IAWA Journal, Vol. 17 (4), 1996: 445–461

BETWEEN- AND WITHIN-TREE VARIATION IN THE ANATOMY AND SPECIFIC GRAVITY OF WOOD IN OREGON WHITE OAK (QUERCUS GARRYANA DOUGL.)

by

Hua Lei, Michael R. Milota & Barbara L. Gartner[1]

Department of Forest Products, Oregon State University, Corvallis, OR 97331-7402, USA

SUMMARY

In order to analyze the variation in wood properties within and between trees of an underutilized tree species, we sampled six Oregon white oak (*Quercus garryana* Dougl.) trees from an 80-year old mixed stand of *Q. garryana* and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) in the Coast Range of Western Oregon, USA. Fibre length, earlywood vessel diameter, tissue proportions, and specific gravity were measured on samples across the diameter at two heights. Trees had a slight lean (2–12°), so we sampled separately both radii of a diametric strip that ran from the lower to upper side of lean.

Variation between trees, between the two heights, and between the lower and upper sides of lean was not significant for most measured wood characteristics. The exceptions were vessel proportion, higher at the upper height, and specific gravity, higher at breast height ($P < 0.05$). There was significant variation ($P < 0.05$) between the youngest juvenile wood (growth rings 2, 4, and 7) and the oldest sampled mature wood (growth rings 32, 39, and 48) in fibre length (1.1 vs. 1.2 mm); earlywood vessel diameter (164 vs. 272 µm); proportion of fibre (64 vs. 46%), vessel (12 vs. 27%), and axial parenchyma (10 vs. 14%); and specific gravity (0.83 vs. 0.66). These characteristics showed demarcation ages between juvenile and mature wood of 10–26 years, depending on the characteristic. The ray proportion (about 14%) showed no definite pattern of radial change. The results of this study may be used for estimating wood and fibre quality of ring-porous hardwoods such as this species.

Key words: *Quercus garryana*, radial variation, ring-porous, specific gravity, wood anatomy, wood quality.

INTRODUCTION

Decreased logging of public lands in the Pacific Northwest of the USA has resulted in a decreased supply of conifers to the mills. At the same time, the nature of the remaining conifer supply has changed: younger trees with characteristics that are different from those of older trees now form a greater proportion of the softwood supply. This

---

[1] To whom correspondence should be addressed.

situation has increased economic interest in native hardwoods. Although estimates of average properties for these hardwoods are available, there is little information on the tree-to-tree and within-tree variation. This research details the pith-to-bark and between-height variation of wood characteristics in a ring-porous species, Oregon white oak (*Quercus garryana* Dougl.). Companion studies detail wood characteristics of a diffuse-porous species, red alder (*Alnus rubra* Bong.; Gartner et al. 1997) and relationships between anatomy and mechanical properties of *Quercus garryana* and *Alnus rubra* (Lei 1995; Gartner et al. 1995; Evans 1996).

Oregon white oak is a deciduous hardwood common in inland areas along the Pacific coast from Vancouver Island (lat. 49° N) to southern California (lat. 34° N). It is the only native oak in Washington state and in British Columbia, and the main one in in Oregon (Stein 1990), and one of only four deciduous oaks native to the west coast. It is locally abundant in dry sites or under regimes of periodic fire, and lives in association with a wide variety of other species (Niemiec et al. 1995). Its primary uses are fuel (it is considered one of the best woods for home heating), fenceposts, and specialty items, but it is also used for furniture, flooring, railroad ties, tight cooperage, turnings, veneer, millwork, fence posts, mine timbers, and pulp chips (Stein 1990; Niemiec et al. 1995). *Quercus garryana* is not cultivated for its wood, but it is harvested where individuals are present within an area of other species that are to be cut. Open-grown individuals are prized (when left standing) for their beauty.

A large concern in the utilization of wood is the degree of variation of wood properties at different scales. This variation can result from site-to-site differences in wood (Hernández & Restrepo 1995) and from population-level differences within a site (Hamilton 1961), but a major portion of the variability is often within the trees themselves (Kandeel & Bensend 1969; Panshin & De Zeeuw 1980; Zobel & Van Buijtenen 1989; Zhang et al. 1994).

Most studies on within-tree variation in wood properties focus on radial (pith-to-bark) trends. Stems can be classified into two concentric zones, juvenile and mature, based on radial variations in wood characteristics. Generally, rapid changes in properties characterize the juvenile wood zone and slow or non-existent changes characterize the mature wood zone. Unfortunately, this terminology connotes discrete and synchronous changes in many values at the boundary between the zones. In this paper, as in most papers in the literature, the terms 'juvenile' and 'mature' are used only as convenient labels, with the understanding that properties actually change gradually and independently of one another.

Because of its impact on utilization, juvenile-wood characteristics in softwoods have been studied extensively (e.g., Dadswell 1958; Erickson & Harrison 1974; Erickson & Arima 1974; Bendtsen 1978; Thomas 1984; Bendtsen & Senft 1986; Krahmer 1986; Maloney 1986; Cown 1992). In most softwoods, juvenile wood has lower specific gravity and strength than mature wood, and so has lower quality for structural applications (Haygreen & Bowyer 1989). In hardwoods, information is scarce and inconsistent on variation in wood properties and on juvenile wood characteristics. The inconsistency is probably exacerbated by the diversity of hardwood xylem patterns (e.g., ring-porous, diffuse-porous, without annual rings) and their lower commercial importance relative to softwoods.

