

Heartwood decay resistance by vertical and radial position in Douglas-fir trees from a young stand

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Abstract: Heartwood durability of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) was studied as a function of vertical and radial position in boles of trees with a wide range of leaf area/sapwood area ratios. Six 34-year-old trees were harvested from each of three plots established 14 years before: very dense, thinned, and thinned and fertilized. Heartwood samples from three radial positions and five heights were incubated with the decay fungus *Postia placenta* (Fr.) M. Larsen et Lombard. There were no significant differences in wood mass loss (decay resistance) by vertical or radial position. One could expect that trees with high leaf area/sapwood area could have the carbon to produce heartwood that is more resistant to decay than trees with lower leaf area/sapwood area. However, we found no relationship between leaf area above node 20, sapwood area there, or their ratio, and the decay resistance of outer heartwood at that node. These results suggest that, for young Douglas-fir trees, heartwood durability does not vary with position in the bole or with environments that alter the tree's balance of sapwood and leaf area. We suggest that young stands may thus be robust with respect to the effect of silvicultural regimes on heartwood durability.

Résumé : La durabilité du bois de cœur du Douglas (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) a été étudiée en fonction de la position verticale et radiale dans le tronc des arbres avec une vaste gamme de surface foliaire ou de superficie de bois d'aubier. Six arbres âgés de 34 ans ont été récoltés dans chacune des trois parcelles établies 14 ans auparavant : très dense, éclaircie et éclaircie avec fertilisation. Des échantillons de bois de cœur provenant de trois positions radiales et de cinq positions verticales ont été incubés avec le champignon de carie *Postia placenta* (Fr.) M. Larsen et Lombard. Il n'y avait pas de différences significatives dans la perte de masse du bois (résistance à la carie) entre les diverses positions radiales ou verticales. On s'attendrait à ce que les arbres avec une surface foliaire ou une superficie de bois d'aubier élevées aient le carbone nécessaire pour produire du bois de cœur plus résistant à la carie que les arbres avec une surface foliaire ou une superficie de bois d'aubier moindre. Cependant, nous n'avons trouvé aucune relation entre la surface foliaire au-dessus du verticille 20, la superficie de bois d'aubier à cet endroit, ou leur ratio et la résistance à la carie du bois de cœur récent au niveau de ce verticille. Ces résultats suggèrent que, chez les jeunes Douglas, la durabilité du bois de cœur ne varie pas avec la position dans le tronc ou avec les facteurs du milieu qui modifient la proportion de bois d'aubier et de surface foliaire chez les arbres. Par conséquent, nous croyons que les régimes sylvicoles n'affectent pas la durabilité du bois de cœur chez les jeunes peuplements.

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Introduction

Some tree species have evolved to produce heartwood that is highly resistant to attack by various agents of deterioration (Scheffer and Cowling 1966). Natural durability may convey a competitive advantage to the living tree because fungal or insect attack through wounds that expose heartwood will tend to progress more slowly in durable woods than in nondurable woods. As a result, the boles of these trees will remain strong and are more likely to survive forces caused by wind or snow loads. For example, tree breakage is related to how much of the central core is intact. Mattheck et al. (1993, as cited in Mattheck 1995) measured over 800 hollow trees that were either broken or intact. All

trees with more than the outer 30% of their radius intact were standing; many trees with less than 30% of their radius intact were broken. Information on durability is also useful for utilization of the wood as a product because species with durable heartwood have many uses and have strong worldwide markets.

The effects of such factors as site, growth rate, crown position, silvicultural practice, and genetic source on durability are poorly understood. Young-growth heartwood often lacks the durability of old-growth lumber, such as in coast redwood (*Sequoia sempervirens* (D. Don) Endl.; Clark and Scheffer 1983) and baldcypress (*Taxodium distichum* (L.) Rich; Scheffer and Cowling 1966). In other species like Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), there is little difference in durability between old-growth and young-growth (100- to 150-year-old) trees (Scheffer and Englerth 1952). Douglas-fir is generally classified as having moderately durable heartwood owing to the presence of the extractive taxifolin (Kennedy 1956).

