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Title: The Effects of Growth Rate and Cambial Age on Wood Properties of Red Alder (*Alnus rubra* Bong.) and Oregon White Oak (*Quercus garryana* Dougl.)

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This study was to investigate effects of growth rate and cambial age on properties of wood from two increasingly used hardwood species, red alder (*Alnus rubra* Bong.) and Oregon white oak (*Quercus garryana* Dougl.), for better understanding factors affecting wood quality in hardwoods. Thirty 7-year-old trees grown at widely varying rates were sampled from a red alder plantation to determine the effect of growth rate on anatomical, physical, and bending properties. Six 40-year-old red alder trees and six Oregon white oak trees older than 50 years were sampled from pith to bark at two heights to study the radial variation in anatomical characteristics and specific gravity (SG).

The growth rate of 7-year-old red alder trees had no effect on fiber and vessel proportions, SG, modulus of elasticity (MOE), and modulus of rupture (MOR). Fiber length, vessel diameter, and ray proportion increased slightly while fiber wall thickness and axial parenchyma decreased slightly with growth rate. Findings indicate

that increasing growth rate of red alder through silvicultural practices does not negatively affect wood and fiber quality.

Variations among 40-year-old red alder trees were significant for SG and vessel diameter but not for other anatomical properties. The differences between two heights and between the lower and upper sides were not significant for any measured properties. Fiber length, vessel diameter, and fiber and vessel proportions varied greatly from pith to bark at both heights. Ray proportion and SG remained unchanged across the radius at both heights. SG was better correlated with MOE and MOR than any single or several anatomical characteristics combined.

In Oregon white oak, there was significant variation in fiber length, vessel diameter, and fiber and vessel proportions from pith to bark. The demarcation age between the core and outer wood was around 10 to 26 years, depending on characteristic. SG decreased linearly from pith to bark at both heights. Ray proportion showed little change across the radius. Outer wood revealed stronger relationships between anatomical characteristics, SG, MOE and MOR than did core wood. SG was not a good estimator of bending properties.

The Effects of Growth Rate and Cambial Age on Wood Properties of Red Alder (*Alnus rubra* Bong.) and Oregon White Oak (*Quercus garryana* Dougl.)

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Hua Lei, Author

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF APPENDICES

THE EFFECTS OF GROWTH RATE AND CAMBIAL AGE ON WOOD PROPERTIES OF RED ALDER (*Alnus rubra* Bong.) AND OREGON WHITE OAK (*Quercus garryana* Dougl.)

INTRODUCTION

Wood is one of the most wonderful natural materials. As a biological product, wood exhibits great variability, which allows wide versatility in its use. This same variability in wood also impedes its efficient utilization. Therefore, it is important to understand the cause and extent of the variability for the best use of this renewable resource.

Increased demand for wood products from forest resources and long-term harvesting of forests have resulted in diminished quantities of old growth forest. Since it is not economical to wait until regenerated forests reach the same level of maturity as old growth, young, small trees, and alternate species are becoming a major forest resource. As a result, the wood quality, quantity, and species composition from forests are changing throughout the world (Zobel, 1984; USDA, 1988). A higher proportion of wood produced near the pith, juvenile wood, is contained in the wood from intensively managed plantations and seed-selected plantations. Also, a higher proportion of hardwoods is being used, especially in pulp and paper industry (Higgins and Puri, 1976; Foelkel and Zvinakevicius, 1980).

Increasing resource diversity will adversely affect utilization efficiency. Variability in the wood supply, while not new, today comes from many sources. A major source of variability in wood is the presence of juvenile wood. Despite the fact that juvenile wood and its associated problems have been extensively studied and are well understood in conifers (Thomas, 1984; Zobel and van Buijtenen, 1989), little information is available regarding the existence and characteristics of juvenile wood in hardwoods. There are indications, however, that the juvenile wood in hardwoods shows many of the same characteristics as that in softwoods, except to a lesser degree (Bendtsen, 1978). It is possible that many of the problems encountered when processing and utilizing juvenile wood from softwoods will also appear with hardwoods (Youngs and Erickson, 1984). Further research on the hardwood resource is needed to understand inherent variability that could affect its use.

Because of its economic importance, the relationship between growth rate and wood quality is the subject of many tree improvement programs and research projects. However, the lack of standard research methods and the confounding effect of cambial age and growth rate have produced contradictory results (Zobel and van Buijtenen, 1989). The effect of growth rate on wood properties must be studied independently of the age effect to avoid misleading results.

In the Pacific Northwest, softwoods traditionally have dominated the wood industry. Consequently, the wood properties and use of hardwoods have received little attention. Red alder (*Alnus rubra* Bong.) and Oregon white oak (*Quercus garryana* Dougl.) are two common species of hardwoods that grow in the Pacific Northwest. Red alder is diffuse-porous and Oregon white oak is ring-porous. In Oregon, the 1991 hardwood harvest had increased 28% since 1987 and 76% of this was red alder (Ahrens, 1994). There are more than nine billion board feet of red alder sawtimber in Oregon and greater red alder resources are in Washington (Tarrant et al. 1994). Oregon white oak is distributed throughout Western Oregon.

Studies have shown that red alder has the potential for use as studs (Layton et al., 1986), OSB (Murad, 1984), pulp (Hrutfiord, 1978), and in pulp as a substitute for juvenile pine (Amidon, 1984). Oregon white oak is used for furniture, flooring, veneer and pallets. However, information about wood and fiber properties of red alder and Oregon white oak is scant, particularly the anatomical and mechanical properties and the degree to which they vary.

To better use these hardwoods in products that compete with or complement softwoods, it is important to understand the basic properties of both juvenile wood and mature wood. In this dissertation, the radial variation (from pith to bark) of wood properties at two heights for red alder and Oregon white oak was determined and analyzed. This information will allow more efficient utilization of these species. Information is also presented for hardwood stand managers about how silvicultural treatments and growth rate affect wood properties in red alder.

The primary objective of this study was to investigate the radial variation of selected wood properties in red alder and Oregon white oak with special reference to the influence of cambial age and the effect of the growth rate on wood properties. The specific objectives were to:

1. determine the effect of growth rate on the anatomical, physical, and mechanical properties of wood from young red alder trees, independent of cambial age;

2. determine the effects of spacing, fertilization, and irrigation on the growth rate of young red alder trees and on the properties of wood from these trees;

3. quantify the anatomical characteristics and specific gravity across the radius at two heights and estimate the age of demarcation between juvenile and mature wood in the two hardwoods;

4. compare the wood properties of juvenile wood to those of mature wood in the two hardwoods, and

5. analyze interrelationships among anatomical characteristics, specific gravity, and mechanical properties in the two hardwoods.

This dissertation consists of seven sections: a general literature review, four chapters of research papers, dissertation conclusions, and a bibliography.

CHAPTER I

VARIATION OF WOOD PROPERTIES AS RELATED TO RADIAL POSITION, GROWTH RATE, AND SILVICULTURAL TREATMENTS IN HARDWOODS

—— A Literature Review

Introduction

As a product of a biological system (the tree), wood is a variable material. Zobel and van Buijtenen (1989) extensively reviewed and summarized wood property variation from species to species, from tree to tree within a individual, and even within a single tree. Many external factors such as environment, site quality, and silvicultural treatments and internal factors such as genetics and growth rate affect the wood properties of each species. The variation of wood properties within a tree has been studied because understanding and reducing the variation is a very important objective of forestry (Bendtsen, 1978). Variation within a tree may occur vertically from the base to the top, radially from the pith to the bark, and intra-ring from the inside to the outside of a growth ring. This literature review will focus on the radial variation and its causes, such as growth rate and silvicultural treatments in hardwoods.

Radial Variation

Wood properties vary from pith to bark because the tree is at different ages when the wood is formed. So the age, or, more precisely, the cambial age of wood, is one of the most important factors associated with wood properties (Zobel and van Buijtenen, 1989). Cambial age is the age of the vascular cambium at the time a particular growth ring is formed (Esau, 1977) and is referred to throughout this dissertation.

Hardwoods can be divided into two major groups, ring-porous and diffuse-porous, based on the transition in size of pores from earlywood to latewood. Ring-porous woods have an abrupt size change while diffuse-porous woods have little or gradual change. Generally, radial variation in wood properties follows one pattern for ring-porous and a second one for diffuse-porous hardwoods, each of which is considerably different from softwoods (Panshin and deZeeuw, 1980). In this section, major anatomical characteristics, specific gravity, and selected strength properties that vary with cambial age will be reviewed for both ring-porous and diffuse-porous hardwoods.

Fiber length

Fibers in hardwoods specifically refer to libriform fibers and fiber tracheids. Fiber length strongly influences the properties of paper and wood products (Dinwoodie, 1965). Dinwoodie (1961) extensively covered the literature on the radial variation of fiber length. Panshin and deZeeuw (1980) suggested three classifications for the radial variation of fiber length:

1. Type 1 reaches a maximum at very early age, such as 10 to 20 years, and then remains constant.

2. Type 2 increases throughout the life of the tree.

3. Type 3 increases to a maximum, then tends to decrease.

Although patterns of radial variation depend on species, fiber length variation in many hardwoods follows the Type 1 pattern (Bisset, 1949; Dinwoodie, 1961). Saucier and Hamilton (1967) concluded that age and height explain 85% of the variation in fiber length within *Fraxinus pennsylvanica*.

The only published data on fiber length in red alder gave an average of 1.08 and a range from 0.89 to 1.18 mm (Bergman, 1949). No data on its radial variation have been reported. In black alder (*Alnus glutinosa*), fiber length rapidly increased during the first eight years and then increased slowly and leveled off (Vurdu and Bensend, 1979; Robison and Mize, 1987).

No data on fiber length were reported exclusively for Oregon white oak, but an average fiber length of 1.33 mm (from 0.6 to 2.2 mm) was reported for eight species of white oak including Oregon white oak (Maeglin and Quirk, 1984). Radial variation in fiber length for Oregon white oak has not been reported. For some oaks other than Oregon white oak, fiber length increased throughout advanced age (Taylor and Wooten, 1973).

Vessel diameter

Available information about variation in vessel diameter is presented in Table I.1. All species studied show an increase in vessel diameter from pith to bark. Red alder has an average vessel diameter of 45 microns (Stark, 1953). Eight species of white oaks (including Oregon white oak) have an average vessel diameter of 255 microns (Maeglin and Quirk, 1984). Although no reports on the radial variation of vessel diameter in red alder or Oregon white oak were found, it is expected that both species will show an increase in vessel diameter with age.

Proportion of cell-types

Hardwoods contain four major types of cells: fibers, vessels, axial parenchyma and ray parenchyma. The average proportion of fiber volume in hardwoods is about 50%; however, this can vary from 27% to 76% depending on species. The vessels and ray and axial parenchyma account for remaining wood volume (Panshin and deZeeuw, 1980). Because of the substantial proportion of vessels and parenchyma tissue in hardwoods, the relative volume of each affects properties of the wood and utilization. For example, vessels conduct fluids in a tree and are, therefore, very important for growth, but they are not desirable when manufacturing pulp and paper. Vessels

Table I.1 All species studied show an increase in vessel diameter from pith to bark.

SPECIES	REFERENCE
DIFFUSE-POROUS	
Eucalyptus nitens	McKimm and Ilic, 1987
Eucalyptus pilularis	Bamber, 1981
Hyeronima alchorneoides	Butterfield et al., 1993
Liriodendron tulipifera	Foulger et al., 1975
Salix nigra	Furukawa and Hashizume, 1987
Shorea spp.	Aytug, 1962
Tilia japonica	Fukazawa and Ohtani, 1982
Vochysia guatemalensis	Butterfield et al., 1993
RING-POROUS	
Celtis laevigata	Fukazawa and Ohtani, 1982
Quercus acutissima	Fukazawa and Ohtani, 1982
Quercus phellos	Taylor and Wooten, 1973
SEMI-RING-POROUS	
Platanus occidentalis	Taylor and Wooten, 1973

reduce the inter-fiber bonding in paper (Marton et al., 1965) and tend to pick from the paper surface during printing (Byrd et al., 1967; Byrd and Fahey, 1969). Parenchyma cells are the cause of fines that slow the pulping process (Klungness and Krause, 1980; Klungness and Sanyer, 1981). Large amounts of parenchyma and ray tissue, large vessels and short fibers cause other problems in paper-making (Horn, 1978; Marton et al., 1979). Larson (1967) indicated that probably the most important wood characteristic for processing is anatomical uniformity. Therefore, knowing the magnitude and variation of the tissue proportions is important for both manufacturing and stand management.

Stark (1953) indicated that wood of red alder is remarkably uniform in structure, but he did not report the proportion and variation of each type of cell. In European black alder (*Alnus glutinosa*), the percentage of fibers increases, the percentage of vessels decreases, and the percentage of ray and axial parenchyma are nearly constant from pith to bark (Vurdu and Bensend, 1980). A very strong negative correlation ($r = -0.90$) was also reported between the percentages of fibers and vessels.

Maeglin (1976) and Maeglin and Quirk (1983) found great variability in proportions of various types of tissues between red oaks (three species) and white oaks (eight species including Oregon white oak). He reported that white oak has a higher volume of fibers (60%) but a lower volume of axial parenchyma (9%) than red oak (40% and 23%, respectively). Variation from pith to bark was not reported.

Investigation into radial trends of tissue proportions in hardwoods other than red alder and Oregon white oak are listed in Table I.2. The general pattern is an increase in vessel proportion and a corresponding decrease in fiber proportion with age, while ray proportion generally remains constant or increases slightly. However, this pattern does not always hold. An exception occurs in black alder where fiber proportion increases with age (Vurdu and Bensend, 1980). Some species, like *Populus euramoricana, Carya illinoensis* and *Eucalyptus grandis*, do not exhibit a significant change from pith to bark in any type of tissues (Table I.2). Little information about the variation in the axial parenchyma proportion is available because it is too scant to be significant in many species such as *Acer* spp., *Populus* spp. and some others (Panshin and deZeeuw, 1980). But the substantial portion of axial parenchyma in oaks, ranging from about 10% to 30% (Maeglin and Quirk, 1984), cannot be ignored.

Specific gravity

Specific gravity is a measure of the amount of cellwall substance in a given volume of wood. Specific gravity and its variation have been widely studied because of its strong relationship with mechanical properties (Armstrong et al., 1984). Specific gravity consistently increases from pith to bark in most softwoods (Zobel and van Buijtenen, 1989). However, the variation in hardwoods is inconsistent and confusing.

Table I.2 The variation of tissue proportions from pith to bark in hardwoods.

SPECIES	REFERENCE	FIBER %	VESSEL %	RAY %
DIFFUSE-POROUS		VARIATION PATTERN*		
Acer saccharinum	Kandeel and Bensend, 1969	-	+	+
Alnus glutinosa	Vurdu and Bensend, 1980	+	-	
Eucalyptus grandis	Taylor, 1973	=	=	
Gmelina arborea	Akachuku, 1985		+	
Liriodendron tulipifera	Taylor, 1968	-	+	=
Platanus occidentalis	Taylor and Wooten, 1973	-	+	=
Populus deltoides	Isebrands, 1972	-	+	=
Populus euramericana	Scaramuzzi, 1958	=	=	=
Salix nigra	Taylor and Wooten, 1973	-	+	
RING-POROUS				
Carya illinoensis	Taylor and Wooten, 1973	=	=	
Celtis laevigata	Taylor, 1971	-	+	
Celtis occidentalis	Taylor and Wooten, 1973	-	+	+
Quercus phellos	Taylor and Wooten, 1973	-	+	

* = no change,
  + increase,
  - decrease.

A summary of studies on radial variation of specific gravity in hardwoods is listed in Table I.3. There are three basic patterns of change for specific gravity from pith to bark. The first pattern is a general increase from pith to bark, with a leveling off toward the bark. The second is a decrease from pith to bark. The third is no significant change from pith to bark.

The specific gravity of red alder appears to change little radially (Parker et al., 1978; Harrington and DeBell, 1980; Lowell and Krahmer, 1993). Generally, in diffuse-porous hardwoods, an increase (or decrease) in specific gravity results from an increase (or decrease) in the proportion of fibers or fiber wall thickness, or both (Panshin and deZeeuw, 1980).

No reports on variation in specific gravity of Oregon white oak are available. The specific gravity of most oaks decreases from pith to bark because the percentage of fiber tissue decreases (Wheeler, 1987). Panshin and deZeeuw (1980) attributed this to a constant amount of earlywood but ecreasing amount of latewood from pith to bark, resulting in a decreasing proportion of fibers. An exception occurs in *Quercus phellos* (Taylor and Wooten, 1973), however, which shows an increase in specific gravity from pith to bark.

Table I.3 The variation of specific gravity from pith to bark in hardwoods.

SPECIES	REFERENCE	*
RING-POROUS		
Carya illinoensis	Taylor and Wooten, 1973	+
Carya tomentosa	Taylor, 1979	=
Celtis laevigata	Taylor and Wooten, 1973	-
Fraxinus americana	Quanci, 1988	-
Fraxinus mandshurica	Fukazawa, 1984	-
Kalopanax piclus	Fukazawa, 1984	-
Quercus mongolica	Fukazawa, 1984	-
Quercus phellos	Taylor, 1973	+
Quercus stellata	Taylor, 1973	-
Quercus nigra	Taylor, 1979	=
Quercus falcata	Taylor, 1979	-
DIFFUSE-POROUS		
Alnus acuminata	Hernández and Restrepo, 1995	+
Alnus rubra	Harrington and DeBell, 1980	=
Alnus rubra	Parker et al., 1978	=
Betula maximowiczano	Fukazawa, 1984	+
Cercidiphyllum japonica	Fukazawa, 1984	-
Eucalyptus grandis	Malan, 1991	+
Liquidambar styraciflua	Taylor, 1979	+
Nyssa sylvatica	Taylor, 1979	-
Populus tremuloids	Roos et al., 1990	=
Populus deltoides	Bendtsen and Senft, 1986	+
Salix nigra	Taylor, 1977	=
Tilia japonica	Fukazawa, 1984	-

* + increase
- decrease
= not significant change

Mechanical properties

The variation in mechanical properties radially in the tree is unknown for most hardwoods. Bendtsen and Senft (1986) studied the variation of mechanical properties from pith to bark in eastern cottonwood (*Populus deltoides*) and found that MOE and MOR both show a marked increase from pith to bark, but no definite transition from juvenile to mature wood. Another group (Roos et al., 1990) found that the radial profiles of specific gravity, modulus of elasticity (MOE) and modulus of rupture (MOR) indicate an apparent change from juvenile to mature wood between the ages of 16 and 30 years in quaking aspen (*Populus tremuloides*). However, Quanci's (1988) research on white ash (*Fraxinus americana*) shows no change in MOR and only a small increase in MOE along the radial direction. There is not enough information to generalize any radial variation pattern in mechanical properties for either the ring- or diffuse-porous species.

Juvenile Wood

Juvenile wood (the central portion of the tree stem) is characterized by a progressive radial change in cell features and wood properties (Panshin and deZeeuw, 1980). Based on this definition, every tree, softwood or hardwood, contains juvenile wood. The characteristics of juvenile wood in softwoods have been well studied and documented (Dadswell, 1958; Erickson and Harrison, 1974; Erickson and Arima, 1974; Zobel, 1975 and 1976; Bendtsen, 1978; Megraw, 1985; Krahmer, 1986; Barrett and Kellogg, 1986; Jackson and Megraw, 1986; Zobel and van Buijtenen, 1989). However, research on the characteristics of juvenile wood in hardwoods is very limited.