To our knowledge, no previous research has been reported on either radial or vertical variation in wood properties of *Q. garryana*. However, we expected its properties to be similar to other ring-porous species. Typically, ring-porous species have declining specific gravity with cambial age (Hamilton 1961; Fukazawa 1984; Quanci 1988; Zhang et al. 1993; but see also Taylor & Wooten 1973). Although ring width declines with cambial age as well, cambial age explains more of the variation in wood density than does ring width in both East-Liaoning oak (*Q. liaotungensis*, Zhang & Zhong 1991) and European oak (*Q. petraea* and *Q. robur*, Zhang et al. 1994). The declining specific gravity is explained by about constant amounts of earlywood and declining amounts of latewood with cambial age (Zhang & Zhong 1994), and also with declining earlywood and latewood density with cambial age (Zhang et al. 1993). In general in ring-porous species, as cambial age increases, the vessel proportion increases and fibre proportion decreases (Taylor & Wooten 1973). This pattern is caused by the decline in proportion of latewood with cambial age, higher vessel proportion in earlywood than in latewood, and an increase in vessel proportion within earlywood with cambial age (Phelps & Workman 1994). Fibre length increases with cambial age in ring-porous species (Dinwoodie 1961; Hamilton 1961; Taylor & Wooten 1973), as do vessel element and tracheid length in oak (Helińska-Raczkowska & Fabisiak 1991).

The literature is scanty on vertical variation in wood properties in ring-porous species. The model of wood density developed by Zhang et al. (1993) for *Q. petraea* and *Q. robur* predicted no systematic differences in wood density with height, but increases have been reported in *Q. phellos* (Taylor & Wooten 1973). Hamilton (1961) showed that for a given cambial age, wood density increased with height in *Q. falcata*. For a given cambial age, the proportion of latewood decreased with height in the stem up to about 80% of the tree's height; above that point it increased (Hamilton 1961). Phelps and Workman (1994) looked at the proportion of vessels in earlywood tissue with height. They found significant but only slight increases in this characteristic with increased height for *Q. alba*, and this pattern only for the wood of oldest cambial age studied in their 48-year-old trees. *Quercus phellos* showed no significant change in fibre length or in fibre or vessel volume with height (Taylor & Wooten 1973) but *Q. falcata* had a small decrease in fibre length with height for wood of the same cambial age (Hamilton 1961).

The goal of this research was to learn more about variation (or uniformity) in the wood of *Q. garryana* to facilitate its increased use in value-added products, such as wine barrels, chairs, and flooring. Specifically, we wanted to analyze the variation of wood properties between and within trees to characterize their vertical and radial variation, and to identify the demarcation age between juvenile and mature wood for different characteristics. The characteristics we studied included growth ring width, percent earlywood, fibre length, vessel diameter, specific gravity, and tissue proportion of vessel, fibre, axial parenchyma, and ray.

MATERIALS AND METHODS

Material collection

Six *Quercus garryana* trees were selected from an 80-year-old mixed stand of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and *Q. garryana* in the McDonald-Dunn Forest of Oregon State University (44° 40' 15" N latitude, 123° 17' 30" E longitude; 190 m elevation). To minimize tree-to-tree variation, we randomly selected trees with fairly straight stems, little lean, similar diameters, and no evidence of defects (such as large scars; Table 1). The lean direction was marked on the bole and the lean angle from vertical was recorded for each of the six trees. We felled trees in March, 1992, then removed one disk from breast height (1.3 m) and a second from an upper height below the first fork (average of 4.4 m, Table 1). This second height was chosen to get information as high up as possible on the part of the bole that could be used as one merchantable log, because forks are usually cut out and left on site. The site was on a 21% east-facing slope on well-drained clay loam soil.

Sample preparation

A 2.5-cm-wide slab was cut across the diameter of each disk, going through the lean mark and the pith. To prevent drying defects, the slabs were coated with paint on both transverse faces and put in a conditioning room at 30 °C and 95% relative humidity for slow drying. After eight weeks, the slabs were moved into a room with a 12% equilibrium moisture content until their moisture content was stable.

Table 1. Information on the *Quercus garryana* trees sampled for this study. Tree fork refers to the lowest fork or substantial branch along the bole.

Tree	Lean direction	Lean angle from vertical	Basal diameter (cm)	Diameter at breast height (cm)	Age at breast height (years)	Tree height (m)	Fork height (m)	Upper sampling height (m)
1	10°	5°	41	27	68	21.1	5.7	4.4
2	80°	2°	35	29	60	22.0	5.6	4.3
3	200°	12°	32	27	58	18.8	7.1	4.5
4	155°	2°	31	26	65	19.6	8.2	4.6
5	50°	2°	33	30	70	21.6	3.8	4.2
6	85°	2°	38	32	68	24.0	8.1	4.6
mean		4°	35	29	65	21.2	6.4	4.4
s.e.		2°	2	1	2	0.8	0.7	0.1

A series of samples was cut from the slabs. Although trees were in an 80-year-old stand, we concentrated effort only on the first 48 growth rings to study the juvenile/mature changes, to limit sampling to maintain feasibility, and to avoid the difficulty of sampling very narrow growth rings. Samples were centered on rings with cambial ages of 2, 4, 7, 10, 15, 20, 26, and 32 at both heights and, in addition, of 39 and 48 at breast height. Samples were analyzed separately from the two sides of the pith (representing the upper and lower sides of lean). Samples were 0.64 cm (0.25 inches) in the tangential direction.

Measurements

The specific gravity of each sample was determined using volume at 12% moisture content. Volume was the product of the three dimensions (measured with calipers). Specimens were subsampled for the anatomical measurements. Slides of macerated fibres and microtome sections from both the transverse and tangential planes (of the earlywood) were made from each sample. Anatomical measurements were made with the help of an image analysis system. We used a video camera on a compound or dissecting microscope to capture images that were digitized automatically and displayed on a computer monitor with the software NIH Image (Rasband 1992). We estimated fibre length and tangential earlywood vessel diameter from 80 fibre and 80 vessel measurements per sample. Four microtome sections of the transverse surface (taken from the same location) were used to obtain the growth ring width, earlywood vessel diameter, latewood percentage, and the fibre, vessel, and axial parenchyma proportion for each sample. The technique of image analysis that we used lends itself to a different way of determining vessel diameter than has been the standard in the literature (tangential vessel diameter measured). We digitized all the vessel lumens, had the computer determine their areas, and calculated diameter from the areas as if all vessels were circular in cross section. Thus, diameter was of the lumens only, and assumed round vessels. An advantage to the use of image analysis is the large number of vessels one can characterize semi-automatically. The fibre proportion included vasicentric tracheids. Earlywood was distinguished from latewood on the basis of its relatively wide vessels. Ray proportion, including broad and narrow rays, was measured from four tangential sections. Only one of the trees had substantial lean (Table 1), and we detected no tension wood in it.