Heartwood durability may be related to many factors. On the basis of limited evidence, Toole (1963) suggested that

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oak trees grown on poor soils produced heartwood that is more susceptible to decay. Site also can affect the level of inorganic elements in eastern redcedar (*Juniperus virginiana* L.), and these differences may affect subsequent resistance to decay (Guyette et al. 1992). However, site does not appear to influence the cellulose to lignin ratio in shortleaf pine (*Pinus echinata* Mill.) (Burkart and Watterston 1968). Studies of heartwood durability often are confounded by inherent variations among trees (Morita et al. 1995; DeBell et al. 1999) and by the continued change in durability as heartwood ages (Anderson et al. 1963; Nelson and Heather 1972).

There has been very little research on decay resistance in Douglas-fir as a function of position within the tree. In a study of 100- to 150-year-old Douglas-fir, Scheffer and Englerth (1952) evaluated wood mass loss of heartwood from three radial positions at one height (6–8 ft (1 ft = 0.305 m) above the ground) for trees from the Coast Range of Oregon. In laboratory decay tests they found no significant differences by radial position, but in field decay tests the outer heartwood had lower mass loss than the inner heartwood. Their evaluation of wood from six different heights (which were not given) found no differences in decay resistance. These studies were conducted on much older trees than many of the trees that are now entering mills.

Practices such as thinning and pruning have become increasingly common with the increase in intensive forest management, but the effects of these processes on decay resistance, as well as other final wood properties, remain unclear in many species. These practices are likely to change the leaf area/sapwood areas of trees, as well as their carbon balance among various compartments (leaf, root, stem, storage, defense). In keeping with results of previous studies on Douglas-fir and other softwoods (Scheffer and Englerth 1952; Anderson et al. 1963; Scheffer and Cowling 1966; DeBell et al. 1999), we hypothesized that decay resistance is highest at the base of the tree and in the outermost heartwood, and declines toward the tip and the inner heartwood. We also hypothesized that trees with higher leaf area/sapwood area ratios develop more decay-resistant heartwood than those with lower leaf area/sapwood area ratios because, other things being equal, the former trees should have more available photosynthate per unit sapwood for production of carbon-based heartwood defenses.

Materials and methods

Plant materials and plots

Studies used 34-year-old *P. menziesii* var. *menziesii* from the H.J. Andrews Experimental Forest (site L107, 44°15'N, 122°10'W, 705 m elevation) in the central Cascades in Oregon. The trees had been planted in 1963 as 2-year-old seedlings. In 1981 when trees were 18 years old, plots of trees were left unthinned (at 1190 trees/ha), thinned (to 400 trees/ha), or thinned and fertilized. The fertilizer application was based on tree size: trees with higher diameter at breast height received more fertilizer. The average application was 51, 11, 10, 7, 4, and 0.3 kg/ha for N, P, K, Ca, S, and Fe, respectively (Velazquez-Martinez et al. 1992). We selected trees from these three plots to increase the likelihood that trees would be sampled with a wide range of leaf area/sapwood area ratios.

Harvest

In March 1995, 18 trees were harvested, six from each plot. To choose the trees for harvest, we first measured diameter at breast height (DBH) of all surviving trees per plot in a 50-tree subplot that had been established in 1981. Outside the reference plot, we flagged at least 10 trees in a diameter range of $\pm 10\%$ of the reference mean. We then harvested the first six of those trees (randomly chosen) that would not threaten plot integrity (too close to the reference plot or clumped with another chosen tree to leave too large a gap). The downslope side of the tree was marked so all disks could be studied along the same radius.

Disks were removed from each tree at the 5th, 10th, 15th, and 20th internodes from the top, at breast height, and at the tree's base (about 25 and 30 internodes from the top, respectively). These disks were at an average height of 17.5, 13.5, 9.0, 4.9, 1.3, and 0.1 m from the ground, respectively.

Heartwood and sapwood areas were determined on each fresh disk. We drew two perpendicular diameters, highlighted the boundary area with the indicator stain alizarine-red, measured sapwood depth and heartwood diameter, averaged values for the two diameters, then used geometry to estimate sapwood and heartwood areas. The top disk lacked heartwood and was not studied. These disks (total of 108) were air dried for a week in the field, then oven-dried at 60°C before the assays were begun.

To estimate leaf (=needle) biomass, we removed one third of all primary branches of each tree from each zone (from nodes 0–5, 6–10, 11–15, 16–20, and ≥ 21 if branches were there). After the branches were dried, we removed their needles, redried them, determined oven-dry mass, then estimated tree needle biomass (unpublished). To convert needle biomass to needle area, during the harvest we collected >70 subsamples of fresh needles (one subsample for each zone for each of the 18 trees). We used an image analysis system to estimate one-sided needle area for each of the subsamples. These subsamples were then oven-dried and weighed, and the conversion from needle mass to area was calculated. An average conversion value was calculated for each of the four or five zones and for each of the three plots, then leaf areas were estimated (unpublished).