Commonly, the juvenile zone is defined by the radial pattern of specific gravity rather than that of other wood properties (Zobel and van Buijtenen, 1989). Fukazawa (1984) found clear differences in specific gravity between juvenile and mature wood in three diffuse-porous and one ring-porous species. Other ring porous species studied did not have an apparent demarcation, but a gradual change occurs between core wood and outer wood. Juvenile wood as defined by specific gravity is not pronounced in eastern cottonwood (Bendtsen and Senft, 1986) and white ash (Quanci, 1988). Red alder did not show any definite radial variation in specific gravity (Parker et al., 1979; Harrington and DeBell, 1980).

Haygreen and Bowyer (1989) indicated that the boundary between juvenile and mature wood depends upon the properties used to define it. Wood properties other than specific gravity, such as anatomical characteristics, may be better indicators of juvenile wood. Fukazawa and Ohtani (1982) found that juvenile wood in *Tilia japonica* is characterized by a marked increase or decrease in the proportions of fiber types. Thinner walls, larger microfibril angle, smaller fiber diameter, and larger volumetric proportion of vessels occurs in the juvenile wood than the mature wood for most hardwoods (Maeglin and Quirk, 1983). Bendtsen and Senft (1986) reported that the microfibril angle in juvenile wood in *Populus* spp. is larger than that of mature wood. However, for white ash, Quanci (1988) found that nearly all anatomical, physical and mechanical properties remain constant from pith to bark.

Based on the literature above, questions are raised about the existence of juvenile or mature wood in some species of hardwoods. Earlier, Boyd (1968) even suggested that juvenile wood is usually negligible in hardwoods. A brief review by Bendtsen (1978) stated that juvenile wood occurs in hardwoods but that the degree of juvenility is lower in hardwoods than in softwoods, and no adequate information is available to generally characterize juvenile wood in hardwoods.

Effect of Growth Rate

The influence of growth rate on wood properties has not been studied as extensively in hardwoods as in softwoods. Publications on the relationship between growth rate and wood properties are limited and controversial.

Anatomical characteristics

Fiber length as a function of growth rate was the most studied anatomical property. Denne and Whitbread (1978) concluded that growth rate does not affect fiber length in ash (*Fraxinus excelsior*). Similar conclusions were reported for both the ring-porous and diffuse-porous species by Aytug (1962), Webb (1964), McElwee and Faircloth (1966), Hunter and Goggans (1969), Oteng-Amoako et al. (1983), and Wilks and Abbott (1983). On the other hand, Amos et al. (1950), Bhat and Bhat (1983) and Helinska-Raczkowaska and Fabisiak (1991) reported that fast grown trees have short fibers in *Eucalyptus* spp. and *Quercus* spp. In contrast, a positive correlation between fiber length and growth rate was found by Kennedy and Smith (1959) and Yanchuk et al. (1983) for *Populus* spp.

Studies by Malan (1991) on *Eucalyptus grandis* and Peszlen (1993) on *Populus x euramericana* showed no consistent or significant relationships between growth rate and other anatomical characteristics. But a negative relationship between vessel diameter and growth rate was found for *Fagus* spp. (Koltzenburg, 1966).

There is no significant change of tissue proportions with growth rate for some diffuse-porous species (Scaramuzzi, 1958; Akachuku, 1985). But Wilks and Abbott (1983) found that fast-grown trees have a greater volume of vessels while ray and fiber proportions are not affected by growth rate in *Eucalyptus* spp. Taylor and Wooten (1973) found that fast-grown wood contains lower vessel but higher fiber proportions in both the ring-porous and diffuse-porous hardwoods. Maeglin and Quirk (1984) found that the proportion of tissues by volume and by weight is related to growth rate and site conditions in a number of *Quercus* spp. species.

The relationship between growth rate and anatomical properties is confusing and contradictory because of diverse species and research methods. Wood often has wide growth rings in the juvenile zone and basing growth rate on ring width while ignoring cambial age will confound the two. As stressed by Zobel and van Buijtenen (1989), whatever the causes, comparisons of different growth rates must be made between widths of rings of the same age. In addition, a consistent intra-ring sampling location is also critical to avoid the confounding effect of intra-ring and between-ring variations (Seth et al., 1988).

Specific gravity

Specific gravity varies differently with growth rate for ring-porous and diffuse-porous hardwoods, according to studies by Taylor (1977) and Fukazawa (1984) on many hardwoods, Brasil et al. (1979) on *Eucalyptus* spp., Land

and Lee (1981) on *Platanus occidentalis*, and Durand (1983) on *Terminalia* spp. They concluded that most diffuse-porous hardwoods can be grown quickly without reducing the specific gravity. For example, the growth rate of red alder has little effect on specific gravity (Parker et al., 1978; Lowell and Krahmer, 1993). A few investigators even found that fast growth results in an increase in specific gravity (Briscoe and Harris, 1963; Saucier and Ike, 1972; Oteng-Amoako et al., 1983).

A fast growth rate in ring-porous hardwoods usually results in higher density (McDonald and Franklin, 1969; Fukazawa, 1984; Wheeler, 1987). Fukazawa (1984) reported that the density of three ring-porous species is most influenced by ring width and that a decrease in ring width within a tree would result in lower specific gravity. But other investigators has found that growth rate does not affect specific gravity in ring-porous hardwoods (Taylor and Wooten, 1973). Zhang and Zhong (1990) concluded that growth rate has little effect on specific gravity of juvenile wood, but faster-grown trees had higher specific gravity in mature wood of *Quercus liaotungensis*.

Effect of Silvicultural Treatments

The impact of silvicultural practices on wood properties has been less widely investigated in hardwoods than in softwoods. For hardwoods, there are many papers reporting the effect of silvicultural practices on tree growth and tree form, but few deal with wood properties. Although Kellison et al. (1983) made the generalization that silvicultural practices improve tree growth and tree form without adversely affecting wood properties in southern hardwoods, some researchers found that wood properties are indeed adversely affected. In this section, the effects of fertilization, spacing, and irrigation on wood properties are reviewed.

Fertilization

Results concerning the effect of fertilization on hardwoods are inconclusive. It is most often reported that fertilization has little effect on wood properties in both the ring-porous and diffuse-porous species. Fertilization increases growth but does not affect the wood quality for furniture, millwork and paneling from red oak (*Quercus rubra*), yellow poplar (*Liriodendron tulipifera*) and ash (*Fraxinus americana*) (Mitchell, 1971). Fertilization has little effect on specific gravity in *Eucalyptus globulus* (Cromer and Hansen, 1972), *Platanus occidentalis* (Saucier and Ike, 1972) and *Populus tremuloides* (Einspahr et al., 1972).

Fertilization resulting in higher wood density was reported by Farrington et al. (1977) in *Eucalyptus globulus* and by Polge (1975) in *Quercus robur*. On the contrary, a significant decrease in specific gravity was found by Ross et al. (1979) in *Liriodendron spp*. and by Higgs and Rudman (1973) in *Eucalyptus regnans*.

It seems that effect of fertilization on wood properties is unique for a species. Ring-porous or diffuse-porous woods do not fit into general categories. Also, different types of fertilizer may have different effect on wood properties. McAdoo and Murphey (1968) reported that calcium resulted in higher specific gravity, while manganese caused lower specific gravity.

Spacing

Controlling plantation stand density is a common silvicultural practice. Stand density had tremendous influence on branching characteristics and growth rate, both of which affected wood properties (Larson, 1969). Stand density can be achieved by means of thinning and/or initial spacing during planting. In this portion of the literature review, only effects of initial spacing on wood properties as discussed.

Information about the effect of spacing on wood properties in hardwoods is very limited. Schonan (1973), Vital et al. (1984), and Vital and Lucia (1987) found that spacing affected the growth rate but had no effect on specific gravity in *Eucalyptus grandis*. Dewaulle (1985) showed that increasing planting spacing from 1 x 1 m to 4 x 4 m resulted in a change in specific gravity from 0.52 to 0.60 in *Eucalyptus* spp. Spacing has significant effects on the specific gravity, fiber length, diameter, wall thickness, vessel element length and diameter in *Populus* spp. (Kasir, 1990).

Irrigation

Generally irrigation tends to reduce the occurrence of spiral grain (Boyd, 1968; Smith et al., 1972; Brazier, 1977). Growth acceleration by irrigation results in longer fibers in both ring-porous and diffuse-porous species (Kennedy, 1957; Kennedy and Smith, 1959; Maeglin, 1976). Einspahr et al. (1972) reported that irrigation significantly increases growth ring width and fiber length, but significantly decreases the specific gravity in quaking aspen (*Populus tremuloides*). However, Omran's (1986) report showed that both specific gravity and fiber length are unaffected by irrigation in *Populus* spp. In a special case of using sewer water to irrigate *Populus* spp., Murphey and Bowier (1975) found that growth ring width increased and specific gravity decreased but vessel-to-fiber ratio did not change with irrigation level.

Anatomy-property Relationships

Explaining the properties and performance of wood based on its structure has long been an interest of wood scientists (Bodig and Jayne, 1982). However, information in this area is limited due to lack of quick and efficient methods suitable for quantifying the anatomical characteristics (Beery et al., 1983). Recently, image analysis has become a powerful tool in wood anatomy research (Gartner, 1991; Wimmer, 1991; Peszlen, 1993), and valuable time can be saved when measuring the anatomical characteristics and dimensions of large numbers of cells and determining tissue proportions. In addition, multivariate analysis methods are appropriate for establishing the relationships among these properties when multiple properties are measured on one sample (Burley and Miller, 1982).

Specific gravity is highly correlated with the strength of wood of many species from all parts of the world (Armstrong et al., 1984). Dinwoodie (1989) indicated that "perhaps the single most important parameter influencing strength is the density of wood." Maeglin (1976) indicated that density can serve as a good estimator of strength for softwoods because they are simple in composition. For hardwoods, however, density is not as good of an index of strength because of their diverse and complex structure

(Hillis, 1989; Zhang and Zhong, 1992). Table I.4 shows examples in which certain anatomical properties are better indicators of strength than specific gravity in both ring-porous and diffuse-porous hardwoods. Anatomical properties such as tissue proportions could greatly affect the mechanical properties because different combinations of various types of cell tissues give rise to the differences in strength while the specific gravity is the same (Bamber, 1981). Leclercq (1980) also indicated that fibrous tissue could give, in practice, a better estimation of wood quality than other criteria like specific gravity. For eight species of hardwoods, Beery et al. (1983) concluded that transverse modulus of elasticity is more related to specific gravity but failure is more associated with anatomical properties. Quanci (1988) concluded that no consistent relationship existed among wood properties for *Fraxinus americana*. Because hardwood species are not often used as a structural material, studies on the mechanical properties of hardwoods are limited. More studies are needed on the relationships among anatomy, specific gravity, and strength in hardwoods.

In case of the static bending test, the loading direction is critical. Loading through the tangential surface is required by ASTM, D-143 (1986) for 5 by 5 by 76 cm specimens. For a mini-specimen in bending, the location of earlywood or latewood in the depth profile of the bending

Table I.4. Publications showing that specific gravity (or density) is not the most important indicator of mechanical properties in hardwoods.

Species	Reference	Comments
Quercus liaotungensis	Zhang and Zhong, 1992	Microfibril angle is a better estimator of tensile strength than the specific gravity.
Beechwood (No scientific name given)	Leclercq, 1980	Density is really not a good estimator of wood quality.
Red oak (No scientific name given)	Hill, 1954	The proportions of vessels and fibers are better indicators of wood quality than density for strength evaluations.
Liriodendron spp.	Hunt et al., 1989	Specific gravity is a poor predictor of strength.
Fagus grandifolia *Liriodendron tulipifera* *Betula* spp. *Platanus occidentalis* *Fraxinus americana* *Catalpa speciosa* *Celtis occidentalis* *Quercus* spp.	Beery et al. 1983	Transverse strength is more associated with anatomical properties than the specific gravity.
Fraxinus americana	Quanci, 1988	No consistent relationship between anatomy and bending properties.

specimen could greatly affect the test results, particularly for ring-porous species. In studies on *Populus* spp. (Bendtsen and Senft, 1986 and Roos et al., 1990), loading through radial surface instead of tangential surface was applied for the bending test of mini-specimens. This would greatly reduce the effect of earlywood and latewood orientation in the specimen.

Summary

As demonstrated throughout this literature review, studies on wood properties in hardwoods, particularly in the area of the effects of juvenile wood, growth rate, and silvicultural treatments, has been insufficient. The most consistent radial changes occur for fiber length and vessel diameter, which usually increase from pith to bark in both ring-porous and diffuse-porous hardwoods. The radial variation of other anatomical properties, specific gravity, and mechanical properties are best described as inconsistent. Nearly all possible patterns of radial change occur in different species of hardwoods. Therefore, it is important that these patterns be determined for each species for effective use of wood. Because the anatomical properties across growth rings are more variable in ring-porous than in diffuse-porous species, growth rate and cambial age would be expected to have a larger effect on wood properties in ring-porous than in diffuse-porous species.

CHAPTER II

EFFECT OF GROWTH RATE ON THE ANATOMY, SPECIFIC GRAVITY, AND BENDING PROPERTIES OF WOOD FROM SEVEN-YEAR-OLD RED ALDER (*Alnus rubra* Bong.)

Abstract

The association between growth rate and wood properties is of practical important if wood and fiber production are to be maximized and sustained. Thirty 7-year-old trees grown at widely varying rates were sampled from a red alder plantation. Anatomical characteristics, specific gravity, and bending properties were determined for wood samples from the growth ring having a cambial age of five years in each tree. The relationship between each wood property and the growth rate in terms of annual ring width or area was analyzed.

The results of regression analysis show that growth rate had no effect on specific gravity, or modulus of elasticity and modulus of rupture in bending. Fiber and vessel percentages as well as fiber diameter were unchanged with growth rate. However, fiber length, vessel diameter, and ray percentage were positively correlated with growth rate while fiber wall thickness and axial parenchyma percentage slightly decreased with growth rate. The results indicate that the growth rate of red alder trees can be increased through silvicultural practices without a negative effect on most aspects of wood and fiber quality.

Introduction

Red alder (*Alnus rubra* Bong.) is the most important hardwood in the Pacific Northwest (Harrington and DeBell, 1980). Traditionally red alder wood is used for pulp, furniture, cabinets, and pallets. It has also been proven that red alder wood is a satisfactory material for making oriented strand board (Murad, 1984) and studs (Layton et al., 1986). There is great potential for increasing use of this hardwood resource (Briggs and Bethel, 1978; Resch, 1988; Plank et al., 1990). In Oregon, the 1991 hardwood harvest had was 28% greater than in 1987 and 76% of the harvest was red alder (Ahrens, 1994). Interest in managing and utilizing red alder is at an all-time high (Hibbs et al., 1994).

DeBell et al. (1992) reported that intensive management of red alder plantations greatly influenced growth rate. However, it is not known how the accelerated growth affects wood and fiber properties. From a perspective of utilization, the primary interest is in whether accelerated growth rate lowers the wood and fiber quality. Thus, understanding the relationship between growth rate and wood properties is of practical importance in maximizing fiber production without lowering wood and fiber quality.

Previous investigations on the effect of growth rate on wood properties in hardwoods focused almost exclusively on specific gravity and fiber length (Zobel and van Buijtenen, 1989). The results are often contradictory for diffuse-porous species. Limited studies showed that anatomical properties other than specific gravity and fiber length have little relationship to growth rate for diffuse-porous hardwoods (Scaramuzzi, 1958; Malan, 1991; Peszlen, 1993). The effect of growth rate on the mechanical properties of hardwoods is unknown. No publications are found showing a direct relationship between growth rate and mechanical properties. Red alder, as a diffuse-porous species, showed no relationship between its growth rate and specific gravity (Parker et al., 1978; Lowell and Krahmer, 1993).

A serious and common error as indicated by Zobel and van Buijtenen (1989) in evaluating the relationship between growth rate and wood properties is confounding the growth rate with cambial age. For instance, a conclusion that there is a difference between the properties of wood from fast-grown and slow-grown trees can be incorrectly drawn if we fail to sample from rings of the same cambial age.

The objective of this study was to determine the effect of growth rate on anatomical characteristics, specific gravity, and bending properties of wood from seven-year-old plantation-grown trees.

Materials and Methods

Materials

Wood samples of red alder from an intensively managed plantation were provided by the USDA Forest Service Research Station in Olympia, Washington. The plantation was originally designed to study biomass production of cottonwood (*Populus* spp.) and red alder (DeBell et al., 1991 and 1992). One purpose of the plantation was to assess the influence of silvicultural treatments on tree growth and stand development. The red alder plantation was a split-split-plot experimental design with three replications (Appendix A). In any one of the three blocks, one main plot was randomly selected for irrigation. Each main plot was subsequently split into two sub-plots, one of which was randomly selected to receive fertilizer. Each sub-plot was further divided into three sub-sub-plots for three spacings. Therefore, there were 12 treatment combinations, each having three replicated sub-sub-plots. There were 100 trees in each sub-sub-plot and 300 trees for each treatment combination. A small, a median, and a large tree were determined by diameter at breast height and taken from three different sub-sub-plots within each treatment combination. In this manner, a small, a median, and a large tree were taken from each of 12 treatment combination for total of 36 trees (DeBell, 1994). Six sample trees were excluded from the study because they had fewer than five growth rings at breast height. The descriptive data for the 30 sample trees provided by DeBell et al. (1992) are in Appendix B.

A 25-cm thick disk was removed from each tree at breast height (1.3 m). Disks were wrapped in plastic and brought back to the Forest Research Lab at Oregon State University. A saw cut from bark to pith was made in each disk to prevent checking. Disks were dried in a kiln at 65°C with 8°C wet-bulb depression until the target moisture content of 12% was reached. Then the disks were stored in a room with a 12% equilibrium moisture content.

Sample preparation

Four samples were prepared from the fifth ring in each disk (Figure II.1, A). Aggregate rays were avoided because they are absent or rare in the inner core of the lower half of the tree stem (Noskowiak, 1978). The first sample was randomly located on the circumference of the ring. The others were located at 90°, 180° and 270° from first one. Sample size was 0.51 (0.20 inches) cm in the tangential direction, 0.64 cm (0.25 inches) in the radial direction and 8.26 cm (3.25 inches) in the longitudinal direction (Figure II.1, B).