Data analysis

We conducted t-tests between the two heights for both sides pooled for each of the wood properties. We also used t-tests to compare properties of the youngest juvenile wood (cambial age < 10 years) with those of the oldest mature wood tested (cambial age 30–50 years).

An analysis of variance (ANOVA) with a SAS general linear model (SAS Institute 1988) was performed to evaluate the variation in wood properties among trees (tree effect), between the two heights (height effect), and between the lower and upper sides (lean effect). To prevent an unbalanced effect of cambial ages between heights, we used only samples from the same growth rings for both heights; that is, samples from growth rings 39 and 48 at breast height were excluded.

We used a regression analysis to describe the radial profiles of wood properties at each height as a function of cambial age. Before the regression analysis, a preliminary analysis was conducted to check if the data from the six trees could be pooled. In all cases, tree effect and its interaction with age and the variable (e.g., vessel diameter) were not significant ($P < 0.05$), so regressions were calculated on pooled data from the six trees. A simple linear regression was used when the relationship between a wood property and cambial age was linear. We used a piecewise linear regression model (Neter et al. 1989; also called a segmented regression) to fit two or more linear regressions together. It calculates the best fit regression lines that conjoin at one or more inflection points. This approach has been used before to detect demarcation ages between juvenile and mature wood (e.g., Bendtsen & Senft 1986; Quanci 1988; Abdel-Gadir & Krahmer 1993).

RESULTS AND DISCUSSION

Effects of height (t-tests)

There were no significant differences between the two heights for fibre length, vessel diameter, proportion of fibre, or proportion of ray (Table 2, $P > 0.05$). At breast height compared to the upper height, vessel proportion was 28% lower, specific gravity was 8% higher, and axial parenchyma proportion 20% higher. The higher specific gravity at breast than upper height contrasts with other observations (see introduction) but in the literature as well as here, the magnitude of the variation is small. The decrease in vessel volume with height also contrasts with Taylor & Wooten's (1973) finding of no significant change.

Variation among trees (ANOVAs)

Variation in properties among trees was not statistically significant ($P < 0.05$) for any measured characteristics (Table 3). Note, however, that only six trees were sampled; a larger number of trees could have shown significant between-tree variation.

Table 2. Mean values for wood characteristics of *Quercus garryana* and results of t-tests (paired by tree). Samples had cambial ages of 2, 4, 7, 10, 15, 20, 26, and 32 for both heights; cambial ages of 39 and 48 from breast height were excluded.

Property	Breast height (n = 48)	Upper height (n = 48)	P
Fibre length (mm)	1.2	1.1	n.s.
Vessel diameter (mm)	222	212	n.s.
Fibre proportion (%)	61	59	n.s.
Vessel proportion (%)	13	18	*
Ray proportion (%)	14	13	n.s.
Axial parenchyma proportion (%)	12	10	*
Specific gravity	0.80	0.74	*

* = $P < 0.05$; n.s. = $P > 0.05$.

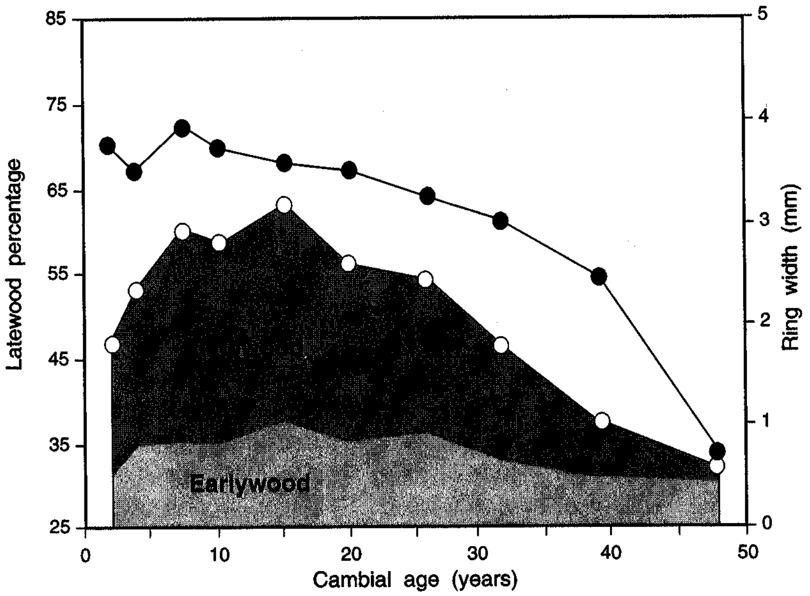

Fig. 1. Earlywood width, latewood width, growth ring width (O) and percentage of latewood (●) as a function of cambial age at breast height in *Quercus garryana*.

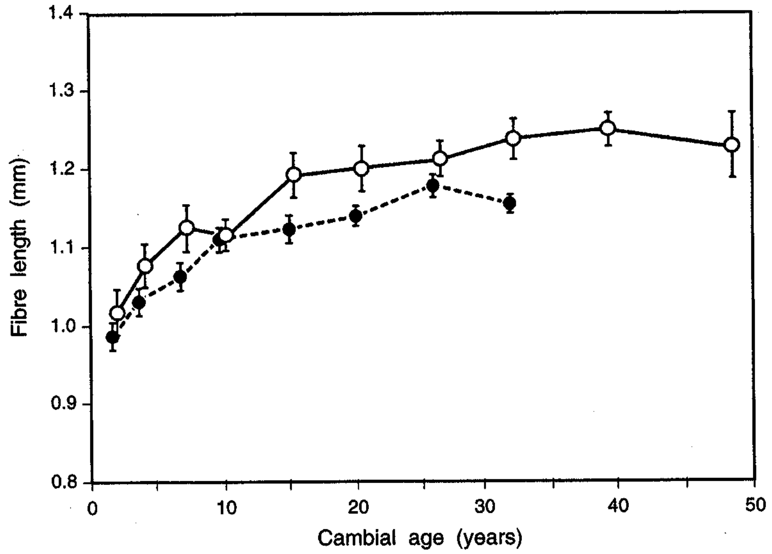

Fig. 2. Fibre length as a function of cambial age at breast height (O) and the upper height (●, average of 4.4 m) in *Quercus garryana*. Standard error bars show the variation among trees (n = 6).