Assays for decay resistance

Blocks (1 cm³) were cut from the heartwood of each disk. Three radii were established at 120° to one another, with one radius oriented along the downslope mark. Blocks along each radius were removed from the newest heartwood (along the heartwood-sapwood border, "outer"), intermediate heartwood ("middle"), and if the disk were wide enough, older heartwood ("inner;" Fig. 1).

Standard wood block tests (AWPA 1996) were performed as follows. Wood blocks were oven-dried (70°C), weighed, soaked in water to saturation, and sterilized by exposure to 2.5 mRads of ionizing radiation from a cobalt-60 source. Afterwards, 11 of the 752 blocks were discarded, because they were cracked or split. Glass bottles (56 mL) were half-filled with moist forest loam and a 15 × 20 × 3 mm thick wafer of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) was placed on the soil surface. Water was added to raise the soil moisture content to 100% (water mass/wood dry mass basis), and the jars were autoclaved for 45 min at 121°C. A 3-mm disk of agar cut from an actively growing culture of *Postia placenta* (Fr.) M. Larsen et Lombard (Isolate No. Madison 698, USDA Forest Products Laboratory, Madison, Wis.) was placed on one edge of the hemlock wafer and the jars were incubated at 28°C until the fungus had covered the wafer. Blocks were placed on the wafers, and the bottles were incubated for 12 weeks at 28°C, two blocks to a bottle. At the end of the incubation period, blocks were scraped clean of fungus and soil and weighed, to allow calculation of minimum moisture content during the experiment to ensure that moisture levels were adequate for microbial growth throughout the experiment (>40%). Blocks were oven-dried (70°C) and reweighed

Fig. 1. Locations on disks (stem cross sections) from which study blocks were taken. The downslope marker allowed vertical alignment of all disks from a tree.

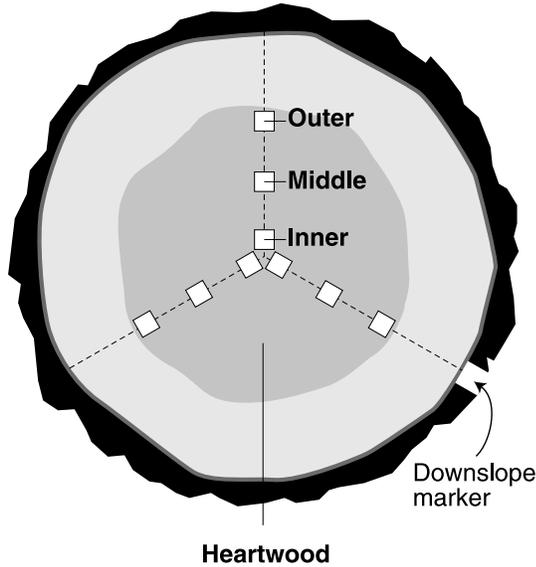
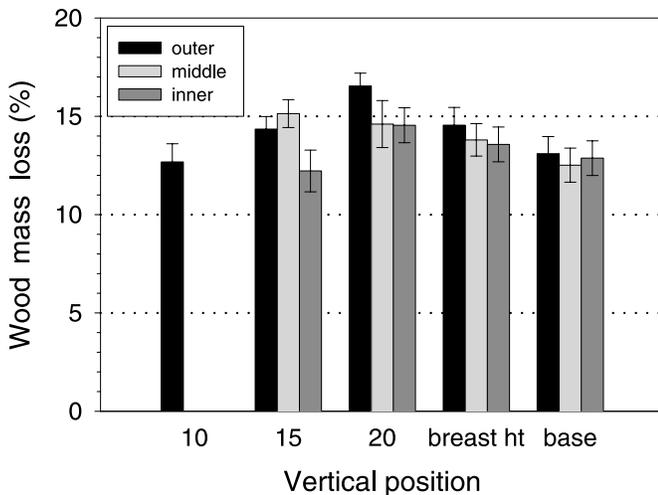


Fig. 2. Wood mass loss as a function of vertical and radial position. Vertical positions are 10, 15, or 20 nodes down from the tree top, breast height (about 25 nodes down), and tree base (about 30 nodes down). Values are means \pm SE ($n = 18$), where each of the 18 values is the mean of three blocks from 120° apart.



to allow calculation of mass loss, expressed as a percentage of the original mass. The most decay-resistant blocks were the ones that lost the lowest proportion of their mass.