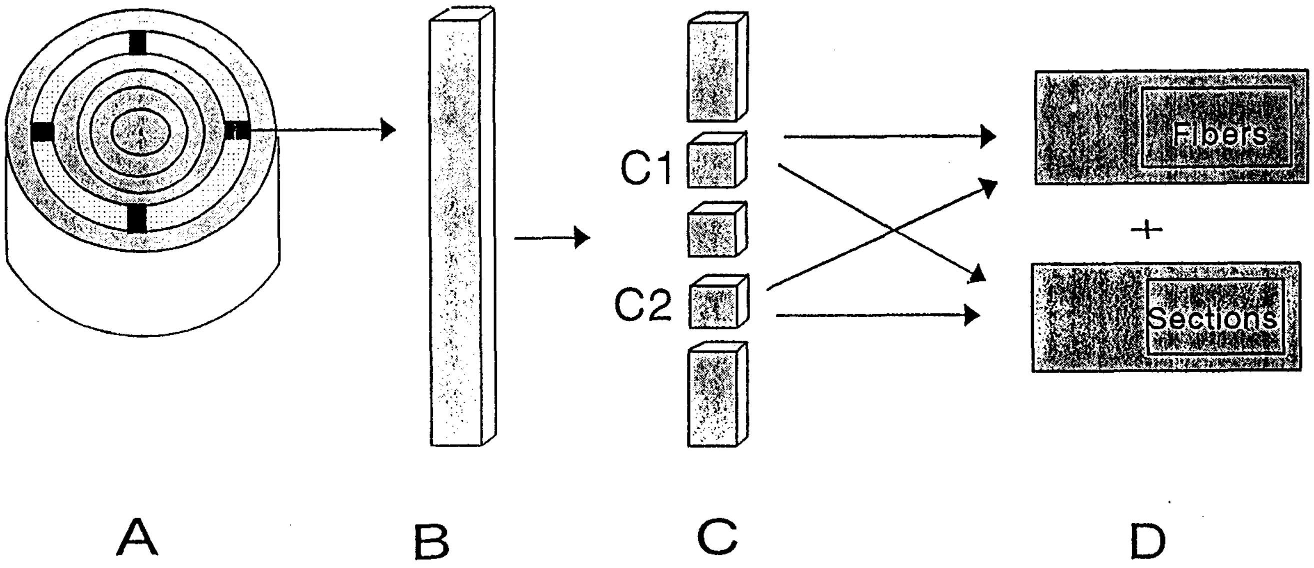


Figure II.1 Diagram of sample preparation from a disk. (A) Disk; (B) bending and specific gravity sample; (C) two locations (C1 and C2) from which anatomical materials were cut after bending test; (D) maceration and microtome section slides.

Bending tests

A Universal Instron test machine and an electronic automatic data acquisition system were used for the bending tests. Deflection was measured using an LVDT (linear variable differential transducer) with a 0.0787 ± 0.0008 mm/v resolution and 3-cm travel span. The load was measured using a 110-kg loadcell with a 4.313 ± 0.005 kg/v resolution. A data acquisition program, Quicklog for PC DOS, recorded, processed, and graphed the data (voltages) of deflection and load. Central point loading and a span length of 7.1 cm were used for static bending tests. The curvature radius of the load head and support rollers was proportionally reduced to 0.83 cm for mini-bending samples based on the ASTM D 143-83 (ASTM, 1986). As samples were 0.51 cm in depth, the 7.1 cm span provided a 14:1 span-to-depth ratio as recommended by ASTM. Load speed was 1.17 mm/min. Loading on the radial surface instead of tangential surface was applied to reduce the effect of earlywood and latewood orientation in the top and bottom layers of the sample. All bending tests were carried out in an air-conditioned room at 23 ± 1°C and 57 ± 3% relative humidity. A daily calibration of the Instron was performed by testing an aluminum bar before testing wood samples. A full calibration including loadcell and LVDT check was repeated weekly. The modulus of elasticity (MOE) was calculated based on the linear portion of the load versus deflection curve for each sample. Load values between 20% and 35% failure load were regressed on the corresponding deflection values to make sure the regression line is linear. The slope (β) with at least a 99.9% determination coefficient was accepted for calculation of MOE as follows:

$$MOE = \beta * \frac{S^3}{4*B*H^3} \quad (Pa) \qquad (II.1)$$

Where β = slope from regression (N/m),

S = span of test (m),

B = width of sample (m),

H = depth of sample (m).

The modulus of rupture (MOR) was calculated from the following formula:

$$MOR = \frac{3*P*S}{2*B*H^2} \quad (Pa) \qquad (II.2)$$

where P = failure load (N),

S, B and H are the same as in equation II.1.

Specific gravity and moisture content

Prior to bending testing, each sample was weighed to an accuracy of 0.001 grams. Its depth and width at midspan, and its length were measured to an accuracy of 0.01 mm. After the test, samples were ovendried at 105 °C and weighed again. Specific gravity was determined based on following equation:

$$\text{Specific gravity} = \frac{W_{OD}}{V_T * \rho_{wat}} \qquad (II.3)$$

Where W_{OD} = Ovendry weight of the sample (g),

V_T = Volume of sample at test moisture content (cm^3),

ρ_{wat} = Density of water (g/cm^3).

The moisture content at the time of the test was calculated as follows:

$$MC = \frac{W_T - W_{OD}}{W_{OD}} * 100 \qquad (II.4)$$

Where W_T = Weight of sample at test (g).

Anatomical characteristics

After the bending tests were completed, pieces of each sample were removed for the measurement of anatomical characteristics (Figure II.1, C and D). Transverse and radial sections were cut 20-μm in thickness. Temporary slides of two radial sections were made using glycerin as mounting medium. The transverse sections were stained in aqueous safranin for 10 minutes and then washed two times in water before going through the dehydration process. Sections were prepared for mounting by dehydrating in 50% ethanol for three minutes, 75% ethanol for two minutes, 95%

ethanol for one minute, dipping in 100% ethanol twice, and clearing in xylene for three seconds. Two permanent slides with two defect-free transverse sections on each were made using 'Permount' brand mounting medium.

To prepare macerated fiber slides, several match-sized sticks were boiled in test tubes with water for 15 minutes and then boiled at 85°C for about 20 minutes in 20 ml of 20% nitric acid with 0.5 gram of sodium chlorite. Next, the acid was replaced by water and the fibers were boiled an additional 10 minutes. Then water was exchanged several times to completely remove excess acid for better staining. The fibers were stained in aqueous safranin overnight for good image contrast. Finally temporary slides of the macerated fibers were made using glycerin as the mounting medium.

Wood and fiber characteristics including fiber length, fiber diameter, fiber wall thickness, vessel diameter and tissue proportions were measured using an image analysis system. The images of macerated fibers and minute structure of wood were acquired through a CCD video camera attached to a stereo-microscope (for low magnification) or compound microscope (for high magnification). Images were processed and analyzed with an Apple Macintosh Quadra 800 using the public-domain program NIH Image (version 1.47, Rasband, 1992).

Fiber length

The stereo-microscope at 40X magnification was used to measure 80 whole fibers for each sample. First, a micrometer was used to calibrate the length measurement tool in the NIH Image Program. Then the actual length of a fiber was measured by clicking with the mouse cursor at each end of a fiber and pushing the 'measure' key to record the result to a temporary data file. This method worked very well even though there were many overlapping fibers on the slide. The temporary data file was saved as a spreadsheet file for future analysis.

Vessel and fiber diameters, fiber wall thickness

Vessel diameter, fiber diameter, and double thickness of the fiber wall were measured tangentially from the cross section slides. The technique was similar to that for fiber length measurement with the exception that 200X, 400X and 600X magnifications were used and the calibration was done accordingly.

Tissue proportions

The percentage of vessels was obtained by measuring their relative cross sectional areas. The vessels were distinguished from fibers and axial parenchyma by defining

620 μm^2 as the lower threshold value for the area of a vessel. The axial parenchyma cells on the cross section were painted and their relative area was measured. Similarly on the radial section, the ray tissue was painted and its fractional area was measured. The relative area of each type of cell including both the lumens and walls was an average of four measurements from four sections. The percentage of fibers was obtained by subtracting fractional areas of vessel, ray, and axial parenchyma from unity. The relative area of each type of tissue represents its relative volume in the wood.

Regression analysis

Growth rate effect

Simple linear regression models were used to analyze the relationship between growth rate and various wood properties. Growth rate was expressed as annual ring width (mm) or ring area (mm^2). Each wood property was plotted and regressed against growth rate. The regression equation is:

$$Y_i = \beta_0 + \beta_1 X_i + \epsilon_i \qquad \text{(II.5)}$$

Where Y_i = property of interest,

X_i = annual ring width or area (mm or mm^2),

β_0 = intercept,

β_1 = regression coefficient,

ϵ_i = independent, normally distributed random error.

Silvicultural treatments

The previous analyses of the effect of growth rate on wood properties were based on the overall growth rate in terms of annual ring width or ring area regardless of what caused the change of the growth rate. In order to analyze the effects of irrigation, fertilization, and spacing treatments on the growth rate and various wood properties, visual graphic comparison and regression analysis techniques were used instead of an analysis of variance (ANOVA). Because sample trees were not randomly selected from each sub-sub-plot of the plantation, an ANOVA could not be used. Regression lines of wood property on growth rate for different levels of treatment of interest were compared while the other treatment effects were pooled. This was repeated for each treatment.

For fertilization or irrigation treatment with only two levels, the following regression model was used:

$$Y_i = \beta_0 + \beta_1 X_i + \beta_2 Z_i + \beta_3 X_i Z_i + \epsilon_i \qquad \text{(II.6a)}$$

where Y_i = property of interest,

X_i = growth rate,

$$Z_i = \begin{cases} 1 & \text{If treatment applied} \\ 0 & \text{If control (no treatment applied),} \end{cases}$$

ϵ_i = independent, normally distributed random error.

When the treatment was applied, the above model became:

$$E\{Y_1\} = (\beta_0 + \beta_2) + (\beta_1 + \beta_3)X \qquad \text{(II.6b)}$$

When treatment was not applied, the model used:

$$E\{Y_0\} = \beta_0 + \beta_1 X \qquad \text{(II.6c)}$$

For spacing treatment with three levels, the regression equation was:

$$Y_i = \beta_0 + \beta_1 X_i + \beta_2 Z_{i1} + \beta_3 Z_{i2} + \beta_4 X_i Z_{i1} + \beta_5 X_i Z_{i2} + \epsilon_i \qquad \text{(II.7a)}$$

Where Y_i = property of interest,

X_i = growth rate,

$$Z_{i1} = \begin{cases} 1 & \text{If 1 x 1 meter spacing,} \\ 0 & \text{Otherwise,} \end{cases}$$

$$Z_{i2} = \begin{cases} 1 & \text{If 2 x 2 meter spacing,} \\ 0 & \text{Otherwise,} \end{cases}$$

ϵ_i = independent, normally distributed random error.

When spacing is 0.5 x 0.5 meter, $Z_{i1} = Z_{i2} = 0$,

$$E\{Y_{0.5}\} = \beta_0 + \beta_1 X \qquad \text{(II.7b)}$$

When spacing is 1 x 1 meter, $Z_{i1} = 1$, $Z_{i2} = 0$,

$$E\{Y_1\} = (\beta_0 + \beta_2) + (\beta_1 + \beta_4)X \qquad \text{(II.7c)}$$

When spacing is 2 x 2 meter, $Z_1 = 0$, $Z_2 = 1$,

$$E\{Y_2\} = (\beta_0 + \beta_3) + (\beta_1 + \beta_5)X \qquad \text{(II.7d)}$$

Comparisons of two regression functions for two levels of irrigation or fertilization treatment were done in two steps. The first was to test the null hypothesis ($\beta 2 = \beta 3 = 0$) in the equation (II.6b) for each wood property. If the null hypothesis was true (the two regression functions were identical), it was concluded that the treatment had no significant effect. If not, further analysis was conducted to examine whether the slopes of regression lines were the same. A similar procedure was used for the comparisons of three levels of spacing treatment.

Results and Discussion

Growth rate

At a cambial age of five years, the annual growth rate of sample trees in terms of ring width varied from 3 to 9.25 mm/year, more than a three-fold difference. When the annual growth rate was expressed as the change in cross sectional area, the difference was more than twelve-fold, ranging from 264 to 3350 mm^2/year. It is apparent that wood samples used in this study represented a very wide range of growth rate expressed either as ring width or as ring area.

From a standpoint of plant development, ring width and ring area have different meanings. In the wood industry, growth ring width, often referred to as the growth rate, is largely a measure of periclinal division of cells. When the diameter of a tree increases, tangential growth resulting from anticlinal division of cells is required to keep up with change in girth expansion or circumference of the tree. Ring area encompasses both radial and tangential expansions and therefore, is probably a better indicator of growth rate. However, the data from 30 trees show that ring width and ring area have a strong linear relationship (Figure II.2).

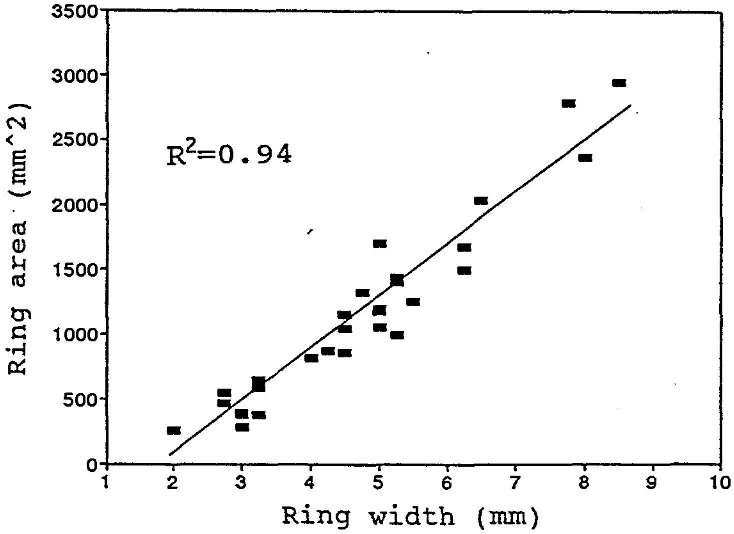


Figure II.2 Linear relationship between annual ring width and ring area.

Effect of growth rate

In this section, the effect of growth rate on various wood properties is analyzed, ignoring the cause.

Anatomical properties

The statistically significant regression equations for anatomical properties on ring width and ring area are shown in Table II.1. Anatomical properties other than those in the table have no consistent relationship with growth rate.

Fiber length was positively correlated with ring width ($P = 0.048$, $R^2 = 0.13$) and ring area ($P = 0.014$, $R^2 = 0.15$) respectively, although the determination coefficients are very low for both (Figure II.3, A and B). The results show that fiber length was not adversely affected by increasing growth rate. This result agree with the statement by Zobel and van Buijtenen (1989) that fast growth, whatever the cause, does not always result in shorter fibers.

Fiber diameter did not significantly vary with ring width ($P = 0.97$) or ring area ($P = 0.94$)(Figure II.3, C and D).

The thickness of the fiber wall tended to decrease slightly as the growth rate increased (Figure II.3, E and F), but the relationship was very weak with determination coefficients of 0.14 ($P = 0.034$) and 0.13 ($P = 0.021$) for ring width and ring area, respectively.

The combination of slight increase in fiber length and decrease in thickness of fiber wall with growth rate raised the ratio of fiber length to cell wall thickness (L/T). This result suggests that accelerating growth of red alder

Table II.1 Fitted regression equations of some wood properties[a] versus growth rate (annual ring width and ring area).

Dependent variables (Y)	Independent variable (X)			
	Ring width (mm)		Ring area (mm^2)	
	Fitted model	R^2	Fitted model	R^2
Fiber length (mm)	$Y = 0.93 + 0.013X$ (0.032)[b](0.006)	0.13	$Y = 0.95 + 0.00005X$ $(0.020)\ (0.0000135)$	0.15
Double thickness of fiber wall (μm)	$Y = 3.75 - 0.048X$ $(0.115)\ (0.022)$	0.14	$Y = 3.64 - 0.000101X$ $(0.073)\ (0.00049)$	0.13
Vessel diameter (μm)	$Y = 56.8 + 1.02X$ $(1.96)\ (0.38)$	0.21	$Y = 59.6 + 0.0179X$ $(1.28)\ (0.0087)$	0.20
Ray (%)	$Y = 11.1 + 0.69X$ $(0.73)\ (0.14)$	0.47	$Y = 12.8 + 0.00145X$ $(0.475)\ (0.00032)$	0.42
Axial parenchyma (%)	$Y = 1.33 - 0.0767X$ $(0.11)\ (0.021)$	0.33	$Y = 1.175 - 0.000179X$ $(0.066)\ (0.000045)$	0.37

a Only the anatomical characteristics significantly (0.05 level) related to growth rate are listed.
b Inside the parenthesis is the standard error of a regression coefficient.

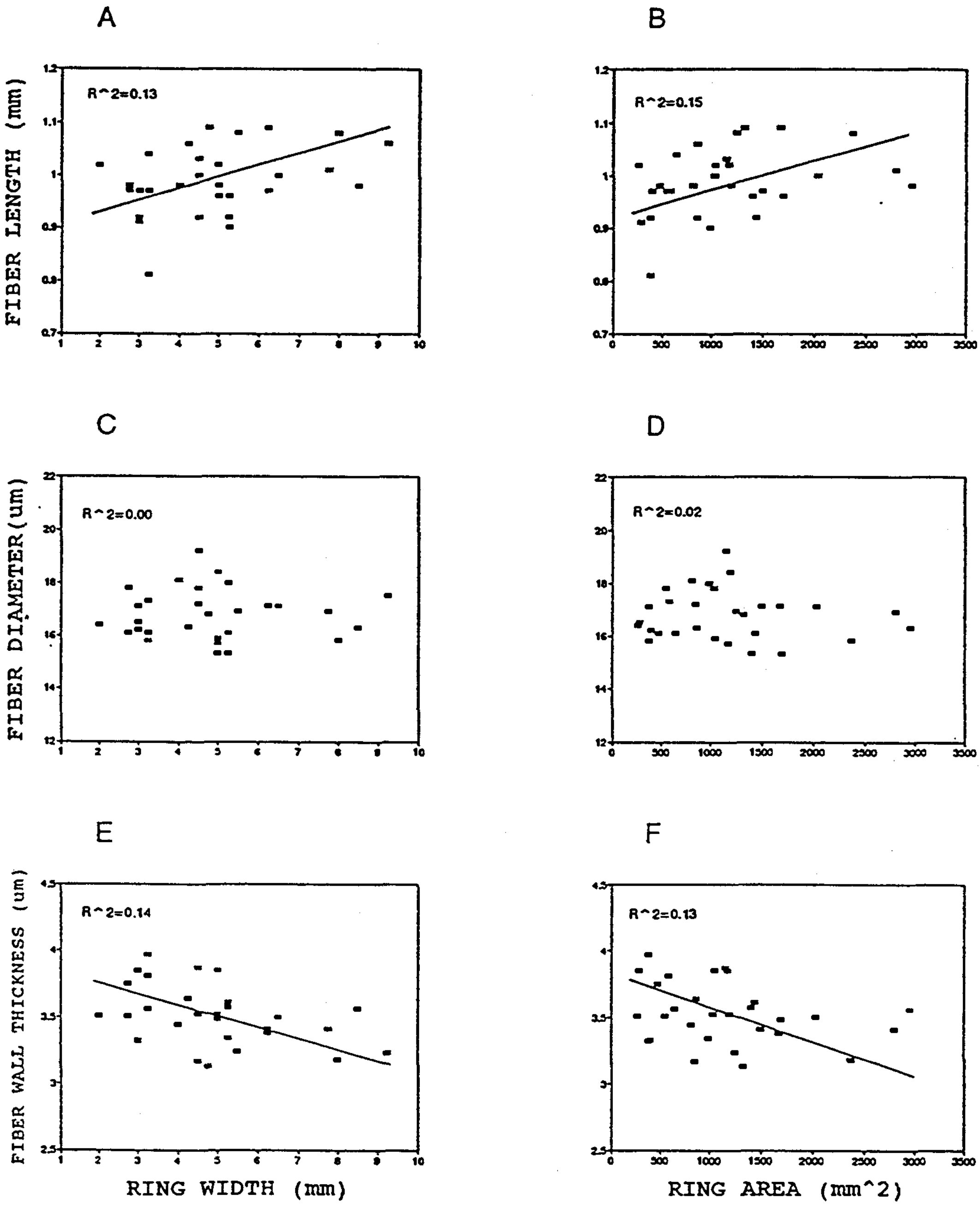


Figure II.3 The relationships between fiber length (A and B), fiber diameter (C and D), and cell wall thickness (E and F) and ring width or ring area. Regression lines show statistically significant relationships at 0.05 level.

should increase rather than lower fiber quality for paper manufacturing because a higher L/T ratio is an indicator of higher tensile strength, modulus of elasticity, and burst factor for the paper (Horn, 1978).