Table 3. P-values from analyses of variance of wood characteristics of *Quercus garryana* among and within trees as a function of height (upper vs. breast height), side of the lean (upper vs. the lower), and the interaction of height and side of the lean.

Source of variance	DF	Fibre length	Vessel diameter	Fibre proportion	Vessel proportion	Ray proportion	Axial parenchyma proportion	Specific gravity
Tree	5	0.15	0.15	0.22	0.50	0.73	0.89	0.19
Height (tree)	1	0.07	0.16	0.20	0.009**	0.09	0.22	0.01**
Lean (tree)	1	0.07	0.29	0.52	0.11	0.39	0.12	0.88
Height × lean (tree)	5	0.47	0.21	0.17	0.003**	0.14	0.47	0.40

** = $P < 0.01$.

Within trees vessel proportion was significantly higher at breast height than at the upper height, and specific gravity was significantly lower at breast height than at the upper height (Table 3). The effects of lean and the interaction between height and lean were not significant for any measured characteristics ($P < 0.05$; Table 3) except for vessel proportion. It is possible that the interaction between height and lean is related to tension wood, but that it is not manifested through gelatinous fibres (which we did not detect) or that gelatinous fibres were present but we did not detect them.

Zhang et al. (1994) took a different approach by partitioning the variance into individual components. This enabled the authors to state the relative contribution of each source to the total variance.

Radial patterns

Ring width — At breast height, the average ring width was higher in juvenile (rings 2, 4, and 7) than mature wood (rings 32, 39, and 48; 2.5 ± 0.8 mm vs. 1.2 ± 0.6 mm, respectively, mean ± s. d., n = 36). The coefficient of variation for ring width is lower for the juvenile wood (32%) than for the mature wood (50%).

Annual ring width increased for the first 10–20 rings and then decreased for the disks from breast height (open circles, Fig. 1). Growth ring width averaged 2.6 mm for rings 0–10 (from the pith), 2.9 mm for rings 11–20, 2.3 mm for rings 21–30, and only 1.1 mm at > 30 rings. Earlywood width was about constant throughout the radial profile, and latewood width decreased from about 10–20 years outward toward the bark (Fig. 1). This situation resulted in a decrease of latewood percentage with age (filled circles, Fig. 1), consistent with the pattern seen by others for ring-porous species (e.g., Panshin & De Zeeuw 1980; Zhang et al. 1993). At breast height, from 0–10 years

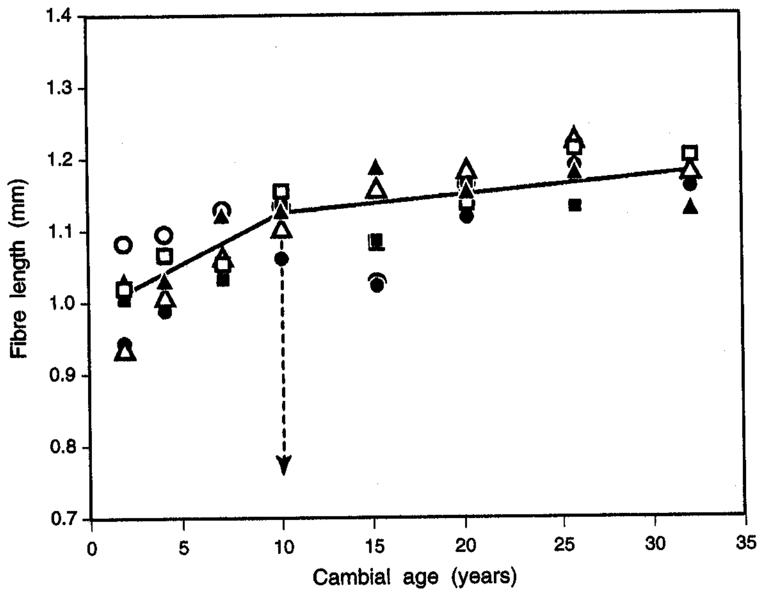

Fig. 3. An example of a piecewise regression model fitted to the data of fibre length at the upper height as a function of cambial age for *Quercus garryana*. Symbols represent different trees (n = 6) and the arrow shows the demarcation age between juvenile and mature wood.

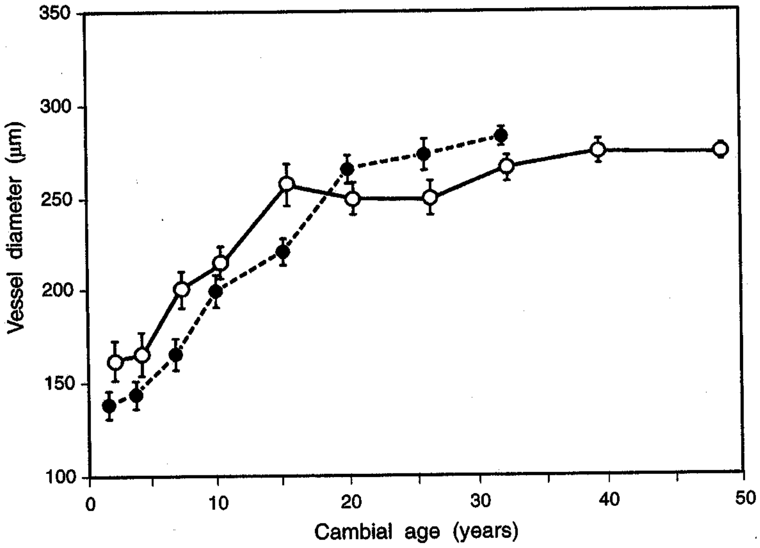

Fig. 4. Vessel diameter as a function of cambial age at breast height (○) and the upper height (●, average of 4.4 m) in *Quercus garryana*. Standard error bars show the variation among trees (n = 6).

