roadside or streamside strips are inappropriate because they accelerate deterioration of the stand and remove the essential structural components. Retention of dead wood is especially important for streams where it is the source of stabilizing debris dams. Salvage logging may be appropriate if losses from catastrophic windthrow or other causes occur. Even then, the salvage should not be complete; some down material should be selected and left on the land and in the stream. A 200-foot-wide (60-m) streamside or roadside strip is not a viable unit in most cases; considerable ingenuity and effort will be necessary to identify and lay out viable reserve strips.

Areas with problems that limit potential for management may also be appropriate sites for perpetuating old-growth ecosystems and organisms. An example could be steep landslide-prone headwall areas that depend on a strong and continuing root mantle for stability.

Structural Attributes in Perpetuating or Re-creating Old Growth. The distinctive structural features—the large, old-growth trees, snags, and logs on land and in streams—provide the major key to management strategies. The unique, important compositional and functional features of an old-growth forest usually accompany these structural elements.

An old-growth forest is much more than simply a collection of large trees. The dead, organic component is as important as the highly individualistic, large trees. Decaying snags and logs, particularly in streams, are beneficial and must be provided for in management schemes: they should not be viewed solely as waste, fire hazards, or impediments to management. Snags and logs play important roles as habitat for various organisms and in conserving and cycling nutrients and energy. To a large degree, success in managing forests for old-growth attributes will depend on learning to manage the dead, organic material as cleverly as the live trees.

There are implications here for management of old-growth stands selected for perpetuation. Salvage logging is inappropriate since it removes at least two of the major structural components—dead and down—that are key elements of the system. In all likelihood, some of the more decadent, live trees would also be removed. Salvage logging is also inappropriate because of the damage inevitably done to root systems and trunks of the residual stand which results in accelerated mortality of trees and overall deterioration of the stand.17

17 When stands are selected for preservation (for example, as roadside or streamside strips), the first (and frequently repeated) management activity is often a salvage program. If a manager wants to retain an old-growth ecosystem or a mature forest stand, entries should be avoided or at least minimized. Trees viewed as safety or fire hazards may better be felled and left in place than
There are also implications if the manager wishes to create an old-growth environment (after a stand is cut) by using a long rotation. Initially, foresters may retain larger amounts of woody residues, especially down logs, from the previous stand. Retention of scattered individual, old-growth trees may be useful as sources of epiphytic flora and eventually of large, dead standing trees and down logs.

Rapid development of large, long-crowned trees as early as possible is a key objective of management that can be aided several ways. Selection of understocked stands of reproduction as sites for creating old-growth stands is one approach since individuals will grow faster and lose lower branches more slowly under open-grown conditions. Many existing old-growth stands may have regenerated slowly (Franklin and Waring 1980); growth patterns of individual trees suggest growing conditions essentially free from competition for a century or more. If initial densities of stands are moderate at current recommended levels for managed stands-precommercial and commercial thinnings will be necessary during the first 100 years of a long-rotation forest management cycle. Growth rates of individual trees will be too low at high densities, or at moderate densities on less productive sites, to produce desired sizes of stems even after 200 years; thinnings and partial cuttings are essential under those conditions. Great care must be taken, however, to minimize damage to residual trees.

Creation of appropriate types and amounts of standing dead and down trees is a specific management objective. Snags and logs from the original stand should be avoided during intermediate cuttings. Up to about 100 years, the size of snags and logs produced by the young stand is probably not of particular ecological importance. Some of this material could be removed along with excess live trees-those that will die before reaching significant diameter (50 cm or 20 inches). Openings for development of shade-tolerant species can also be created this way; if these species do not come in naturally, they could be artificially introduced, possibly by underplanting. The large snags, logs, and any live old growth left from the original stand should not be removed during salvage operations.

After about 100 years, partial cutting of any type becomes increasingly inappropriate. There are fewer live dominants, and their loss, either directly by cutting or gradually through damage to roots and trunks, is undesirable. Standing dead trees and logs now being recruited from the live stands are of sufficient size to fully perform desired habitat and cycling functions.

To summarize, if the objective is perpetuation of an old-growth forest ecosystem, a minimum amount of disturbance should be allowed. Snags and logs perform important functions and are essential structures. When the objective is to create an old-growth forest from scratch, large individual trees with large crowns should be grown as quickly as possible. Scattered old-growth trees and rotten logs from the original stand should be retained and reproduction of western hemlock, western redcedar, and other shade-tolerant associates under the Douglas-fir canopies encouraged. Partial cuttings may be useful and will be necessary in moderate to heavily stocked stands of reproduction if large trees are to be attained as quickly as possible. After trees are about 100 years old, such cuttings are increasingly inappropriate, however.