Vessel diameter was significantly and positively correlated with growth rate (Table II.1 and Figure II.4), with determination coefficients of 0.21 ($p = 0.011$) and 0.20 ($p = 0.004$) for ring width and ring area, respectively. Fast grown red alder trees will produce wood with a slightly larger vessel diameter, which is unfavorable for paper making and solid wood products because large vessel diameter of diffuse-porous species leads to problems in refining and printing processes and difficulties in the finishing of solid wood. Contrary to the above result, other diffuse-porous species such as

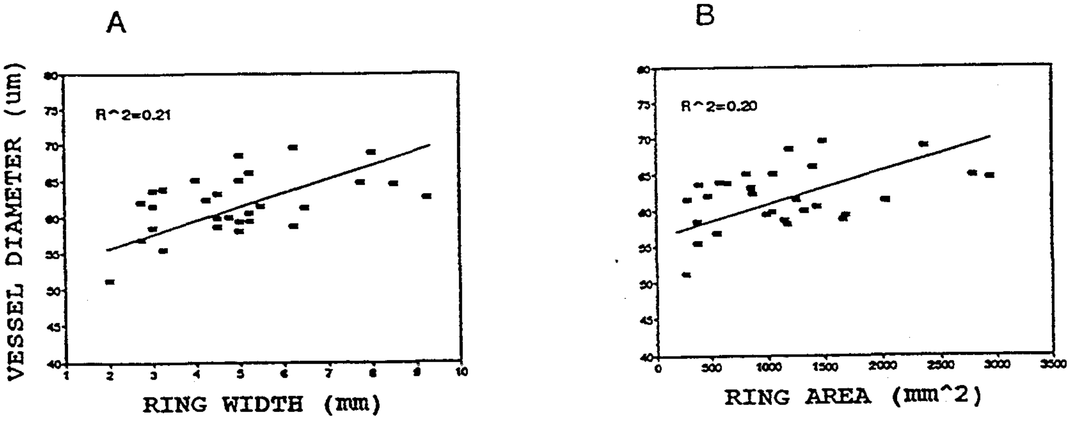


Figure II.4 The relationship between vessel diameter and ring width (A) or ring area (B) with regression lines.

Populus spp. (Peszlen, 1993) and *Fagus* spp. (Koltzenburg, 1966) showed a negative relationship between vessel diameter and growth rate.

The percentage of wood tissue present as fibers and vessels showed no apparent change with growth rate (Figure II.5, A, B, C and D). However, the percentage present as ray tissue increased (Table II.1 and Figure II.5, E and F) from about 10% to 17% as the growth rate increased from 2 to 9.25 mm/year in ring width ($R^2 = 0.47$) or from 263 to 3350 mm^2/year in ring area ($R^2 = 0.42$). Although the percentage of axial parenchyma tended to decrease with growth rate (Table II.1 and Figure II.5, G and H), the negligible amount of axial parenchyma (1% to 2%) in wood should have little practical effect on wood and fiber properties.

Small changes in the fiber and vessel proportions with growth rate will not greatly influence either the specific gravity of wood or the fiber yield when pulp is made, although the ray proportion changes. Similarly, the mechanical properties and machining ability of wood are not expected to change much with growth rate. A higher fraction of ray tissue means more transverse-oriented wood tissue, which may increase the drying rate and affect anisotropy in shrinkage.

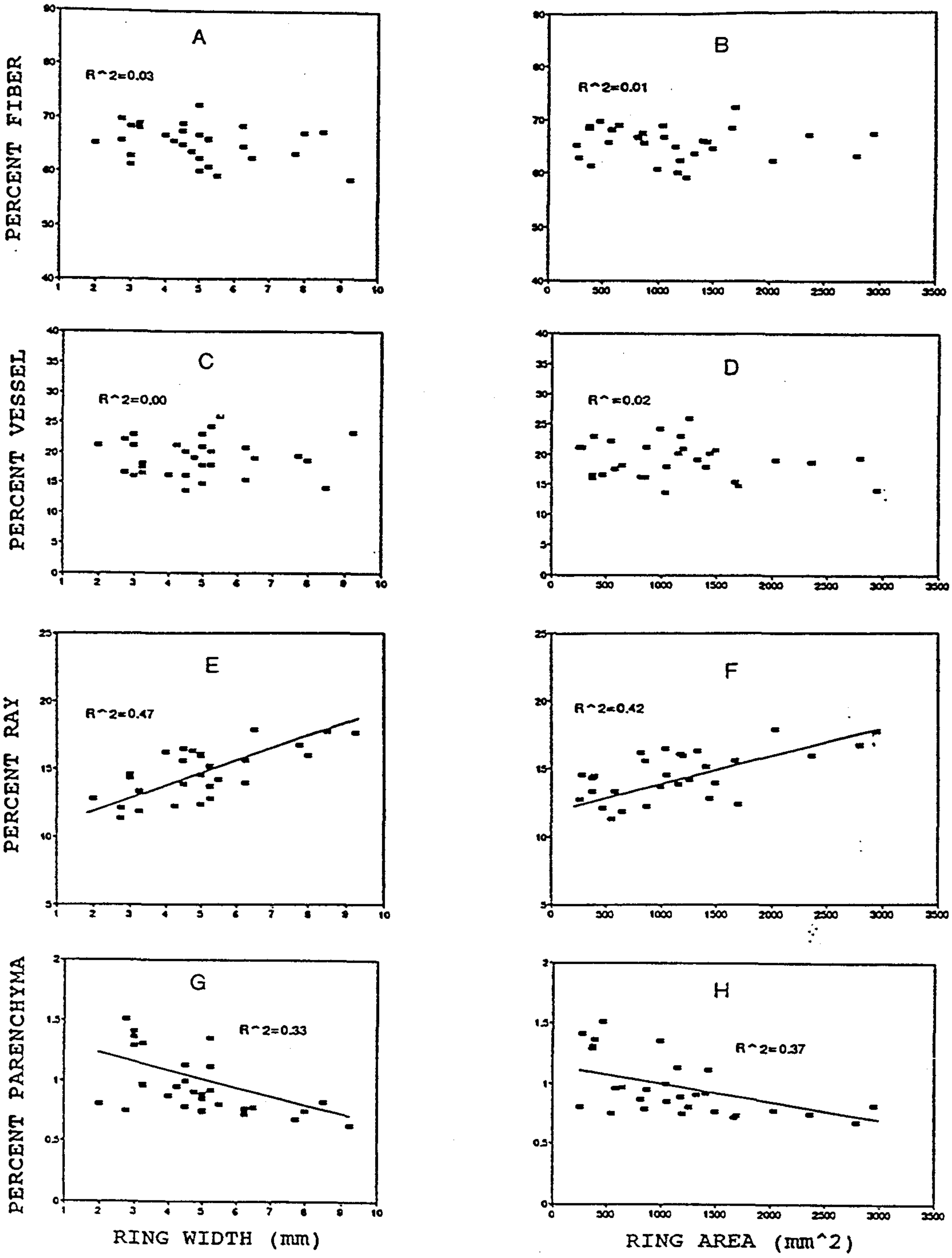


Figure II.5 The relationship between the percentages of wood tissues and growth rate. Fiber percentage vs. ring width (A) or ring area (B); Vessel percentage vs. ring width (C) or ring area (D); Ray percentage vs. ring width (E) or ring area (F); Axial parenchyma percentage vs. ring width (G) or ring area (H).

Specific gravity and bending properties

Specific gravity was not related to growth rate (Figure II.6, A and B). This result supports the statement by Leney et al. (1978) that growth rate has little effect on specific gravity in red alder. Specific gravity did not decrease in spite of a slight decrease in fiber wall thickness with growth rate. One explanation is that the increase of fractional volume of higher-specific-gravity ray tissue offset the effect of fiber wall thickness on specific gravity because higher ray percentage has been associated with higher specific gravity in many species of hardwoods (Taylor, 1969; Fujiwara, 1992). With little change in fiber and vessel percentages, the combined effect of the increase in ray tissue percentage and the decrease in fiber wall thickness led to little change in specific gravity with growth rate.

There was no correlation between growth rate and either of the bending properties, MOE and MOR (Figure II.6, C, D, E and F). This result indicates that increasing growth rate by silvicultural practices neither reduces specific gravity nor lowers the strength of wood.

It should be noted that the results from this study may not be used to explain the relationship between growth rate and wood properties for mature wood because all samples are from the fifth ring which might represent only

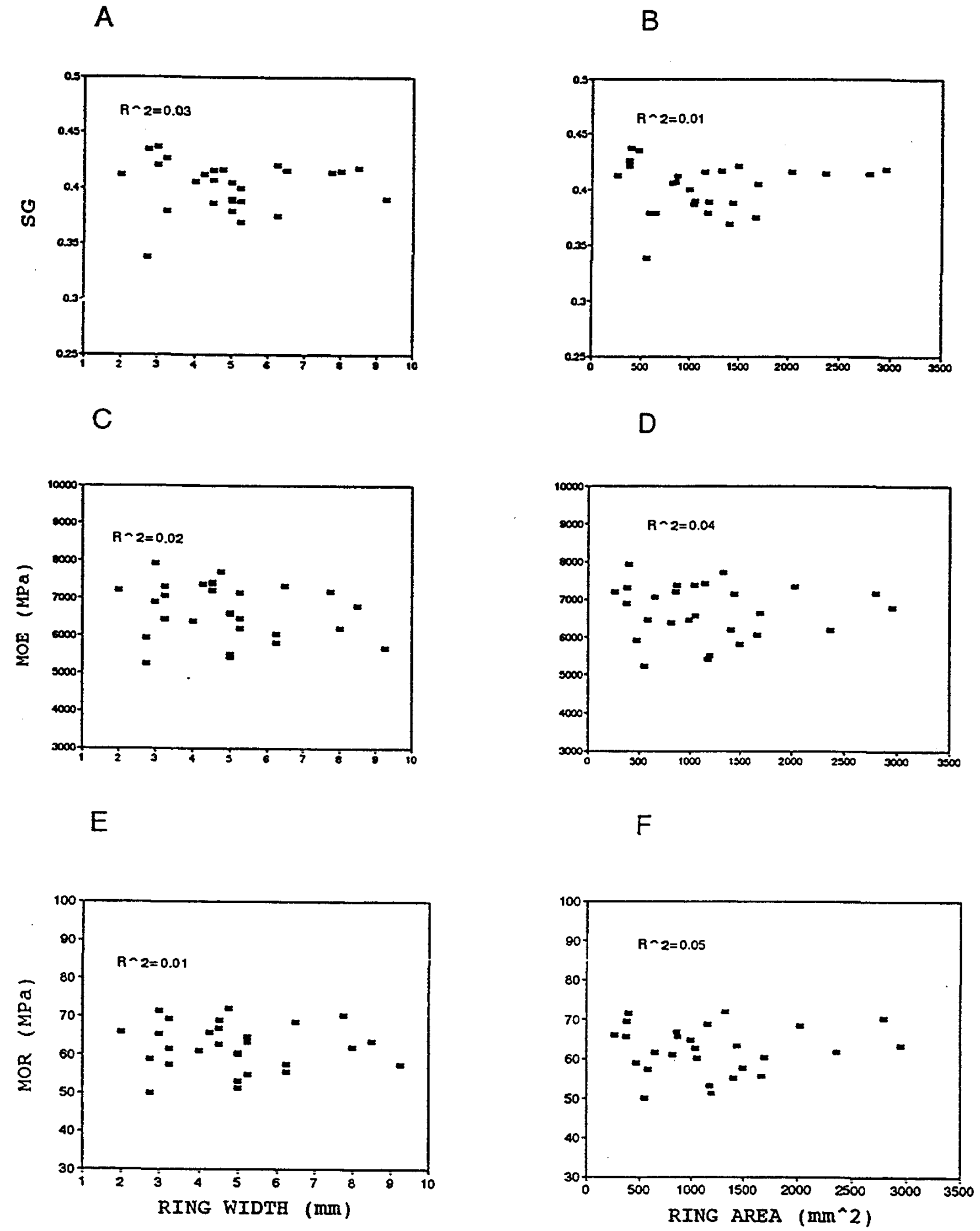


Figure II.6 Specific gravity (A and B), modulus of elasticity (C and D), and modulus of rupture (E and F) show no relationships with ring width or ring area.

the juvenile wood. The relationship between growth rate and wood properties in mature wood needs to be investigated.

Effect of silvicultural treatments

The above results were based on the growth rate expressed as annual ring width or area. In this section, the influence of silvicultural treatments on the growth rate, wood properties, and their relationship is presented and discussed. The nutrient level of the soil, fertilization level, and irrigation conditions of the plantation are shown in Appendix C. Since sample trees were not random, there was no statistical basis for extending inferences from this study to whole plantation in general. Statistical inferences obtained from the analyses of treatment effects applied only to 30 sample trees.

Response of growth rate

Irrigation and spacing treatments were very effective in increasing ring width and ring area when the fertilization treatment is ignored (Figure II.7). Closer spacing or non-irrigation (control) caused less radial growth. Between spacing and irrigation treatments, spacing was a more effective treatment than irrigation in affecting radial growth.

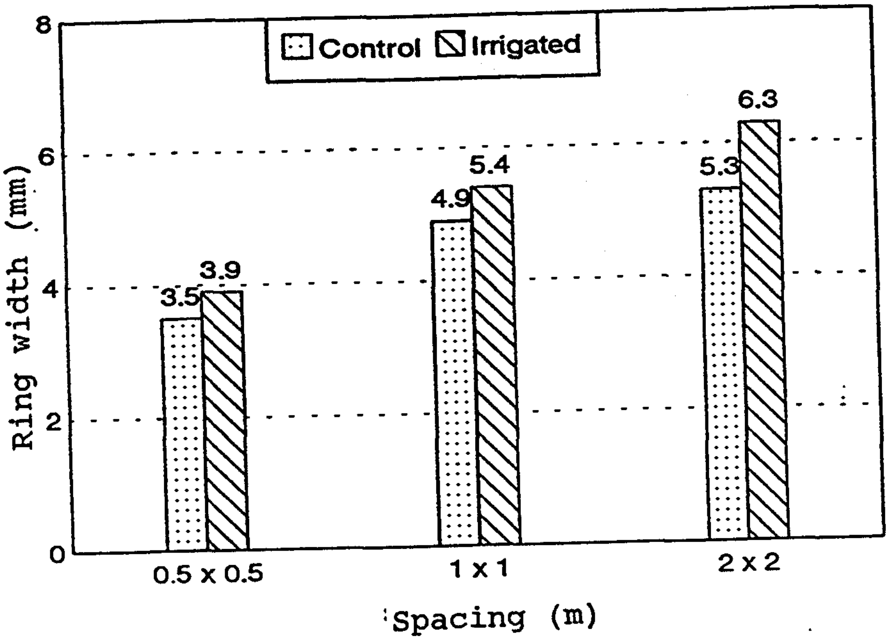
When the irrigation treatment is ignored, fertilization treatment had little effect while spacing again showed a pronounced effect on radial growth (Figure II.8).

When the spacing treatment is ignored, irrigation treatment resulted in an increase in both ring width and ring area. Again, fertilization showed little effect on ring width and even a negative, though small, effect on ring area (Figure II.9).

The above results agree well with the findings on the diameter growth of plantation-grown red alder, that theheight and diameter of plantation trees were strongly influenced by spacing and irrigation, but fertilization had little effect (Appendix D from DeBell et al., 1991).

Effect of fertilization

There were no significant differences between two regression functions for fertilized and unfertilized samples (Table II.2). The responses of all anatomical, physical, and mechanical properties to growth rate were unchanged with the application of the fertilization treatment. Combined with previous results for annual growth, it can be seen that the fertilization treatment was not effective in increasing growth rate, nor did it affect the relationship between wood properties and growth rate.



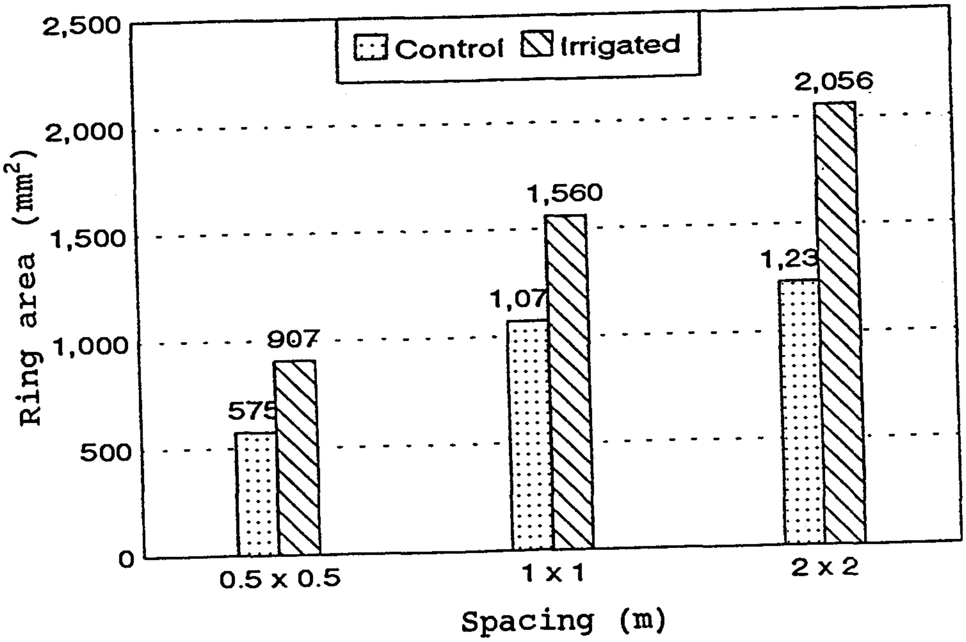


Figure II.7 Response of width or area of the fifth annual ring to the spacing and irrigation treatments.