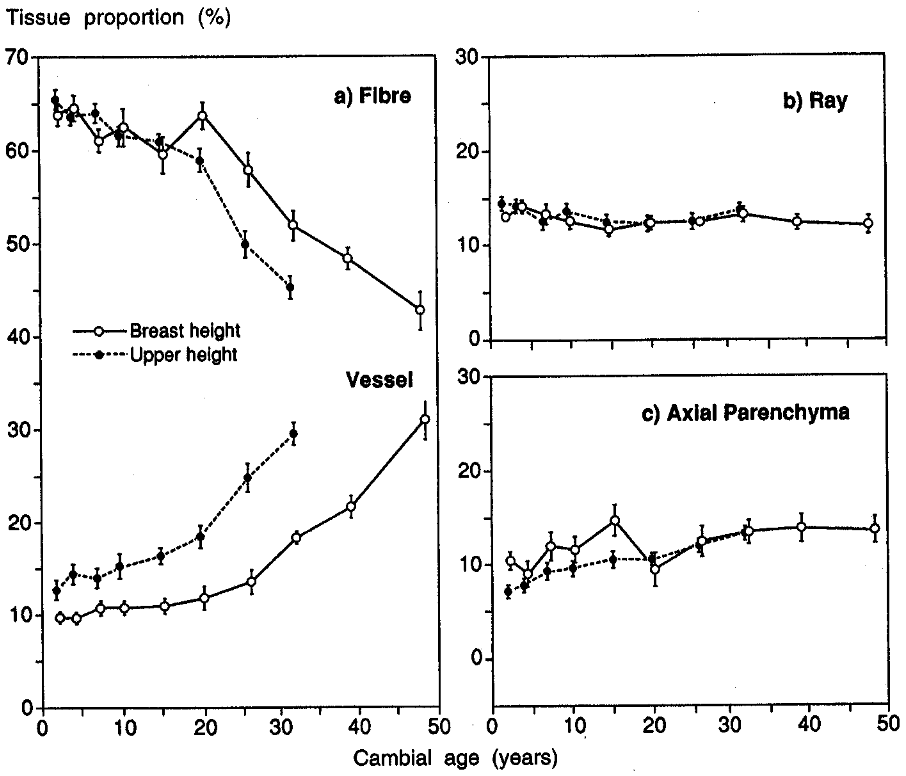

Fig. 5. Tissue proportions as a function of cambial age at breast height (○) and the upper height (●, average of 4.4 m) in *Quercus garryana:* fibre proportion, vessel proportion, ray proportion, and axial parenchyma proportion. Standard error bars show the variation among trees (n = 6).

cambial age the average latewood percentage was 70%; at 11–20 years, 69%; at 21–30 years, 64%; and at > 30 years, 38%. Because of the decreased proportion of latewood with age, the rings at higher cambial ages (> 30 years) would be expected to have a different tissue composition. As shown below, these outer rings were composed of a higher proportion of vessels, and had lower fibre proportion (Fig. 5) and specific gravity (Fig. 6) than did rings of younger cambial ages.

For the radial profiles as a whole, ring width was not correlated significantly with any of the anatomical characteristics (correlations not shown). This can be seen by comparing the shape of the curve of ring width (Fig. 1, open circles) to the shapes of the other curves (Fig. 2, 4, and 5).

Fibre length — Fibre length increased rapidly during the first decade, then leveled off (Fig. 2). The demarcation age from juvenile to mature wood was 10 years at the upper height ($R^2 = 0.74$; Fig. 3; Table 4) and 15 years at breast height ($R^2 = 0.44$; Table 4). The pattern of an increase in fibre length and a juvenile-mature wood transition in cell length from pith to bark is consistent with that of many ring-porous and diffuse-porous hardwoods (reviewed in Dinwoodie 1961; Zobel & Jett 1995).

Table 4. Results of linear regression analyses for wood properties of *Quercus garryana* (Y) versus cambial age (X) at breast height and the upper height. The demarcation age between juvenile and mature wood (X') is given only if the data fit a two-segment line regression better than a simple linear regression. Parameters are only given for significant R^2 ($P < 0.05$).

Regression parameters [a]	Fibre length (mm)	Vessel diameter (mm)	Fibre proportion	Vessel proportion	Ray proportion [b]	Axial parenchyma proportion [b]	Specific gravity [b]
Breast height (n = 48)							
β_0	1.018	0.145	64.8	10.27		7.203	0.867
β_1	0.0124	0.00741	-0.337	0.143		0.182	-0.00472
β_2	0.211	0.838	12.7	-7.58			
β_3	-0.0124	-0.0064	-0.397	0.384			
MSE	0.00688	0.00035	16.2	6.65		3.38	0.00161
R^2	0.44	0.71	0.76	0.91		0.09	0.76
X'	15	15	15	26			
Upper height (n = 48)							
β_0	0.972	0.0124	65.7	11.9	14.05	7.203	0.834
β_1	0.0144	0.00679	-0.35	0.31	-0.054	0.182	-0.00671
β_2	0.131	0.114	15.2	-12.24			
β_3	-0.012	-0.00539	-0.765	0.617			
MSE	0.0014	0.00035	7.745	12.93	3.345	3.38	0.00263
R^2	0.74	0.90	0.86	0.66	0.08	0.51	0.65
X'	10	15	15	20			

a = β_0, β_1, β_2 and β_3 are the regression coefficients. MSE is mean square of error. R^2 is coefficient of determination. X' is the demarcation age between juvenile segment ($Y = \beta_0 + \beta_1 X$) and mature segment [$Y = (\beta_0 + \beta_2) + (\beta_1 + \beta_3)X$] if data fit a two-segment regression function.
b = Data only fit simple regression function.