Data analyses

To look at the effects of vertical and radial position on decay resistance, we used a mixed model using Statistical Analysis Systems software (SAS Institute Inc. 1996). Random effects accounted for correlation among trees within blocks (the three plots), vertical position within trees, and radial position within the disks. Values were considered statistically significant if $P < 0.05$.

To look for relationships among a tree's heartwood decay resistance and its leaf and sapwood areas, we chose to concentrate on

Fig. 3. Wood mass loss of the outer heartwood of disk 20 as a function of cumulative leaf area above disk 20/sapwood area of disk 20 (mean \pm SE, $n = 3$). The 32-year old Douglas-fir trees came from plots that were very dense, thinned, or thinned and fertilized 14 years before this study.

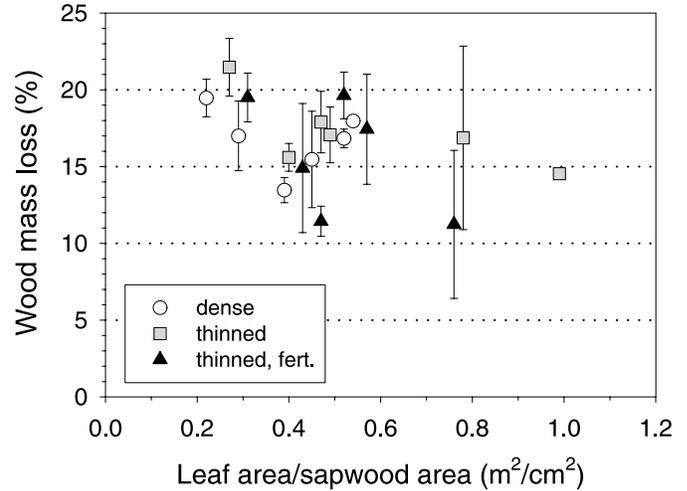


Table 1. Effects of vertical and radial position on wood mass loss.

Source	Numerator df	Denominator df	<i>P</i>
Vertical position (V)	4	8	0.0633
Radial position (R)	2	4	0.1900
V \times R	6	12	0.3575

Note: Vertical positions are 10, 15, and 20 nodes down from the tree top, breast height, and tree base. Radial positions are outer, middle, and inner heartwood.

the tree at node 20. This node was at or below the live crown in 15 of the 18 trees. We reasoned that nodes below 20 (breast height and base) were so far below the crown that its influence could be diluted by other factors, and that nodes above 20 (nodes 10 and 15) would not have much heartwood to study. For disk 20 for each of the 18 trees, mean mass loss of the outer blocks was plotted against cumulative leaf area above (distal to) disk 20, leaf area in the five-node zone immediately above disk 20, and cumulative leaf area above disk 20/disk 20 sapwood area. There were no apparent relationships among these variables, so no further statistical analyses were done.

Results

There were no significant effects of vertical or radial position on wood mass loss, nor was there a significant interaction between the vertical and radial positions (Table 1, Fig. 2). Although vertical position was significant at $P = 0.0633$, we felt that the differences among the disk means was not biologically or practically significant.

Inspection of graphs showed that wood mass loss was not related to cumulative leaf area above disk 20 (data not shown), leaf area in the five-node zone immediately above disk 20 (data not shown), or cumulative leaf area above disk 20/disk 20 sapwood area (Fig. 3). The standard errors

indicate the large variability in wood mass loss among blocks from the same radial position and disk (Fig. 3).

Discussion

Contrary to hypothesis, there were no significant effects of the vertical or radial positions of the sample on its resistance to decay. The current result was the same as those reported for 100- to 150-year-old trees for vertical and radial position assayed in the laboratory but not for radial position assayed in the field (Scheffer and Englerth 1952). Studies in other species have shown that the most durable heartwood often is present at the base of the tree and in the outer heartwood (i.e., Scheffer and Cowling 1966; DeBell et al. 1999), and that these locations have the highest concentrations of defense compounds as well (Morita et al. 1995; DeBell et al. 1999).