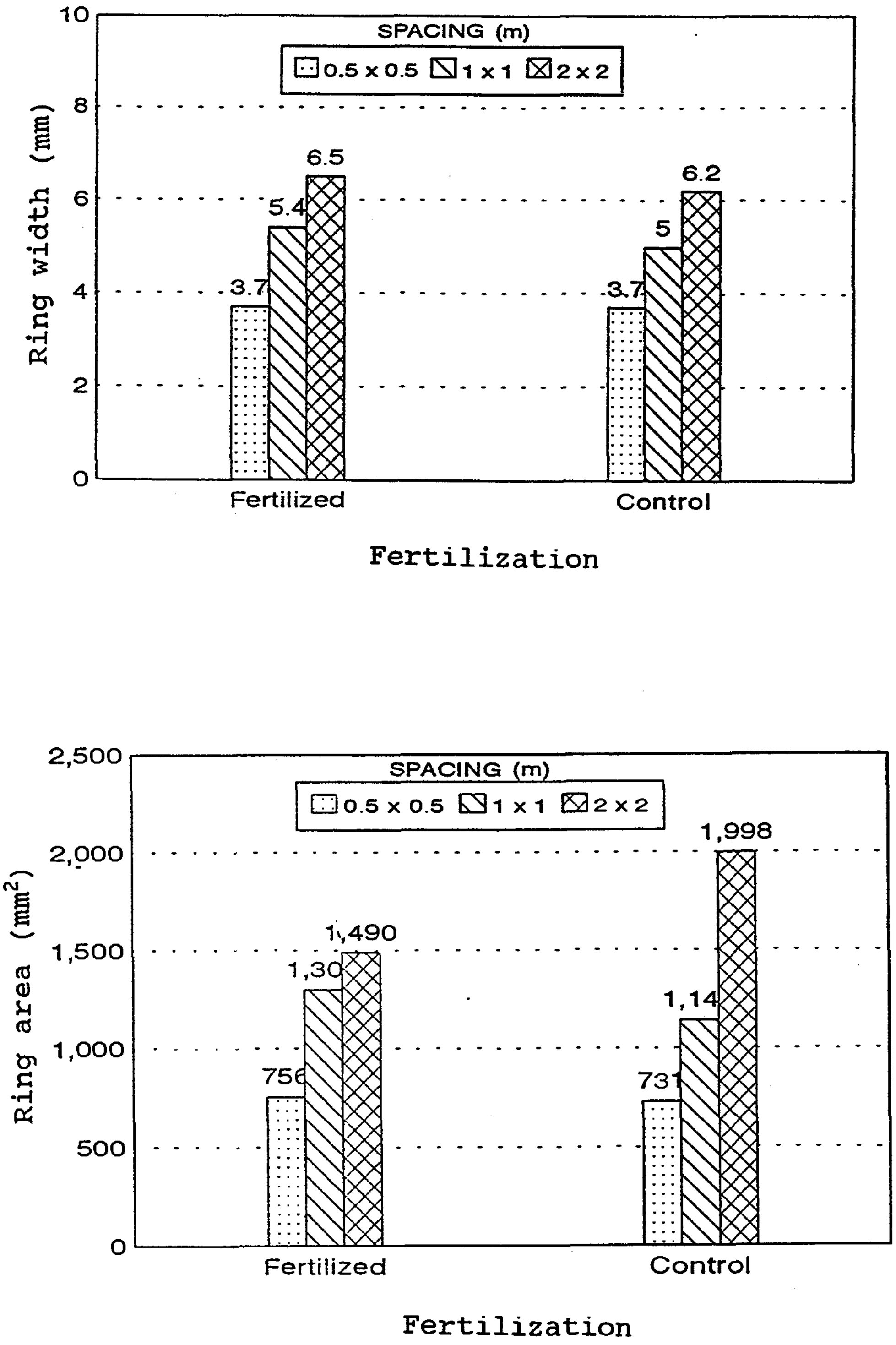
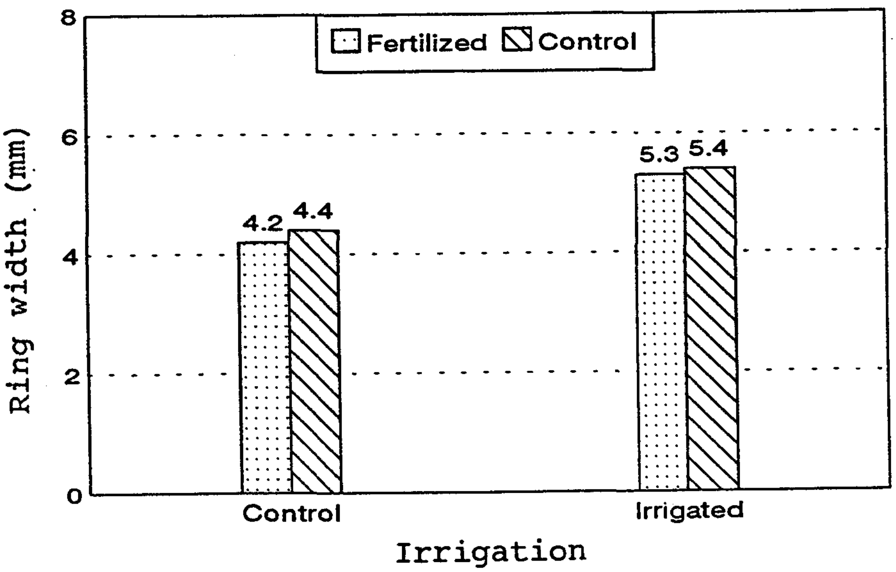


Figure II.8 Response of width or area of the fifth annual ring to the fertilization and spacing treatments.



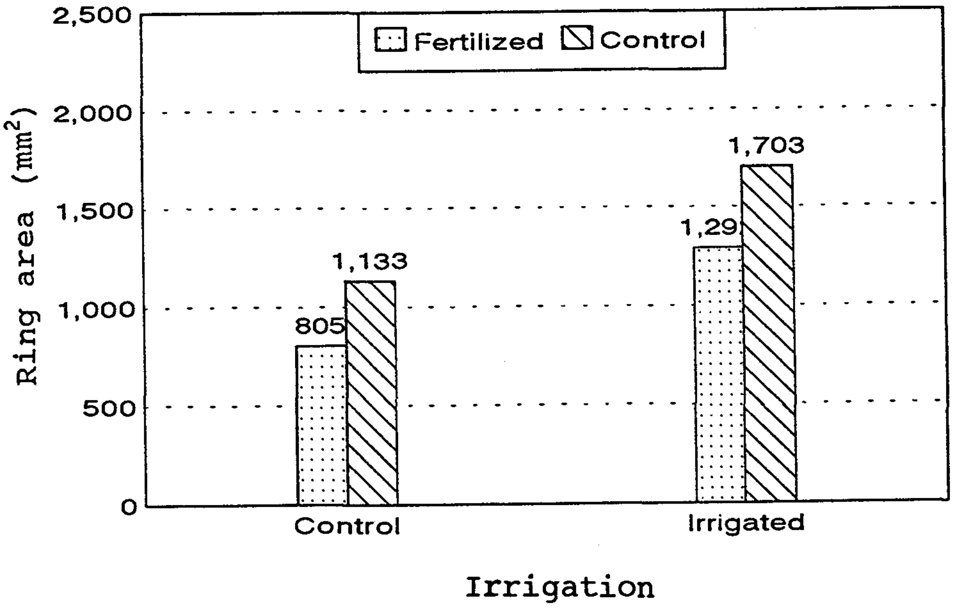


Figure II.9 Response of ring width or area of the fifth annual ring to the irrigation and fertilization treatments.

Table II.2 The results (P-values) of F-test for no difference in wood properties between two regression lines for fertilized and the control.

Dependent variable	Independent variables	
	Ring width/year	Ring area/year
Fiber length	0.77	0.59
Fiber diameter	0.79	0.82
Double thickness of fiber wall	0.40	0.49
Vessel diameter	0.61	0.67
Fiber %	0.78	0.79
Vessel %	0.74	0.54
Ray %	0.13	0.06
Axial parenchyma %	0.82	0.97
Modulus of elasticity	0.23	0.35
Modulus of rupture	0.26	0.41
Specific gravity	0.18	0.23

Effect of irrigation

The effect of irrigation treatment was analyzed in a similar manner (Table II.3). Regression lines for fiber length, specific gravity, and percentage of axial parenchyma versus ring width or area were significantly different between the irrigation treatment and the control. Further analysis found that the slopes of these regression lines were statistically different (Table II.4).

Fiber length was found to increase with growth rate without irrigation (control), but there was no definite relationship with irrigation treatment (Figure II.10).

The percentage of axial parenchyma also responded to the change of growth rate differently for the irrigation and the control. Percentage of axial parenchyma had no significant change with growth rate under irrigation treatment, but decreased rapidly with increasing growth rate without irrigation (Figure II.11).

Table II.3 The results (P-value) of F-test for no difference of two linear regression lines (wood properties vs. growth rate) for irrigated and the control.

Dependent variable	Independent variable	
	Ring width/year	Ring area/year
Fiber length	0.05 *	0.02 *
Fiber diameter	0.94	0.94
Double thickness of fiber wall	0.73	0.62
Vessel diameter	0.21	0.18
Fiber %	0.65	0.63
Vessel %	0.96	1.00
Ray %	0.24	0.25
Axial parenchyma %	0.01 *	0.01 *
Modulus of elasticity	0.19	0.10
Modulus of rupture	0.23	0.16
Specific gravity	0.03 *	0.03 *

* Regression lines are significantly different at 0.05 level.

Table II.4 Test for no difference in slopes of two regression lines (wood property vs. growth rate) for irrigated and the control.

Dependent variables (Y)	Independent variables (X)			
	Ring width (mm)		Ring area (mm^2)	
	Fitted model	P-value	Fitted model	P-value
Fiber length (mm)	[a]Y_0=0.841+0.0292X [b]Y_1=0.992+0.0026X	0.043	Y_0=0.889+0.0000889X Y_1=0.999+0.000046X	0.008
Axial parenchyma (%)	Y_0=1.71-0.147X Y_1=1.031-0.031X	0.005	Y_0=1.4110.000389X Y_1=0.991-0.00008X	0.002
Specific gravity	Y_0=0.4377-0.00636X Y_1=0.3729+0.00424X	0.032	Y_0=0.4245-0.0000163X Y_1=0.3806+0.00000929X	0.037

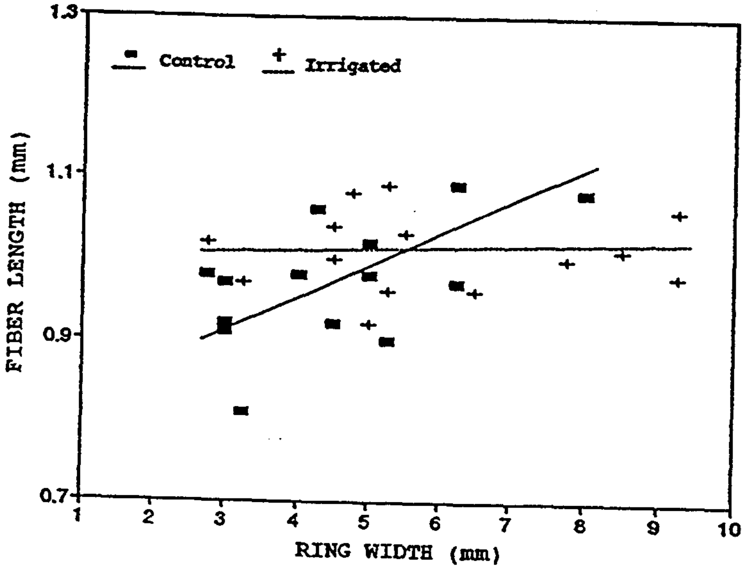
a: Y_0 Control (without irrigation treatment).
b: Y_1 with irrigation treatment.

Specific gravity showed different responses to the growth rate for the irrigated and the control. Specific gravity slightly increased with growth rate without irrigation, but decreased with irrigation (Figure II.12). This result agrees with the finding by Murphey and Bowier (1975) and Einspahr et al. (1972) that specific gravity decreased with irrigation treatment in hardwood species.

Since regular irrigation treatment can be a costly practice (Clerici and Asciuto, 1991) and may lower specific gravity, the tradeoff of the cost and economic return need to be considered before the irrigation treatment is applied.

Effect of spacing

The effect of growth rate on wood characteristics was similar among the three spacing treatments (Table II.5). These results suggest that spacing could be effectively used to increase growth rate without changing the wood properties. Although very few studies on the effect of spacing on wood properties have been reported for hardwoods, lack of correlation between specific gravity and spacing was supported by Schonan (1973) and an increase in specific gravity with wide spacing was found by Delwaulle (1985) in *Eucalyptus* spp.



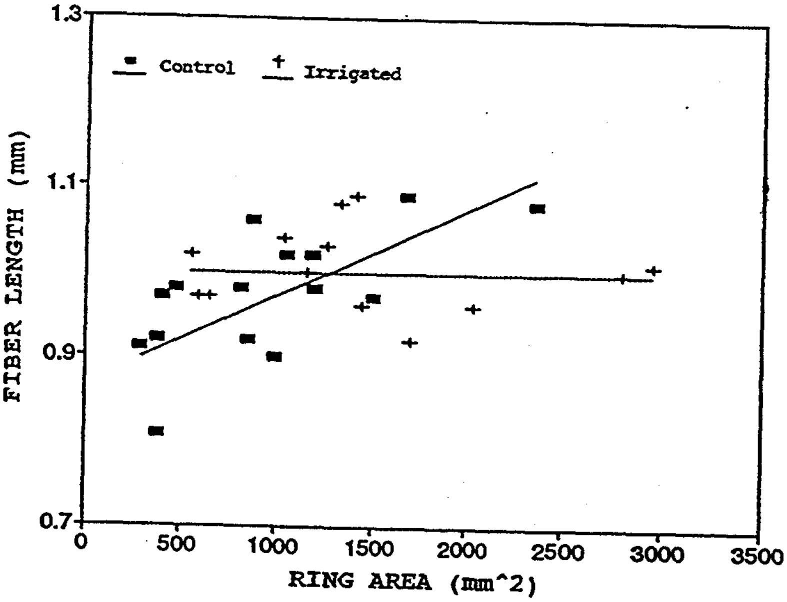


Figure II.10 Relationship between fiber length and ring width or ring area for the irrigated and the control.

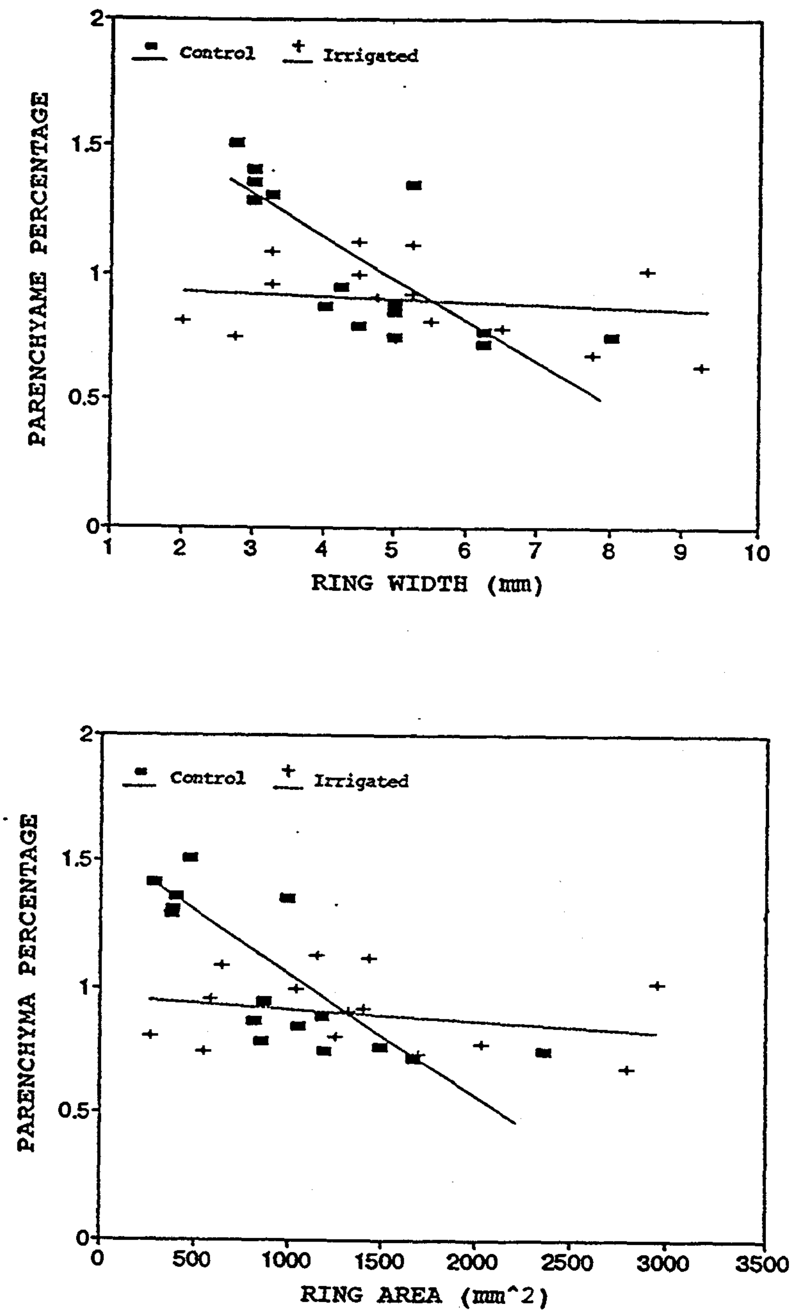
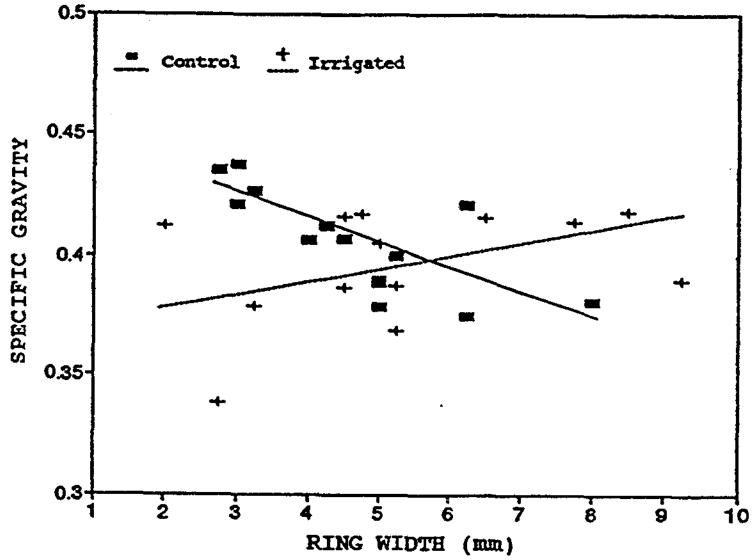


Figure II.11 Relationship between axial parenchyma and ring width or ring area for the irrigated and the control.



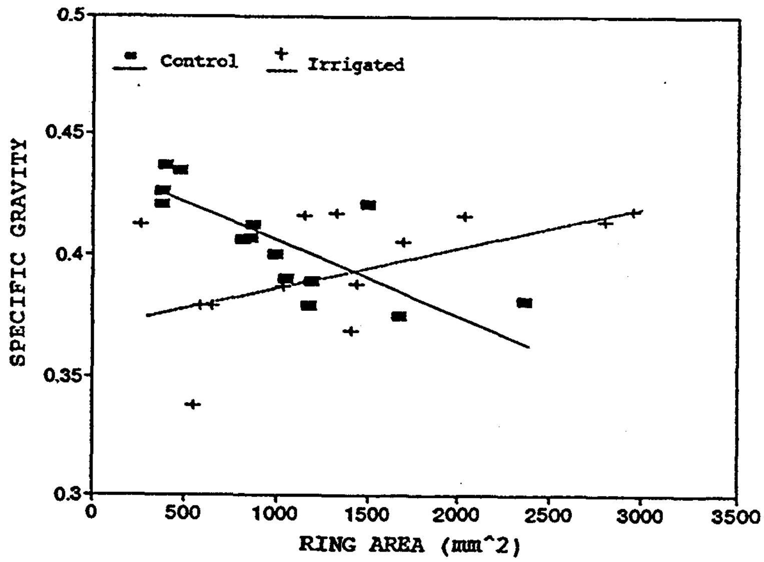


Figure II.12 Relationship between specific gravity and ring width or ring area for irrigated treatment and the control.