Vessel diameter — Earlywood vessel diameter at both heights increased for the first 10–20 years and then leveled off (Fig. 4). Two-segment linear regression of vessel diameter against cambial age showed that cambial age explains much of the variation in vessel diameter at both the upper height ($R^2 = 0.90$) and breast height ($R^2 = 0.71$; Table 4). The demarcation age for vessel diameter between juvenile and mature wood was 15 years at both heights (Table 4).

The pattern of radial variation in vessel diameter of *Q. garryana* corroborates the results of previous studies of ring- and diffuse-porous species in showing a juvenile-mature transition from pith to bark (e.g., Fukazawa & Ohtani 1982; Dodd 1984; Furukawa & Hashizume 1987; Butterfield et al. 1993; Peszlen 1994; Gartner et al. 1997).

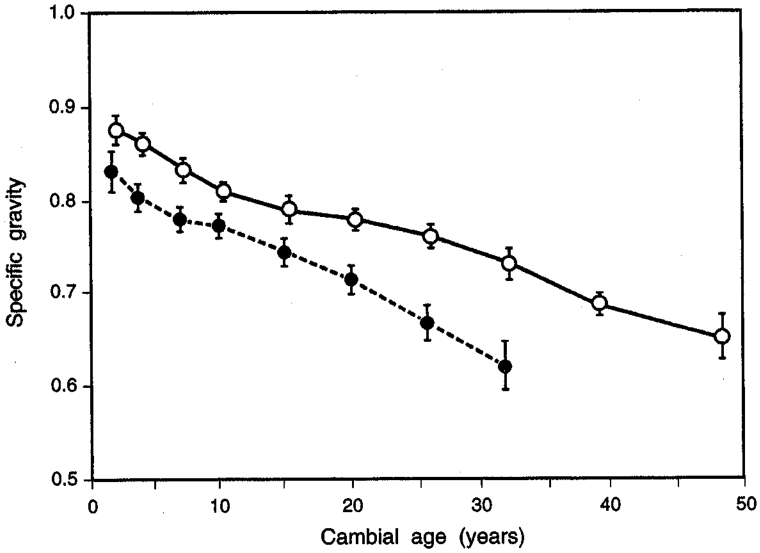

Fig. 6. Specific gravity as a function of cambial age at breast height (○) and the upper height (●, average of 4.4 m) in *Quercus garryana*. Standard error bars show the variation among trees (n = 6).

Tissue proportion — Fibre and vessel proportions showed large radial changes at both heights. The fibre proportion decreased slowly for about 20 years and then decreased rapidly (Fig. 5). The vessel proportion showed the opposite trend, a slow increase for the first few years followed by a rapid increase (Fig. 5). The axial parenchyma proportion increased almost linearly at the upper height but was almost constant at breast height whereas the ray proportion was about constant at both heights (Fig. 5).

The demarcation age for fibre proportion was 15 years at both breast height ($R^2 = 0.76$) and at the upper height ($R^2 = 0.86$; Table 4). The demarcation age for vessel proportion was 26 years at breast height ($R^2 = 0.91$) and 20 years at the upper height ($R^2 = 0.66$; Table 4). Ray proportion is not a function of cambial age at either height ($R^2 = 0.08$; Table 4). Cambial age explained 51% of the variation in axial parenchyma at upper height, but explained little of the variation (9%) at breast height (Table 4).

Bendtsen (1978) and Zobel and Van Buijtenen (1989) indicated that wood properties are quite variable in the juvenile zone and more constant in the mature zone. The radial profiles of fibre and vessel proportion in *Q. garryana*, however, showed the reverse trend: characteristics in the juvenile wood changed slightly and the mature wood changed rapidly with cambial age. Large variability in fibre and vessel proportions with cambial age may have major effects on the fibre yield if loads of *Q. garryana* logs with different size and age are used as raw material for fibre-based products.

Specific gravity — Specific gravity declined almost linearly with cambial age (Fig. 6), and decreased almost 27% from pith to bark at both heights. Wood from breast height had a higher specific gravity than that from the upper height at any given cambial age. Simple linear regression indicated that cambial age accounted for most of the variation in specific gravity (76% at breast height and 65% at upper height; Table 4). The radial variation of specific gravity in *Q. garryana* from pith to bark, along with that of many ring-porous species, is consistent with Panshin and De Zeeuw's (1980: 272–273) Type III pattern. A significant and negative relationship between specific gravity and cambial age was also reported for *Q. petraea* and *Q. robur* (Zhang et al. 1993).

The linear decrease in specific gravity from pith to bark could not be explained solely by the radial variation in latewood percentage or fibre and vessel proportion, because they did not follow linear patterns. Other factors such as fibre wall thickness also affect specific gravity (Scaramuzzi 1960). Likewise, specific gravity (Fig. 6) is not related to ring width (Fig. 1, open circles) in a simple manner: in the juvenile wood zone the two are inversely related and in the mature wood zone they are directly related.

Juvenile and mature wood — After we determined the demarcation age between juvenile and mature wood for each characteristic, we compared the mean values of the characteristics with only the extremes of the cambial ages tested: for juvenile wood we looked at rings < 10 years cambial age (2, 4, and 7 at both heights), and for mature wood we looked at rings > 30 years cambial age (32, 39, and 48 at breast height, and 32 at the upper height; Table 5). Differences between juvenile and mature wood are highly significant for specific gravity and most of the anatomical characteristics (t-tests; $P < 0.01$). Juvenile wood had significantly shorter fibres, narrower vessels, and lower vessel and axial parenchyma proportions than mature wood, about the same ray proportion, and higher specific gravity and fibre proportions (Table 5). Except for axial

Table 5. Comparison of various wood characteristics between juvenile wood (< 10 years cambial age[a]) and mature wood (> 30 years cambial age[b]) in Oregon white oak (*Quercus garryana*).

Property	Juvenile wood (n = 72)	Mature wood	t-test (n = 48)
Fibre length (mm)	1.1	1.2	**
Vessel diameter (µm)	164	272	**
Fibre proportion (%)	64	46	**
Vessel proportion (%)	12	27	**
Ray proportion (%)	14	14	n.s.
Axial parenchyma proportion (%)	10	14	**
Specific gravity	0.83	0.66	**

72 samples: growth rings 4, 7, and 9 for both sides of lean at both heights for 6 trees.