Also contrary to the hypothesis, leaf area/sapwood area was not related to wood mass loss. This lack of relationship suggests that either the proximity to or the quantity of photosynthesizing tissue has little effect on allocation of carbohydrates to ray cells near the zone where heartwood formation occurs. One difficulty in establishing such relationships is the time lag between treatment and heartwood formation: wood produced in a given year may not convert to heartwood for another several to 200 years, depending on the softwood species (Panshin and DeZeeuw 1980, p. 29).

As expected with studies of natural durability, wood mass loss varied widely among samples, reflecting natural variations in heartwood extractive content (Scheffer and Cowling 1966). The overall trends, however, suggest that there is little practical or systematic difference in the durability of heartwood with position in the trees studied.

The trees evaluated in the current study were from relatively young stands (about 34 years old), where the oldest heartwood probably was produced about 15 years ago. Many industrial Douglas-fir forests are typified by short rotations little older than the trees in this study. Our results suggest that the silvicultural regimes that promote rapid growth do not adversely alter the decay resistance of the heartwood in these young Douglas-fir trees, although experiments designed to target the effects of altered tree carbon balance on wood decay would be necessary to make a conclusive statement. Studies with older stands and other species would be useful to further understand the relationships between tree characteristics and heartwood decay resistance.

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References

- American Wood-Preservers' Association (AWPA). 1996. Standard E10: testing wood preservatives by laboratory soil block cultures. *In* American Wood-Preservers' Association wood of standards. American Wood-Preservers' Association, Granbury, Tex. pp. 305–315.
- Anderson, A.B., Scheffer, T.C., and Duncan, C.G. 1963. The chemistry of decay resistance and its decrease with heartwood aging in incense cedar (*Libocedrus decurrens* Torrey). *Holzforschung*, **17**: 1–5.
- Burkart, L.F., and Watterston, K.G. 1968. Effect of environment on ratio of cellulose to lignin in shortleaf pine. *For. Prod. J.* **18**: 25–28.
- Clark, J.W., and Scheffer, T.C. 1983. Natural decay resistance of the heartwood of coast redwood *Sequoia sempervirens* (D. Don) Endl. *For. Prod. J.* **33**: 15–20.
- DeBell, J.D., Morrell, J.J., and Gartner, B.L. 1999. Within-stem variation in tropolone content and decay resistance of second-growth western redcedar. *For. Sci.* **45**: 101–107.
- Guyette, R.P., Cutter, B.E., and Henderson, G.S. 1992. Inorganic concentrations in the wood of eastern redcedar grown on different sites. *Wood Fiber Sci.* **24**: 133–140.
- Kennedy, R.W. 1956. Fungicidal toxicity of certain extraneous components of Douglas-fir heartwood. *For. Prod. J.* **6**: 80–84.
- Mattheck, C. 1995. Biomechanical optimum in woody stems. *In* Plant stems: physiology and functional morphology. *Edited by* B.L. Gartner. Academic Press, San Diego. pp. 75–90.
- Mattheck, C., Bethge, K., and Schäfer, J. 1993. Safety factors in trees. *J. Theor. Biol.* **165**: 185–189.
- Morita, S.I., Yatagai, M., and Fujita, S. 1995. Distributions of the extracts and sesquiterpenes in the trunk of yakusugi (*Cryptomeria japonica*). *Mokuzai Gakkaishi*, **41**: 938–944.
- Nelson, N.D., and Heather, W.A. 1972. Wood color, basic density, and decay resistance in heartwood of fast-grown *Eucalyptus grandis* Hill ex. Maiden. *Holzforschung*, **26**: 54–60.
- Panshin, A.J., and de Zeeuw, C. 1980. Textbook of wood technology. 4th ed. McGraw-Hill, New York.
- SAS Institute Inc. 1996. SAS/STAT user's guide, release 6.12 edition. SAS Institute Inc., Cary, N.C.
- Scheffer, T.C., and Cowling, E.B. 1966. Natural resistance of wood to microbial deterioration. *Annu. Rev. Phytopathol.* **4**: 147–170.
- Scheffer, T.C., and Englerth, G.H. 1952. Decay resistance of second-growth Douglas-fir. *J. For.* **50**: 439–442.
- Toole, E.R. 1963. Site affects rate of decay in cherrybark oak. *Plant Dis. Rep.* **47**: 568.
- Velazquez-Martinez, A., Perry, D.A., and Bell, T.A. 1992. Response of aboveground biomass increment, growth efficiency, and foliar nutrients to thinning, fertilization, and pruning in young Douglas-fir plantations in the central Oregon Cascades. *Can. J. For. Res.* **22**: 1278–1289.