Table II.5 The results (P-values) of F-test for no difference among three regression lines for 0.5 x 0.5 m, 1 x 1 m and 2 x 2 m spacing treatments.

Dependent variable	Independent variables	
	Ring width/year	Ring area/year
Fiber length	0.52	0.76
Fiber diameter	0.54	0.30
Double thickness of fiber wall	0.17	0.11
Vessel diameter	0.98	0.99
Fiber %	0.72	0.44
Vessel %	0.78	0.53
Ray %	0.88	0.85
Axial parenchyma %	0.75	0.70
Modulus of elasticity	0.12	0.14
Modulus of rupture	0.31	0.35
Specific gravity	0.19	0.26

It must be noted that only clear wood samples were used in this study. Other wood quality features such as size and number of knots, proportion of juvenile wood, and taper of logs are also important and need to be investigated.

Another important aspect which needs to be indicated is the fiber yield per unit area. Silvicultural practices such as spacing can greatly increase growth for individual trees, but do not necessarily raise the unit area yield. For example, Figure II.13 (data from DeBell et al., 1992) shows the relationship between the woody yield from five-year tree stems and silvicultural treatments in the red alder plantation. Irrigation strongly influenced the woody yields. At 0.5-m spacing, woody yields under irrigation treatment are nearly double those of the control. Although individual trees grow far more rapidly in the widest spacing, total woody yield remains lower than that achieved in the two closer spacings. Therefore, decisions regarding plantation management must consider a complex combination of factors, including desired size of trees, growth rate, wood and fiber quality, unit area yield and costs.

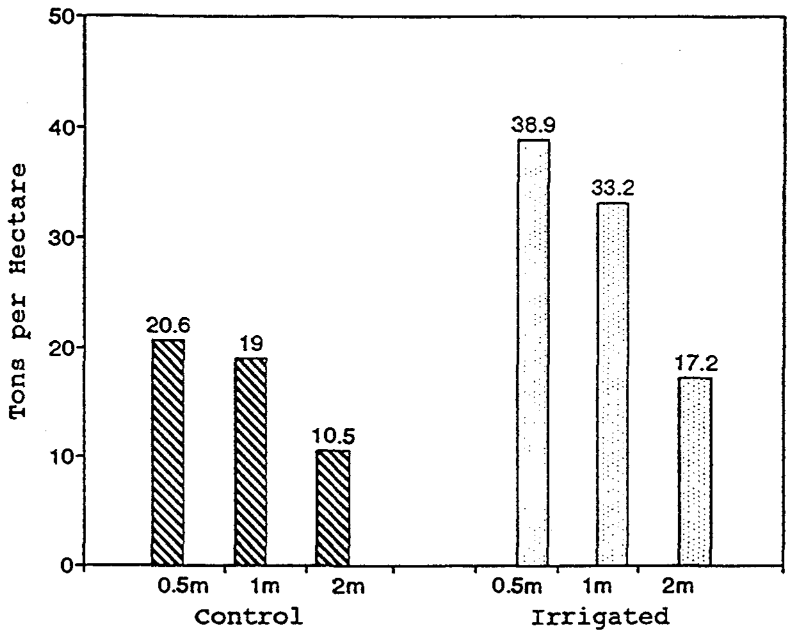


Figure II.13 Woody yield of five-year red alder plantation as related to spacing and irrigation treatments (data provided by DeBell et al., 1992).

Conclusions

Spacing and irrigation treatments applied to red alder plantation trees during their early years greatly changed the growth rates but have little effect on wood and fiber properties. The conclusions drawn from this study are as follows:

1. Using ring width or ring area as a measure of growth rate does not make much difference in the analysis of the relationship between growth rate and wood properties.

2. Silvicultural practices can be used to increase the rate of radial growth in the plantation without deleterious effects on the anatomical characteristics, specific gravity, and bending properties with the exception that irrigation may slightly lower the specific gravity.

3. Irrigation and spacing had apparent positive effects on the growth rate without pronounced a negative effect on wood and fiber properties. Fertilization was not effective in increasing growth rate or in changing the wood properties.

CHAPTER III

VARIATION OF ANATOMY AND SPECIFIC GRAVITY OF WOOD IN RED ALDER (*Alnus rubra* Bong.)

Abstract

To study the variation in wood anatomy and specific gravity of red alder (*Alnus rubra* Bong.), six 40-year-old trees were harvested from a mixed stand of red alder and big-leaf maple in the Oregon Coast Range. Disks were removed from breast height and an upper height (averaging 5.9 m), then wood was sampled sequentially along one diameter. Ring width, fiber length, vessel diameter, tissue volumes (fiber %, vessel %, and ray %), and specific gravity were determined for each sample. The variation of these properties among trees, between two heights, between lower and upper sides of the lean in the tree, and along the radius were analyzed.

Generally, some wood characteristics changed radially, but others showed no definite radial patterns. Fiber length increased rapidly (from 0.8 to 1.2 mm) during the first 10 years and then leveled off. Vessel diameter showed a pattern of radial variation (from 47 to 66 μm) similar to fiber length. From pith to bark, there was no significant change in the percentage of ray tissue (about 13%) but there was a small increase in the percentage of vessel tissue (from 23% to 28%) and a small decrease in the percentage of fiber tissue (from 63% to 57%). Specific gravity was constant from pith to bark but varied considerably among trees (from 0.446 to 0.509). The

variations between two heights and between lower and upper sides were either not significant or minor for all measured properties.

Introduction

The diminishing quantity of old growth forest and the pressure of environmental protection have compelled the wood industry to use alternative forest resources. Red alder is the predominant hardwood species in the Pacific Northwest. Raettig (1994) and Ahrens (1994) reported that in Washington and Oregon, the 1991 hardwood harvest was 635 million board feet; more than 76% of this was red alder. The 1991 hardwood harvest increased 28% over 1987 while, during the same period, the softwood harvest declined 31%. As a short rotation species, red alder produces more wood than the conifers in the first 40 years (Atterbury, 1977). In order to promote increased and improved use of this species, its wood properties and variability must be well understood.

The radial variation of wood properties is studied more often than other variation, such as that with height or intra-ring (Zobel and van Buijtenen, 1989). Radial profiles of wood properties are usually divided into juvenile and mature wood zones. Juvenile wood, the inner portion of the tree stem, is characterized by a progressive change in cell features and wood properties (Panshin and deZeeuw, 1980). Because of its adverse impact on wood utilization, juvenile wood and its characteristics have been extensively studied (Bendtsen, 1978; Thomas, 1984; Maloney, 1986; Jackson and Megraw, 1986; Bendtsen and Senft, 1986; Krahmer, 1986). However, most of these studies have focused on softwood species.

Available information on the wood properties of red alder mainly deal with specific gravity (or density). Harrington and DeBell (1980) found that red alder lacks a low density, juvenile core. Inconsistent trends from pith to bark in wood density of red alder were concluded earlier by Parker et al. (1978). Lowell and Krahmer (1993) reported that radial position affected longitudinal shrinkage but a slight lean had no effect on wood density in red alder.

Based on the limited information above, a question is raised about the existence of juvenile wood core in red alder. However, the patterns of radial variation in wood properties other than specific gravity, such as anatomical properties in red alder, are barely known. In general, the location of juvenile and mature wood boundary depends upon the properties used to define the juvenile zone (Haygreen and Bowyer, 1989). For example, a study (Peszlen, 1993) on *Populus* spp. showed that changes from juvenile to mature wood are not the same for all properties. It is possible that radial variation patterns for anatomical properties are different from those for specific gravity. Therefore, the variation of each property needs to be investigated.

The primary objective of this study was to investigate patterns of radial variation for anatomical properties and specific gravity in order to provide information to the users of this hardwood resource. Because the possible extreme tree-to-tree variation could interfere with the study on radial variation (McKimmy, 1959; Lantican and Hughes, 1973; Quanci, 1988; Zobel and van Buijtenen, 1989), the variation among trees needs to be considered before the radial variation within trees is studied. Therefore, there are two objectives for this study: first was to identify the source and extent of variation in measured wood properties among and within trees and then to quantify the radial variation of these wood properties at two heights.

Materials and Methods

Materials

Study materials were collected from a mixed stand of red alder (*Alnus rubra* Bong.) and big-leaf maple (*Acer macrophyllum*) located in McDonald-Dunn Forest of Oregon State University, Oregon. Six 40-year-old trees with similar diameters (33 ± 3 cm) at breast height, fairly straight stems and without visual defects were selected in order to minimize tree-to-tree variation. Lean direction was marked and lean angle from vertical was measured for each tree. The lean of each individual tree was 5°, 5°, 2°, 5°, 5°, and 14° for trees 1 to 6, respectively. From each tree, two 25-cm thick disks were cut at two heights: one from breast height (1.3 m) and another one from an upper height (averaging 5.9 m) below the first fork or large branch . A detailed description of the sampling site and field records of sample trees are presented in Appendix E.

Sample preparation

Within 24 hours of harvest, a 2.5-cm wide slab was cut from each disk along a diameter from the lower to upper side of the lean in the tree. All slabs were dried in a kiln at 65°C with an 8°C wet-bulb depression until the target moisture content of 12% was reached. Then, the slabs were stored in a room with a 12% equilibrium moisture content.

Each dried slab was divided at the pith into the lower and upper sides. Then a series of radial samples, centering on growth rings 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 23, 26, 30 and 34 at breast height and 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 25 and 30 at the upper height, were cut from both sides of each disk. Each ring number is actually the cambial age of each sample. Aggregate ray tissue was avoided when samples were cut because of its sporadic distribution (Noskowiak, 1978). Sample size was 0.51 cm (0.20 inches) in radial direction, 0.64 cm (0.25 inches) in tangential direction, and 8.26 cm (3.25 inches) along the grain.

Measurements

The specific gravity of each sample was determined on the basis of sample dimensions (± 0.01 mm) at 12% moisture content and ovendry weight (± 0.001 grams). Each sample was then cut into pieces for the measurements of anatomical characteristics. Average fiber length and vessel diameter were obtained by measuring 80 individual fibers and vessels from each sample. Percentages of cross sectional area occupied by fibers, vessels, and ray tissue for each sample were averages of the measurements on four microtome sections from the same block of wood. The details of the techniques used to measure the anatomical properties are given in Chapter II.

Analysis of variance

An analysis of variance (ANOVA) was performed to evaluate the variation in wood properties among trees (tree effect), between the two heights (height effect), and between lower and upper sides (lean effect). The following general linear model (SAS institute, 1988) was applied:

$$Y_{ijk} = \mu + \alpha_i + \beta_{j(i)} + \gamma_{k(i)} + \alpha\beta_{ij(i)} + \alpha\gamma_{ik(i)} + \beta\gamma_{jk(i)} + \alpha\beta\gamma_{ijk(i)} + \epsilon_{ijkn} \quad \text{(III-1)}$$

Where

Y = wood property of interest,

μ = population mean,

α_i = variation associated with between-tree effect,

$\beta_{j(i)}$ = variation associated with height effect within trees,

$\gamma_{k(i)}$ = variation associated with lean effect within trees,

$\alpha\beta_{ij}$ = interaction between tree and height effects,

$\alpha\gamma_{ik}$ = interaction between tree and lean effects,

$\beta\gamma_{jk(i)}$ = interaction between height and lean effects within trees,

$\alpha\beta\gamma_{ijk}$ = interaction among tree, height, and lean effects,

ϵ_{ijkn} = random error.

To prevent an unbalanced effect of cambial ages between two heights, the same number of samples designated to similar growth rings for both heights (2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 26, 30 for breast height and 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 25, 30 for the upper height) were used in the analysis. Details of SAS procedures of ANOVA for testing the significance of tree, height, and lean effects are presented in Appendix F.

Regression analysis

The purpose of the regression analysis was to quantitatively describe the radial profiles of each wood property as a function of cambial age for each height. Before the regression analysis, a preliminary analysis was conducted to check if the data from six trees can be pooled. If tree effect (T) and its interaction with age (X) and indicator variable (Z) are not significant at the 0.05 level, regression analyses would be conducted on pooled data across six trees. Otherwise, regression analyses would be done separately for each tree. Details of SAS procedures for the preliminary analysis are presented in Appendix G.

Simple linear regression was used when the relationship between a wood property and cambial age followed a linear pattern. If the radial profile visually and statistically fits a simple linear model, no transition from juvenile to mature wood can be detected.

A piecewise linear regression model (Neter et al., 1989) fits two or more linear regression models into a single regression model by indicator variables. An indicator variable is qualitative and is composed of two classes, such as juvenile and mature zones. This model is also called segmented regression (Bendtsen and Senft, 1986; Quanci, 1988; Abdel-Gadir and Krahmer, 1993) and can be used to estimate the age of the demarcation from juvenile to mature wood. The statistical model below shows how an indicator variable (Z) is used to fit a two-segment linear regression:

$$Y_i = \beta_o + \beta_1 X_i + \beta_2 Z + \beta_3 X_i Z + \epsilon_i \qquad \text{(III-2)}$$

Where

Y_i = Wood property of interest,

X_i = Cambial age, independent variable,

X' = The cambial age common to both segments of the regression line,

$Z = 1$ if $X_i > X'$, otherwise

$Z = 0$

β_0, β_1, β_2, β_3 = regression coefficients,

ϵ = random error.

When $Z = 0$, $E\{Y\} = \beta_o + \beta_1 X$ (III-3)

represents the juvenile wood segment of regression line.

When $Z = 1$, $E\{Y\} = \beta_o + \beta_1 X + \beta_2 + \beta_3 X$

$$= (\beta_o + \beta_2) + (\beta_1 + \beta_3)X \qquad \text{(III-4)}$$

represents the mature wood segment of the regression line.

Letting $X' = X_1, X_2, \ldots \ldots X_n$, the cambial age from pith to bark, the two-piecewise regression equation with best fit was selected to have significant regression coefficients (0.05 level) and the maximum determination coefficient (or minimum mean square of error). The X' for this model is considered as the point at which wood changes from juvenile to mature.

When three segments in the radial profile are involved, three-segment linear regression is straightforward (Neter et al., 1989). The second indicator variable (Z_2) needs to be added to the model.

$$Y_i = \beta_o + \beta_1 X_i + \beta_2 Z_1 + \beta_3 Z_2 + \beta_4 X_i Z_1 + \beta_5 X_i Z_2 + \epsilon_i \qquad \text{(III-5)}$$

Where

X_i = Cambial age, independent variable,

X' = The cambial age common to the first and the second segments of the regression,

$Z_1 = 1$ if $X'' \geq X_i > X'$, otherwise

$Z_1 = 0$,

X'' = The cambial age common to the second and the third segments of the regression,

$Z_2 = 1$ if $X_i > X''$, otherwise

$Z_2 = 0$

The computation procedure is similar to that in the two-segment linear regression.

Results

Analysis of variance (ANOVA)

Wood properties obtained by averaging the values from each height and each side are shown in Table III.1. The results of analysis of variance for each measured wood property are shown in Table III.2.

Table III.1 Means of measured anatomical properties and specific gravity at two heights (upper height and breast height) and two sides (lower and upper sides) of six red alder trees.

		Sample size	Ring width (mm)	Fiber length (mm)	Vessel diameter (μm)	Fiber volume (%)	Vessel volume (%)	Ray volume (%)	Specific gravity
Upper height		144	3.1	1.05	57.4	60.8	23.5	13.4	0.479
Breast height		144	3.3	1.08	61.2	58.9	27.4	14.3	0.462
Lower side		144	3.2	1.08	58.0	60.0	24.6	13.8	0.470
Upper side		144	3.4	1.08	60.1	59.6	24.9	13.9	0.469
Upper height	lower	72	3.0	1.05	56.4	61.1	23.3	3.3	0.480
	upper	72	3.2	1.05	58.3	60.6	23.7	13.4	0.478
Breast height	lower	72	3.2	1.09	60.1	58.7	26.7	14.3	0.460
	upper	72	3.4	1.08	62.4	59.1	27.9	14.2	0.463
Overall mean		288	3.2	1.07	59.4	59.8	25.6	13.9	0.471

Table III.2 Results (P-values) of analysis of variance for anatomical characteristics and specific gravity among and within red alder trees.

Source of variance	DF	Ring width	Fiber length	Vessel diameter	Percent fiber	Percent vessel	Percent ray	Specific gravity
Tree	5	0.57	0.15	**0.001**	0.51	0.14	0.64	**0.009**
Height(tree)	1	0.23	0.11	**0.04**	0.13	**0.025**	0.22	0.06
Lean(tree)	1	0.20	0.16	0.15	0.53	0.55	0.95	0.41
Height * Lean (tree)	5	0.97	0.24	0.94	0.62	0.75	0.36	0.64

Vessel diameter and specific gravity had significant variation among trees at the 0.01 level. There is no significant variation among trees for other anatomical characteristics. Vessel diameter varied from 43 to 71 μm among six trees. Specific gravity varied from 0.446 to 0.509 among six trees. Based on the results of the LSD (Least significant difference, Steel and Torrie, 1980), there were three homogeneous groups for vessel diameter among six trees: (A) trees 4 and 6 had smallest vessel diameter; (B) trees 1, 2, and 3 had the largest; and (C) tree 5 had a vessel diameter between (A) and (B). Similarly, six trees were classified according to LSD into four homogeneous groups for specific gravity: (A) tree 2 had a specific gravity of 0.446; (B) trees 1, 3, and 4 had specific gravity from 0.460 to 0.467; (C) tree 5 had a specific gravity of 0.482; and (D) tree 6 had a specific gravity of 0.509.

Within trees, there are significant differences in vessel diameter and vessel proportion between two heights (Table III.2). The difference in properties between lower and upper sides is not significant for any of the measured characteristics. Nor was the interaction between height and lean effects significant for any measured characteristic.

Analysis of radial profiles

The results of preliminary analysis in Appendix G indicated that data from six tree can be pooled for the regression analysis for most of wood properties at each height except for vessel diameter and specific gravity. The radial profiles of vessel diameter and specific gravity were analyzed for each tree separately.

Fiber length

Fiber length shows a pronounced change with cambial age (Figure III.1). Fiber length at both heights tends to increase across radius. Fibers at breast height are slightly longer than at the upper height in the early years, but this difference disappears after about 20 years.

The radial profile of fiber length could be described by a two-segment regression model and the demarcation between juvenile and mature wood determined from this model. Table III.3 shows an example of two-segment linear regression analysis for fiber length on cambial age at the upper height across the six trees. All three sets of regression coefficients in the table meet the criteria for accepting the regression function (coefficients significant at 0.05% level), but only the regression function with the greatest determination coefficient (or minimum error mean square) was selected to define the demarcation between juvenile and mature woods. This occurred at a cambial age of 8 years as a boundary between juvenile and mature wood at the upper height. Similarly, a cambial age of 10 years was found to be the demarcation between juvenile and mature wood for fiber length at breast height (Table III.4). Figure III.2 displays the regression plots of fiber length against cambial age for both heights.