48 samples: growth ring 32 for both sides of lean at the upper height for 6 trees, growth rings 32, 39, and 48 for both sides of lean at breast height for 6 trees.

** = $P < 0.01$; n.s. = $P > 0.05$.

parenchyma proportion, for which we found no radial comparisons, these changes are qualitatively the same as those reported for other *Quercus* species (see introduction).

These samples, with average fibre length in mature wood of 1.2 mm, were within the range of other reports on oak. Average fibre lengths for eight white oaks (including *Q. garryana* but no data given exclusively for it) had species means of 0.6–2.2 mm with a species average of 1.3 mm (Maeglin & Quirk 1984). The fibres in the mature wood were shorter than in 10 of the 12 North American *Quercus* species listed by Panshin and De Zeeuw (1980), with species means of 1.2–1.6 mm. The mean earlywood vessel diameters reported here for mature wood (272 μm) are larger than the value (250 μm) given by Maeglin and Quirk (1984) (both values are for lumens only). The means for tissue proportions in the mature wood are in the same general range as the means reported for other white oaks in the literature (Table 6).

Table 6. Tissue proportions of white oaks from this study and the literature.

Study material	Fibre	Vessel	Ray	Axial parenchyma
Quercus garryana mature wood (this study)[a]	46%	27%	14%	14%
White oak logs[b]	57%	15%	15%	13%
White oak chips[c]	64%	17%	14%	5%
Quercus alba[d]	48%	16%	28%	8%
Quercus macrocarpa[d]	41%	27%	21%	12%

[a] *Q. garryana* mature wood (cambial age > 30, includes both heights, from Table 5).

[b] White oak logs of 8 species of white oak: *Q. alba, Q. bicolor, Q. douglassii, Q. garryana, Q. lobata, Q. macrocarpa, Q. muehlenbergi, Q. stellata* (Maeglin & Quirk 1984).

[c] White oak chips of 8 species of white oak (as above, Maeglin & Quirk 1984).

[d] G.E. French, MSc Thesis, New York State College of Forestry, Syracuse, N.Y. (1923) as cited in Panshin & De Zeeuw (1980).

The significant differences in anatomical characteristics between juvenile and mature wood result in a lack of uniformity in wood quality within a tree. In ring-porous hardwoods like *Q. garryana*, the relative characteristics of juvenile and mature wood differ substantially from those of most softwoods: in the current study the juvenile zone had higher specific gravity and several properties changed little from ring-to-ring in contrast to the mature zone.

CONCLUSIONS

The effects of the tree-to-tree variation and the slight tree lean were minor in comparison to the effect of cambial age on wood properties. Cambial age or radial position is a key factor determining most wood properties at both breast height and upper height in the ring-porous species *Quercus garryana*. Radial variation shows a demarcation age between juvenile and mature wood of 10–26 years, depending on the characteristic. The radial and vertical patterns of anatomy of *Q. garryana* are similar to those reported in the literature with the exception that specific gravity increases from breast height to the upper height. There are significant differences between the juvenile and the mature wood in most anatomical characteristics, but, in contrast to the case in most coniferous species, the juvenile wood is not necessarily of lower quality for pulp or structural uses. However, additional studies are necessary to actually determine whether the pulp yield is higher (as suggested by the higher specific gravity and fibre proportions there) and the structural properties show stronger, stiffer wood in the juvenile wood zone than the mature wood zone.

ACKNOWLEDGMENTS

This research was supported by the U.S. Forest Service Red Alder/Value-Added Research and Demonstration Program and by a U.S. Department of Agriculture Special Grant, Wood Utilization Research.

We thank two anonymous reviewers and Elisabeth Wheeler for comments on an earlier draft of this manuscript. This is Paper 3148 of the Forest Research Laboratory, Oregon State University, Corvallis, OR.

REFERENCES

Abdel-Gadir, A.Y. & R.L. Krahmer. 1993. Estimating the age of demarcation of juvenile and mature wood in Douglas-fir. Wood Fiber Sci. 25: 242–249.

Bendtsen, B.A. 1978. Properties of wood from improved and intensively managed trees. For. Prod. J. 28 (10): 61–72.

Bendtsen, B.A. & J. Senft. 1986. Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly pine. Wood Fiber Sci. 18: 23–38.

Butterfield, R.P., R.P. Crook, R. Adams & R. Morris. 1993. Radial variation in wood specific gravity, fiber length and vessel area for two central American hardwoods: Hyeronima alchorneoides and Vochysia guatemalensis: Natural and plantation-grown trees. IAWA J. 14: 153–161.

Cown, D.J. 1992. Corewood (juvenile wood) in Pinus radiata – should we be concerned? New Zeal. J. For. Sci. 22: 87–95.

Dadswell, H.E. 1958. Wood structure variations occurring during tree growth and their influence on properties. J. Inst. Wood Sci. 1: 11–33.

Dinwoodie, J.M. 1961. Tracheid and fiber length in timber: A review of literature. Forestry 34: 124–144.

Dodd, R.S. 1984. Radial and tangential diameter variation of wood cells with trees of Acer pseudoplatanus. IAWA Bull. n. s. 5: 253–257.

Erickson, H.D. & T. Arima. 1974. Douglas-fir wood quality studies. Part II: Effect of age and stimulated growth on fibril angle and chemical constituents. Wood Sci. Technol. 8: 255–265.

Erickson, H.D. & A.T. Harrison. 1974. Douglas-fir wood quality studies. Part I: Effect of age and stimulated growth on wood density and anatomy. Wood Sci. Technol. 8: 207–226.

Evans, J.W. 1996 (expected). Juvenile wood effect in red alder (Alnus rubra Bong.) and Oregon white oak (Quercus garryana Dougl.). PhD Dissertation. Department of Natural Resources, Purdue University, West Lafayette, Indiana.