For multiple-use objectives, an increased awareness of the nature and nontimber value of individual trees is important; for example, potential or current value as habitat for epiphytic communities and wildlife. Knowledge of the ecological roles of standing, dead trees and logs beyond their value as wildlife habitat is also desirable.
Managing for individual Old-Growth Attributes

There is considerable logic in managing entire stands or small drainages for old-growth attributes. The old-growth ecosystem is a system of many interlinked components, including organisms. The serial relationship of the key structural components has been discussed—from a large, old-growth tree to a nearly decomposed, rotten log (fig. 10). Further, some organisms or functions may depend on an intact old-growth forest for their perpetuation.

Nevertheless, a forester may wish to manage for some individual old-growth attributes. This is, in fact, how the forester can put some of the information on old growth to work to increase ecological benefits from intensively managed timberlands. The structural components again provide the key. Perhaps most obvious is providing for large snags and logs. This can be done in the first-generation managed forest by retaining some of this material from the virgin stand. The tendency has been to remove all such materials as a safety measure and to reduce logging residues, which are viewed as fire hazards and impediments in regeneration and other silvicultural activities, in second- and third-generation stands, a forester will have to create appropriate materials since neither large snags nor logs will usually be present.

The need for snags was recognized first by wildlife managers, and they have more recently recognized the value of logs (Maser et al. 1979, Thomas et al. 1979a). Thomas et al. (1979a) led in developing guidelines on sizes and numbers of such material needed to provide for vertebrates; although their research was conducted in the Blue Mountains of eastern Oregon and Washington, the same principles apply on the west side of the Cascade Range, as shown by Mannan et al. (1980) and Cline et al. (1980). These authors suggest that snags be created from defective, living trees and urgent maintenance of large snags covering the spectrum of decomposition. Densities of snags in natural, old-growth stands are proposed as an interim management guide until more data are developed. Cline et al. (1980) also suggest leaving snags in groups to reduce problems of safety and fire control. It is important to remember that much more than habitat for vertebrate animals is involved in preserving snags; standing dead trees and logs serve other functions as well.18

18 The role of dead wood in cycling and conserving nutrients, especially N, is an outstanding example. Ten years ago nothing was known about sources of N in old-growth stands, other than the atmospheric input. In the interim, epiphytic lichens and wood-dwelling bacteria have been identified as significant sites for fixation. There are several important sources for additions of N in both the early stages of forest succession—nonleguminous N fixers, such as alder (Alnus spp.) and ceanothus (Ceanothus spp.)—and in old-growth forests. Existing management strategies call for quick establishment of conifer canopies and short rotations—which effectively eliminate these additions of N to intensively managed sites.

There are currently no good guides to the number and sizes of logs that should be left on cutover areas. Removal of all coarse woody debris is not the best ecological practice. Costs and benefits of some practices (such as yarding unmerchantable material) are not known; negative impacts on long-term site productivity, wildlife, and erosion may offset the benefits to fire protection and ground accessibility. It does appear that at least several larger logs per acre are needed for wildlife, especially small mammals. Defining the types and sizes of logs and other woody debris desired in managed stands is a major problem for research.

Retention of small groups of old-growth trees, or scattered individual trees, may be a useful practice. This was conceived as a technique for providing a source of epiphytic "inoculum" for adjacent young trees. Lack of such a source may be a factor in the absence of the N-fixing epiphytes on trees less than 150 years old. Leaving occasional old-growth trees has another advantage—it will, in the long run, provide a source of large snags and logs. This may be the easiest strategy for perpetuating these structural components into second- and even third-generation managed stands.
Common name  Scientific name
Alaska-cedar  Chamaecyparis nootkatensis (D. Don) Spach
Coast redwood  Sequoia sempervirens (D. Don) Endl.
Douglas-fir  Pseudotsuga menziesii (Mirb.) Franco
Grand fir  Abies grandis (Dougl. ex D. Don) Lindl.
Incense-cedar  Libocedrus decurrens Torr.
Noble fir  Abies procera Rehd.
Pacific silver fir  Abies amabilis (Dougl.) Forbes
Port-Orford-cedar  Chamaecyparis lawsoniana (A. Murr.) Parl.
Sitka spruce  Picea sitchensis (Bong.) Carr
Sugar pine  Pinus lambertiana Dougl.
Western hemlock  Tsuga heterophylla (Raf.) Sarg.
Western redcedar  Thuja plicata Donn
Western white pine  Pinus monticola Dougl. ex D. Don

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Old-growth coniferous forests differ significantly from young growth forests in species composition, function (rate and paths of energy flow and nutrient and water cycling), and structure. Most differences can be related to four key structural components of old growth: large live trees, large snags, large logs on land, and large logs in streams. Foresters wishing to maintain old-growth forest ecosystems can key management schemes to these structural components.

Keywords: Ecosystems, old-growth stands, stand composition, stand structure, Douglas-fir, *Pseudotsuga menziesii*, western hemlock, *Tsuga heterophylla*.
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