Vessel diameter

The average vessel diameter increases from pith to bark (Figure III.3) at both heights. The vessel diameter is slightly greater at breast height than at the upper

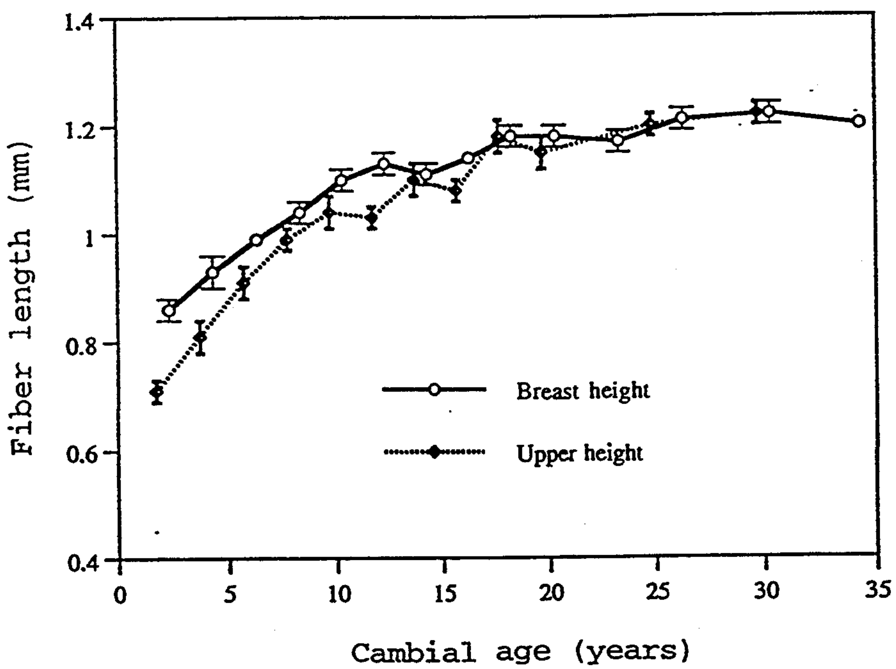
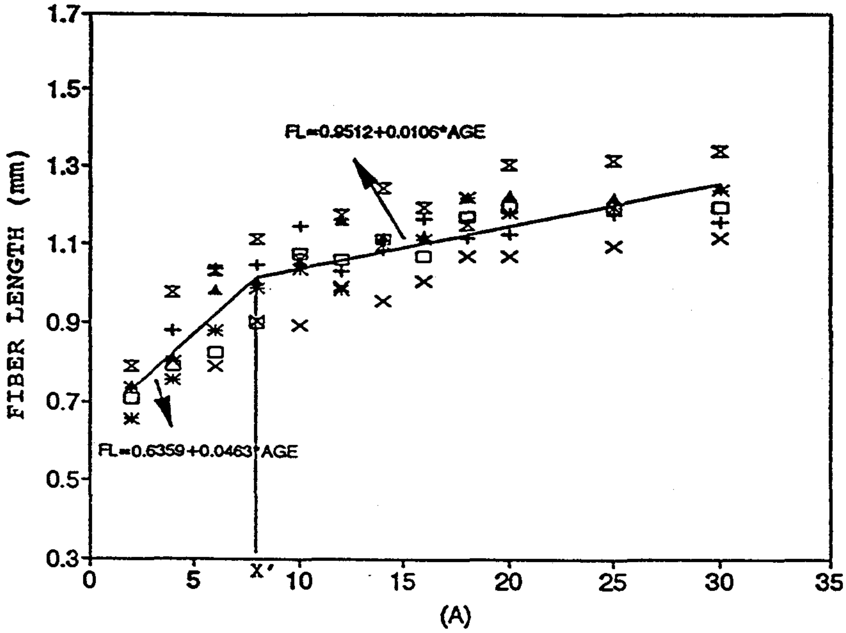


Figure III.1 Average radial changes of fiber length at breast height and upper height for six red alder trees. Standard error bars show the variation among trees.



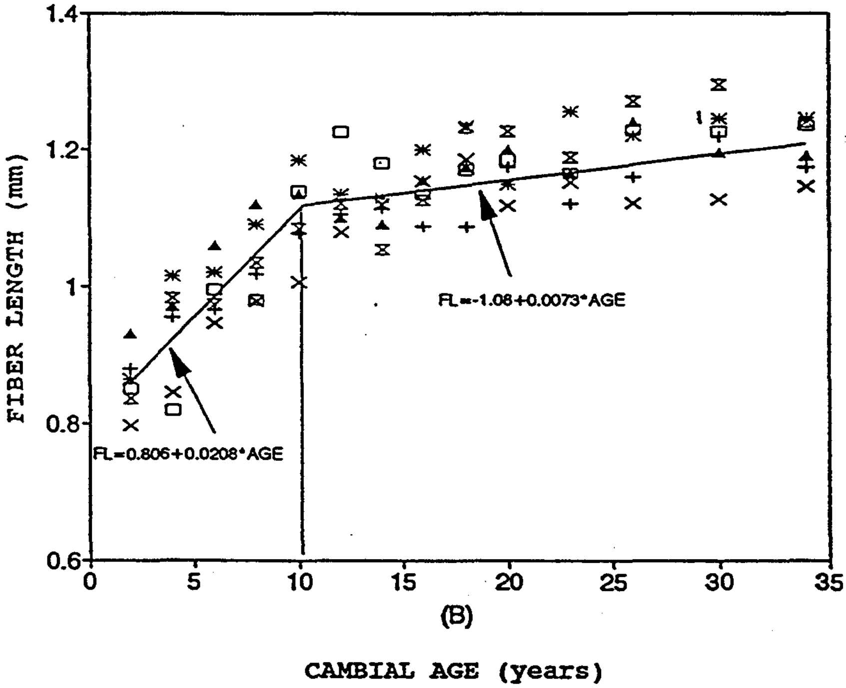


Figure III.2 An example of fitted two-segment regression model of fiber length vs. cambial age at upper height (A) and breast height (B). Symbols represent different trees.

Table III.3 Results of two-segment regression analyses of fiber length against cambial age, corresponding to three demarcation ages around transition zone at upper height. The highlighted is the best accepted regression function to determine transition from juvenile to mature wood.

Demarcation Age	Regression coefficients				
	β_1	β_2	β_3	R^2	MSE
6	0.0527*	0.3359*	-0.0426*	74.00+	0.00789
8	**0.0463***	**0.3411***	**-0.0374***	**75.25+**	**0.00776**
10	0.0408*	0.3381*	-0.0328*	74.20+	0.00787

* Coefficient significant at 0.05% level.
\+ Regression model is significant at 0.05 level.height

Table III.4 Results of the piecewise regression analyses for fiber length on cambial age at two heights. X′ is the demarcation age which fits both the juvenile wood segment ($Y=\beta_0 + \beta_1 X$) and the mature wood segment [$Y=(\beta_0 + \beta_2) + (\beta_1 + \beta_3)X$].

Regression parameter	Fiber length	
	Breast height	Upper height
β_0	0.806	0.636
β_1	0.0298	0.0463
β_2	0.2726	0.3411
β_3	-0.0255	-0.0374
X′	10	8
R^2	0.73	0.75
MSE	0.0011	0.00776

along the entire radius. A rapid increase in vessel diameter for the first few years was followed by a leveling off.

The great variation in vessel diameter among trees prevented pooling the data from the six trees together in the regression analysis for this anatomical property. The piecewise regression analyses were conducted on each tree for each height. The regression results (Table III.5) show that vessel diameter at breast height had a demarcation age from 8 to 12 years, varying among trees. At the upper height, a demarcation age of vessel diameter was determined to be 12 years for tree 1 and 8 years for trees 2, 5, but could not be determined for trees 3, 4, 6.

Tissue proportions

The percentage of fibers at breast height decreases, increases, and then decreases again as cambial age increases (Figure III.5). Based on the results of a three-segment regression analysis (Table III.6), 8 years and 16 years at breast height were determined to be the two turning points for the radial profile of percentage of fibers (Figure III.4, A). The percentage of fibers at the upper height varied considerably from pith to bark, but generally decreased from pith to bark. Only a simple linear model could fit the data (Figure III.4, B).

The percentage of vessels also follows a three-segment radial trend, but the trend is the reverse of that for the percentage of fibers (Figure III.6). When the percentage of vessels increases, the percentage of fibers will decrease. The results of piecewise regression analysis show the same turning points at ages of 8 and 16 years for percentage of vessels as were determined for percentage of fibers at breast height (Table III.6). Only a simple linear regression model was fitted for percentage of vessels at upper height.

The percentage of ray tissue shows little change from pith to bark regardless of height, varying between 13% and 16% from pith to bark (Figure III.7).

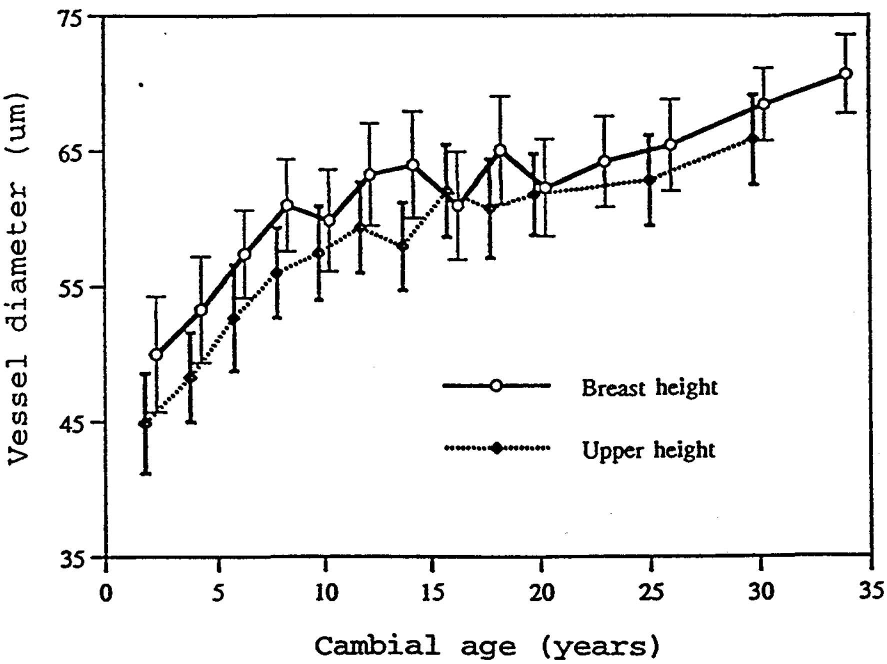
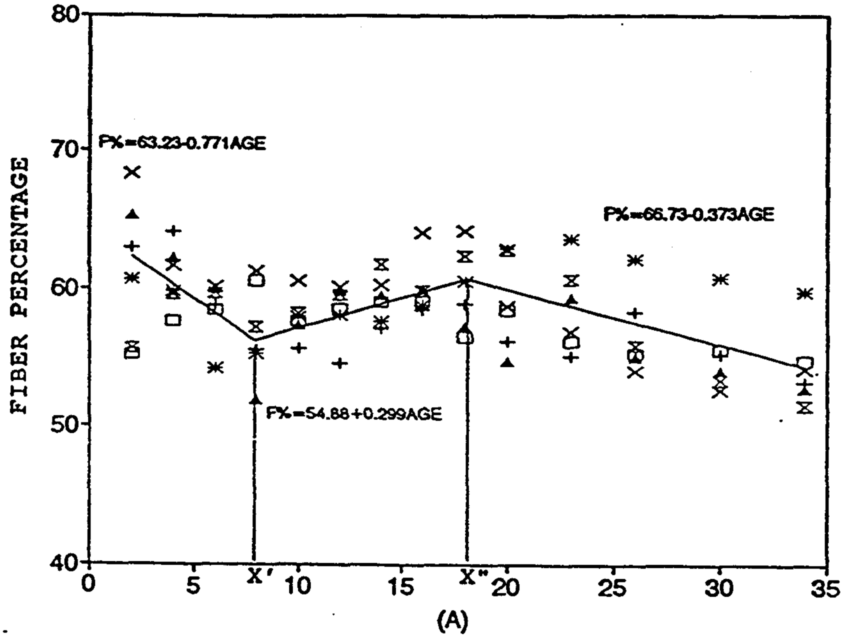


Figure III.3 Radial changes in vessel diameter at breast height and upper height for six red alder trees. Standard error bars show the variation among trees.

Table III.5 Results of the linear piecewise regression analyses for vessel diameter at two heights. X′ is the demarcation age which fits both the juvenile wood segment ($Y=\beta_0 + \beta_1 X$) and the mature wood segment [$Y=(\beta_0 + \beta_2) + (\beta_1 + \beta_3)X$].

	VESSEL DIAMETER									
	Breast height						Upper height			
Parameter	Tree 1	Tree 2	Tree 3	Tree 4	Tree 5	Tree 6	Tree 1	Tree 2	Tree 5	Trees 3,4,6
β_0	43.75	56.55	48.2	45.12	38.33	18.2	43.21	53.7	38.0	Model
β_1	1.79	2.25	1.55	1.98	3.875	3.73	1.93	3.1	3.38	not
β_2	16.86	11.8	7.16	8.97	24.78	18.07	22.98	10.4	19.21	fit
β_3	-1.41	-1.88	-0.99	-1.21	-3.60	-3.23	-1.86	-2.7	-3.02	
X′	10	10	12	10	8	8	12	8	8	
R^2	0.91	0.84	0.84	0.76	0.78	0.88	0.96	0.83	0.91	
MSE	6.50	7.35	10.7	19.2	15.29	9.10	3.18	7.77	5.38	



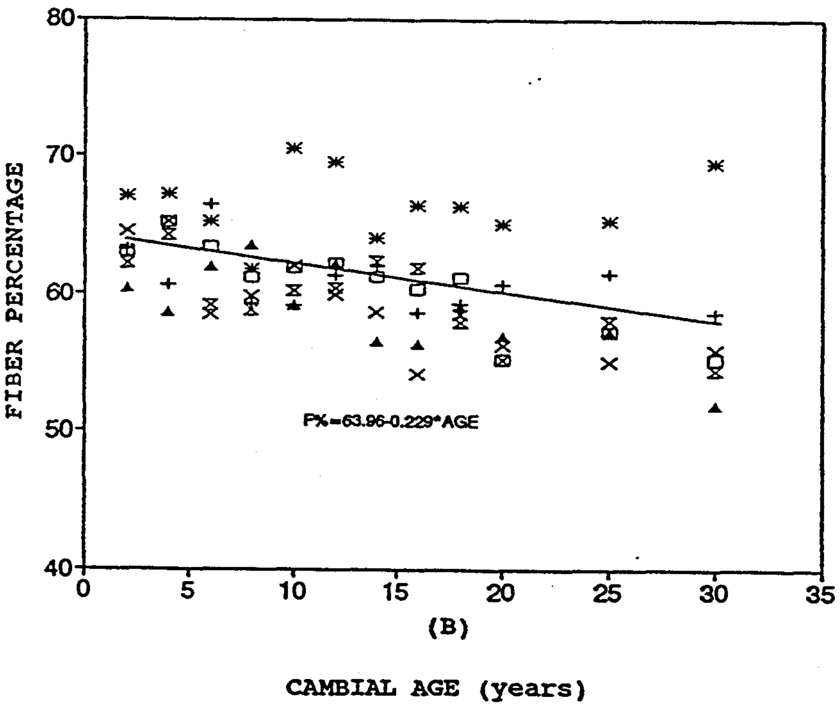


Figure III.4 An example of fitted regression models of fiber proportion vs. cambial age. (A) fitting a three-segment linear model for breast height; (B) fitting a simple linear model for upper height.

Table III.6 Results of the linear piecewise regression analyses of percentage of fibers and percentage of vessels vs. cambial age. Regression model is a three-segment function* at breast height and a simple linear function** at upper height.

Regression parameter	Breast height		Upper height	
	Fiber% (n=167)	Vessel% (n=167)	Fiber % (n=144)	Vessel % (n=144)
β_o	63.23	20.141	63.96	20.53
β_1	-0.771	0.975	-0.229	0.221
β_2	-8.350	9.419	Not applicable to simple linear function	
β_3	11.848	-11.805		
β_4	1.070	-1.248		
β_5	-0.6716	0.654		
X'	8	8		
X"	16	16		
R^2	0.23	0.21	0.15	0.18
MSE	12.78	16.59	17.06	13.21

* When age $\leq$ X', $Y=\beta_o+\beta_1X$; When X"$\geq$age >X', $Y=(\beta_o+\beta_2) + (\beta_1+\beta_4)X$; When age > X", $Y=(\beta_o+\beta_2+\beta_3) + (\beta_1+\beta_4+\beta_5)X$.
** Simple linear function $Y=\beta_o+\beta_1X$.

Specific gravity

The specific gravity is nearly uniform in the radial direction (Figure III.8). No relationship between specific gravity and cambial age was found from regression analyses for any of the six trees.

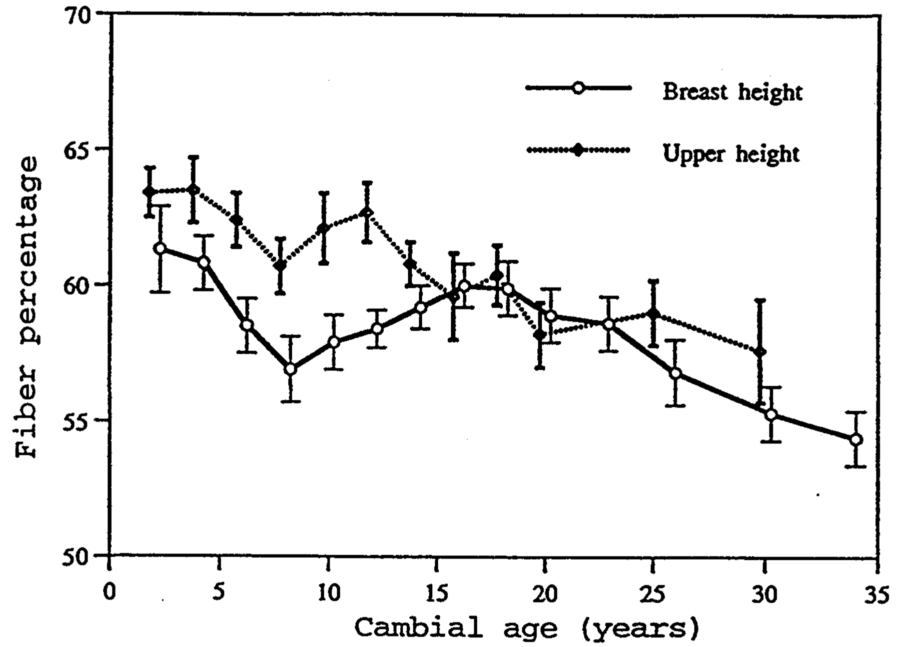


Figure III.5 Radial changes of percentage of fibers at breast height and upper height for six red alder trees. Standard error bars show the variation among trees.