Fukazawa, K. 1984. Juvenile wood of hardwoods judged by density variation. IAWA Bull. n. s. 5: 65–73.

Fukazawa, K. & J. Ohtani. 1982. Within-tree variation of wood element size in Tilia japonica. IAWA Bull. n. s. 3: 201–206.

Furukawa, I. & H. Hashizume. 1987. The influence of fertilization and improvement cutting on the wood quality of mature kunugi trees. Jap. Wood Association 33: 443–449.

Gartner, B.L., H. Lei. & M.R. Milota. (In press) Variation in the anatomy and specific gravity of wood within and between trees of red alder (Alnus rubra Bong.). Wood Fiber Sci.

Gartner, B.L., H. Lei, M.R. Milota, J.W. Evans, J.F. Senft & D.W. Green. 1995. Juvenile/mature wood effects in two western hardwoods: anatomy and mechanical properties. In: D. Green, W. von Segen & S. Willits (eds), Western hardwoods: value-added research and demonstration program: 28–31. Gen. Tech. Rep. FPL-GTR-85. USDA Forest Service Forest Products Laboratory, Madison, WI.

Hamilton, J.R. 1961. Variation of wood properties in southern red oak. For. Prod. J. 11: 267–271.

Haygreen, J.G. & J.L. Bowyer. 1989. Forest products and wood science. 2nd ed. Iowa State University Press, Ames, Iowa.

Helińska-Raczkowaska, L. & E. Fabisiak. 1991. Radial variation and growth rate in the length of the axial elements of sessile oak wood. IAWA Bull. n.s. 12: 257–262.

Hernández, R.E. & G. Restrepo. 1995. Natural variation in wood properties of Alnus acuminata H.B.K. grown in Colombia. Wood Fiber Sci. 27: 41–48.

Kandeel, S.A.E. & D.W. Bensend. 1969. Structure, density and shrinkage variation within a silver maple tree. Wood Sci. 1: 227–237.

Krahmer, R.L. 1986. Fundamental anatomy of juvenile and mature wood. In: D. Robertson (Coordinator), Juvenile wood: What does it mean to forest management and forest products?: 12–16. Proceedings 47309, Forest Products Research Society, Madison, WI.

Lei, H. 1995. The effects of growth rate and cambial age on wood properties of red alder (Alnus rubra Bong.) and Oregon white oak (Quercus garryana Dougl.). PhD Dissertation. Department of Forest Products, Oregon State University, Corvallis, Oregon.

Maeglin, R.R. & J.T. Quirk. 1984. Tissue proportions and cell dimensions for red and white oak groups. Can. J. For. Res. 14: 101–106.

Maloney, T.M. 1986. Juvenile wood: Problems in composition board products. In: D. Robertson (Coordinator), Juvenile wood: What does it mean to forest management and forest products?: 72–74. Proceedings 47309, Forest Products Research Society, Madison, WI.

Neter, J., W. Wasserman & M.H. Kutner. 1989. Applied linear regression models. 2nd ed. Richard D. Irwin, Inc., Homewood, IL.

Niemiec, S.S., G.R. Ahrens, S. Willits & D.E. Hibbs. 1995. Hardwoods of the Pacific Northwest. Research Contribution 8, College of Forestry, Forest Research Laboratory, Oregon State University.

Panshin, A.J. & C.H. de Zeeuw. 1980. Textbook of wood technology. 4th ed. McGraw-Hill, New York.

Peszlen, I. 1994. Influence of age on selected anatomical properties of Populus clones. IAWA J. 15: 311–321.

Phelps, J.E. & E.C. Workman, Jr. 1994. Vessel area studies in white oak (Quercus alba L.). Wood Fiber Sci. 26: 315–322.

Quanci, M.J. 1988. Mechanical, physical, and anatomical properties of short-rotation Douglas-fir and white ash. MSc Thesis, Purdue University, West Lafayette, Indiana.

Rasband, W. 1992. NIH Image 1.47: An instruction manual, public domain image processing and analysis program. National Institutes of Health, Bethesda, Maryland.

SAS Institute. 1988. SAS/Stat User's Guide, 6.03 edition. Cary, NC.

Scaramuzzi, G. 1960. Technological investigations on the wood of some Euroamerican poplar hybrids. Publ. Cent. Sper. Agr. For. Roma 3: 193–216, as cited in B.J. Zobel & J.B. Jett. 1995. Genetics of Wood Production, Springer-Verlag, Berlin. 337 pp.

Stein, W. I. 1990. Quercus garryana (Dougl. ex Hook.): Oregon white oak. In: R.M. Burns & B.H. Honkala (Technical Coordinators), Silvics of North America, Vol. 2. Hardwoods: 650–660. Agriculture Handbook 654, Forest Service, United States Department of Agriculture, Washingon, D.C.

Taylor, F.W. & T.E. Wooten. 1973. Wood property variation of Mississippi delta hardwoods. Wood & Fiber 5: 2–13.

Thomas, R.J. 1984. The characteristics of juvenile wood. Proc. Symp. on Utilization of the Changing Wood Resource in Southern United States: 40–52. North Carolina State University, Raleigh, North Carolina.

Zhang, S.Y., R. Eyono Owoundi, G. Nepveu, F. Mothe & J.-F. Dhote. 1993. Modelling wood density in European oak (Quercus petraea and Quercus robur) and simulating the silvicultural influence. Can. J. For. Res. 23: 2587–2593.

Zhang, S.Y, G. Nepveu & R. Eyono Owoundi. 1994. Intratree and intertree variation in selected wood quality characteristics of European oak (Quercus petraea and Quercus robur). Can. J. For. Res. 24: 1818–1823.

Zhang, S.Y. & Y. Zhong. 1991. Effect of growth rate on specific gravity of East Liaoning oak (Quercus liaotungensis) wood. Can. J. For. Res. 21: 255–260.

Zobel, B.J. & J.B. Jett. 1995. Genetics of wood production, Springer-Verlag, Berlin.

Zobel, B.J. & J.P. van Buijtenen. 1989. Wood variation: Its causes and control. Springer-Verlag, Berlin.