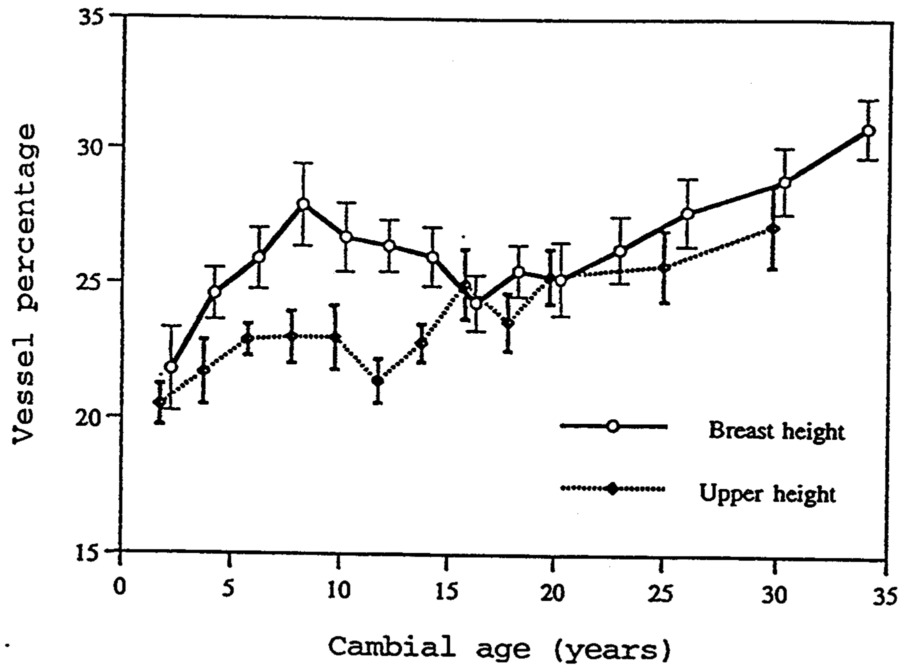


Figure III.6 Radial changes of percentage of vessels at breast height and upper height for six red alder trees. Standard error bars show the variation among trees.

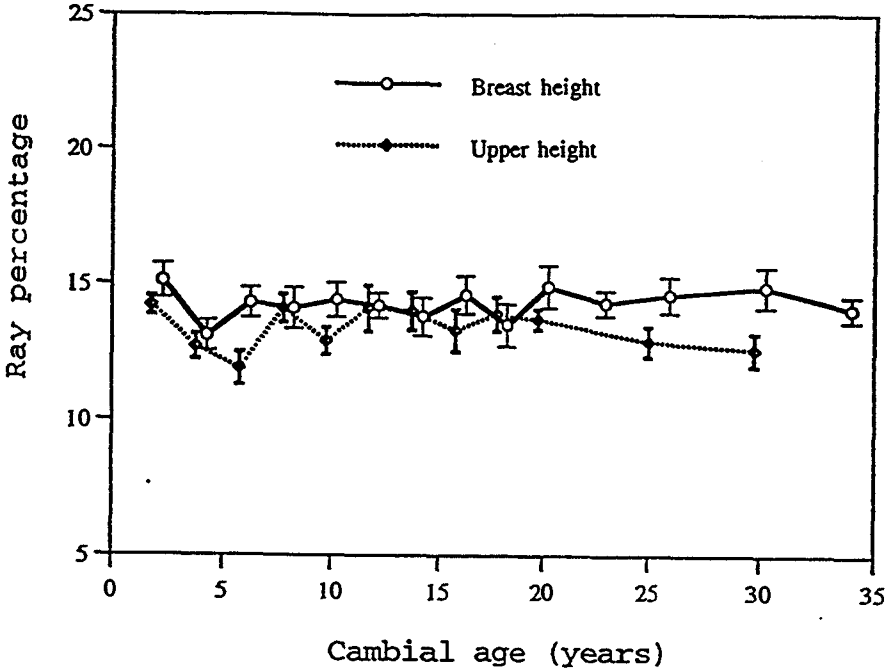


Figure III.7 Radial changes of percentage of ray tissues at breast height and upper height for six red alder trees. Standard error bars show the variation among trees.

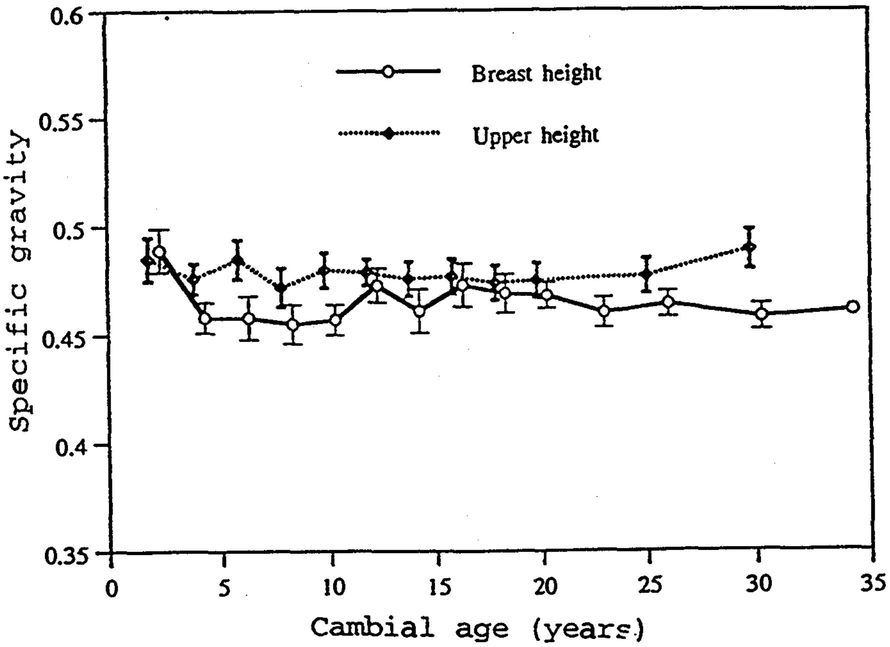


Figure III.8 Radial changes of specific gravity at breast height and upper height for six red alder trees. Standard error bar show the variation among trees.

Discussion

Variation among trees

The extent of variation among trees was not the same for different wood characteristics. Vessel diameter and specific gravity are the two features that vary considerably among trees. Other wood characteristics such as fiber length and percentages of fiber, vessel and ray tissue show little variation among trees. These characteristics are, in fact, quite uniform from tree to tree.

There is no clear explanation for the high inter-tree variation in vessel diameter. It does not seem to be associated with growth rate because there is no significant difference in growth ring width among trees. Genetic variation could be one of the variation sources.

A large variation in specific gravity among trees is not uncommon for diffuse-porous species. Similar results have been reported for *Populus* spp. (Valentine, 1962 and Peszlen, 1993), *Eucalyptus* spp. (Taylor, 1973), and *Platanus occidentalis* (Land and Lee, 1981). Highly significant variation in specific gravity among trees in a red alder stand was also reported by Harrington and DeBell (1980). One contribution to this variation may be the genetic variation among trees. Also, the small amount of radial variation makes the variation among trees appear greater.

The variability among trees may make studies of wood properties difficult, but it also makes possible the selection of trees for better quality.

Height effect

Vessel diameter and vessel proportion are higher at breast height than at the upper height, which is consistent with growth ring width. The differences in vessel diameter and vessel proportion between two heights may not have a significant effect on the use of wood, but they may be important to the tree's biology influencing factors such as water transport to the crown.

The significant differences in vessel proportions between two heights mainly resulted in the juvenile wood zone. As the age increases, the variation in tissue proportions with height becomes less pronounced and mature wood is similar in tissue proportions at the two heights.

For most diffuse-porous species, specific gravity does not change with height (Okkonen et al., 1972). However, red alder in this study and some diffuse-porous species (Fukazawa, 1984) were found to have a greater specific gravity at an upper level than at a lower level. In this study, slightly higher fiber proportion but lower vessel proportions at the upper height may explain the difference in specific gravity between the two heights.

This study found only minor changes in various wood properties with height, consistent with results synthesized by Zobel and van Buijtenen (1989). Although variations in some wood properties between the two heights were statistically significant, practically these variations could be ignored because they were trivial in value, compared to the variation among trees and in the radial direction. Breast height sampling should be adequate to predict upper height values, especially when sampling from mature wood.

Lean effect

In agreement with Leney et al. (1978), no tension wood was observed in the sample trees. Tension wood would result in gelatinous fibers on the upper side of the lean. Because the effect of lean was small, the degree of lean observed in this study should not affect the use of the wood. Lowell and Krahmer (1993) found similar results for specific gravity as a function of lean. In addition, lean effect on wood properties is independent of height effect because the interaction effect between the height and the lean is not statistically significant for all measured wood properties.

Radial variation

The patterns of radial variation are not the same for all wood characteristics. Whether there is a core of juvenile wood depends on which wood characteristic is used to define the transition from juvenile to mature wood.

The radial variation pattern for fiber length falls within the Group I variation described by Panshin and deZeeuw (1980), clearly showing the marked transition from juvenile to mature wood at both heights. A similar conclusion was drawn from studies for other hardwoods (Dinwoodie, 1961; Bendtsen, 1978; Bendtsen and Senft, 1986; Zobel and van Buijtenen, 1989; Peszlen, 1993). Because fiber length most likely has an inverse relationship with microfibril angle (Wardrop and Preston, 1950; Wheeler, 1987), it is expected that microfibril angle in red alder would decrease from pith to bark.

A radial trend of general increase from pith to bark for vessel diameter in red alder agrees with many studies for hardwoods (Fukazawa and Ohtani, 1982; McKimm and Ilic, 1987; Butterfield et al., 1993; Peszlen, 1993). Based on these and other studies on fiber length and vessel diameter, it appears that fiber length and vessel diameter are the two dependable anatomical features showing a juvenile-mature pattern of variation in most hardwoods. In this study, fiber length and vessel diameter showed a clear boundary around 10 years from juvenile to mature wood.

According to the radial profiles of tissue proportions, however, no definite pattern of radial variation or juvenile/mature wood zone could be defined in red alder. Why fiber and vessel proportions in red alder followed a three-segment radial variation was not understood.

Uniformity in specific gravity from pith to bark is a special feature of the species because the results show that red alder wood is not characterized by a low or high specific gravity core. Raw material from red alder of uniform specific gravity is desirable for composites and pulp production. Variable size and age in log loads is not a problem as far as the specific gravity of the raw material is concerned. In addition, stand management of red alder to increase growth rate will not cause an undesirable low density 'juvenile' core.

Conclusions

Variation between two heights and between lower and upper sides of the lean in the tree is practically negligible for all measured anatomical characteristics and specific gravity. The wood of red alder is very uniform with respect to specific gravity in the radial direction, but the wood near the pith has shorter fibers, smaller vessels, a higher percentage of fibers and a lower percentage of vessels than the outer wood. The age of demarcation defined by fiber length and vessel diameter between juvenile and mature wood is from 8 to 12 years. There is significant variation in specific gravity and vessel diameter among six trees.

Further research is needed to determine how environmental and genetic factors influence the wood of red alder.

CHAPTER IV

VARIATION OF ANATOMY AND SPECIFIC GRAVITY OF WOOD IN OREGON WHITE OAK (*Quercus garryana* Dougl.)

Abstract

Six Oregon white oak (*Quercus garryana* Dougl.) trees were sampled from a mixed stand of Oregon white oak and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) in the Coast Range of Western Oregon. Fiber length, vessel diameter, tissue proportions, and specific gravity were measured on samples across the diameter at two heights. Variations between trees and within trees were analyzed for each wood characteristic with special reference to the radial variation from pith to bark.

The analysis of variance indicated that variation between trees, between the two heights, and between the lower and upper sides was not significant for most measured wood characteristics except statistically differences in vessel proportion and specific gravity between two heights. However, there is significant variation along the radius (from 2 to 48 years) in fiber length (from 1.02 to 1.24 mm), vessel diameter (from 0.17 to 0.27 mm), percentages of fibers (from 64 to 43%) and vessels (from 10 to 31%). The profiles of these anatomical characteristics showed a demarcation age between the juvenile wood and the mature wood of 10 to 26 years, depending on the characteristic. The percentage of ray tissue (around 14%) showed no definite pattern of change across the radius. Specific gravity tends to decrease linearly from pith to bark (from

0.872 to 0.642). Each wood characteristic showed a similar radial trends at both the upper height and breast height. The results of this study may be used both for estimating wood and fiber quality and for tree improvement programs.

Introduction

Recently the importance of under-utilized hardwood resources has increased due to diminishing resources of and increasing demand for old-growth softwoods. However, there is very limited information about the variation in wood properties of many hardwood species. This is the second part of the study on the variation in wood properties of two important western hardwoods. A previous paper (Chapter III) dealt with red alder (*Alnus rubra* Bong.), a diffuse-porous species. In this chapter, the variation in wood properties of a ring-porous species, Oregon white oak (*Quercus garryana* Dougl.), is studied.

The degree to which wood properties vary is a major concern in the utilization of wood. For a single species, wood properties vary among trees (inter-tree) and within a tree (intra-tree). A major portion of the variability exists within trees (Kandeel and Bensend, 1969; Panshin and deZeeuw, 1980; Zobel and van Buijtenen, 1989). Larson (1967) stated: "more variability in wood characteristics exists within a single tree than among trees growing on the same site or between trees growing on different sites."

The changes in wood properties from pith to bark are most often studied. Due to a large variation in the radial direction, a tree stem can usually be classified into two concentric zones, juvenile wood and mature wood (Panshin and deZeeuw, 1980). This classification applies to both softwoods and hardwoods; the juvenile wood is usually of lower quality for structural uses, particularly in softwoods (Haygreen and Bowyer, 1989). Because of its impact on utilization, the juvenile wood and its characteristics in softwoods have been studied extensively (Bendtsen, 1978; Thomas, 1984; Krahmer, 1986; Bendtsen and Senft, 1986; Maloney, 1986).

However, the information about the variation in wood properties and the characteristics of juvenile wood in hardwoods is scarce and sometimes contradictory because of the diversity of hardwood species and lack of study. There are many species called white oak in the oak genus (*Quercus* spp.), but none of the studies on the variation in wood properties was specifically conducted on Oregon white oak. Among the studies on ring-porous hardwoods, Fukazawa (1984) found that specific gravity in three ring-porous hardwoods, including a species of oak (*Quercus mongolia*), showed a linear and curvilinear decrease in the radial direction, but the boundary between juvenile and mature wood could not be well delimited. Zhang et al. (1993) reported that there was a general decreasing trend, but no clear demarcation from pith to bark in specific gravity for European oaks (*Quercus petraea* and *Quercus robur*). Quanci (1988) concluded that there were no significant changes across radial profiles for modulus of rupture in bending, fiber length, and microfibril angle in white ash (*Fraxinus americana*). From a study on a number of hardwood species, both ring-porous and diffuse-porous, Taylor and Wooten (1973) found that vessel volume increases, fiber volume decreases, and ray volume remains constant with increasing age or height. Similar results about tissue proportion were reported for *Liquidamber styraciflua* (Ezell, 1979). Based on the above reports, a question arises whether there is juvenile wood in ring-porous species.

To substantiate the information on the wood variation and juvenile wood in hardwoods and to promote more and better use of Oregon white oak, the purposes of this study were to (1) analyze the variation of wood properties among and within trees; (2) characterize the radial variation in some wood anatomical properties and specific gravity at two heights; and (3) identify the demarcation between juvenile and mature wood if the transition exists.

Materials and Methods

Material collection

Six Oregon white oak trees (*Quercus garryana* Dougl.) were selected from an 80-year-old mixed stand of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and Oregon white oak in the McDonald-Dunn Forest of Oregon State University. Sample trees with similar diameters (29 ± 3 cm) at breast height and fairly straight stems without much lean and other evidence of defects were chosen in order to minimize tree-to-tree variation. The lean direction was marked and the lean angle from vertical was recorded for each tree. One section (disk) was removed from breast height (1.3 m) and a second from an upper height below the first fork (about 4.4 m) in each tree (second section in tree 5 was above the fork because of the low fork in this tree). All disks were 20 cm thick. Detailed descriptions of sampling site and trees are in the Appendix H.

Sample preparation

A 2.5-cm wide radial slab was cut from the mark of lean direction across the diameter of each disk. 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.

A radial series of samples was cut from each disk. Samples were centered on rings with cambial ages of 2, 4, 7, 10, 15, 20, 26, 32, 39, and 48 at breast height and 2, 4, 7, 10, 15, 20, 26, and 32 at upper height. In each case, samples were taken from both the lower and upper sides. The size of the sample was 0.51 cm (0.20 inches) in the radial direction, 0.64 cm (0.25 inches) in the tangential direction, and 8.26 cm (3.25 inches) along the grain. Although each sample was centered on one designated growth ring, some samples included several growth rings because of narrow rings in the outer portion of disks.

Measurements

The specific gravity of each sample was determined on the basis of sample dimensions (±0.01 mm) at 12% moisture content and ovendry weight (±0.001 g). Subsequently, every sample was broken down to pieces for the measurements of anatomical properties. Slides of the macerated fibers and the microtome sections from both the transverse and tangential surfaces were made for each sample. Eighty macerated fibers and 80 earlywood vessels from cross section were measured to determine the fiber length and tangential diameter of vessels for each sample. Four microtome sections of transverse surface were measured to obtain the growth ring width, latewood width, percentages of area occupied by fibers, vessels, and axial parenchyma for each sample. Percentage of ray tissue, including broad and narrow rays, was measured from four tangential sections. Details of the procedures for measuring anatomical characteristics are included in Chapter II. Latewood percentage (ratio of latewood width to ring width) was determined from cross sections in slides for each sample. The boundary of the abrupt change in the size of pores on transverse section was used to differentiate between earlywood and latewood.

Data analysis

A general linear model (same as Equation III-1 in chapter III) for analysis of variance (ANOVA) was used to evaluate the tree, height, lean effects and interaction between height and lean effects within trees for each wood characteristic. A piecewise linear regression analysis (same model as Equation III-2 in chapter III) was performed to characterize the radial variation of various wood properties along the radius. A preliminary analysis (Appendix G) was performed to ensure that data from six trees could be pooled for the regression analyses. For detailed procedures for ANOVA and regression analyses, the reader should refer to chapter III in this dissertation.

Results and Discussion

Analysis of variance

The mean properties and the results of paired t-test of properties between two heights are presented in Table IV.1. The percentage of vessels was 28% lower and specific gravity was 8% higher at breast height than at upper height.

P-value from the ANOVA are given in Table IV.2. Variation among trees was not statistically significant at the 0.05 level for any measured characteristics. Within trees, however, the percentage of vessels and specific gravity were significantly different between breast height and the upper height. Effects of the lean and the interaction between the height and the lean were not significant at 0.05 level for all measured characteristics.

Analysis of radial profiles

In this section, the average radial profile of each wood property is first presented and discussed. The results of preliminary analysis (Appendix G) showed that variation among trees was not statistically significant for

Table IV.1 Differences (T-test, paired by tree) in various wood characteristics between breast height and the upper height using samples with cambial ages of 2, 4, 7, 10, 15, 20, 26, and 32 for both heights.

Property	Means	Breast height (n=48)	Upper height (n=48)	Difference (%)
Fiber length(mm)	1.13	1.15	1.11	n.s.
Vessel diameter(mm)	0.217	0.222	0.212	n.s.
Fiber %	59.8	60.7	58.9	n.s.
Vessel %	15.5	12.9	18.0	- 28% *
Ray %	13.7	14.0	13.3	n.s.
Parenchyma %	11.1	12.4	9.8	-21%
Specific gravity	0.768	0.799	0.736	+ 8 *

* Significant different at 0.05 level.
n.s. Not significant at 0.05 level.
+/- Higher or lower from breast height to upper height.

any of the measured characteristics. Data from six trees can be pooled to conduct regression analysis for each wood property at each height. Results of regression analyses describing radial profiles are given in Table IV.3.

Ring width and latewood percentage

Average radial profiles of growth ring width and latewood percentage at breast height are shown in Figure IV.1. Growth rate in terms of annual ring width increased

Table III.2 Results (P-values) of analysis of variance for anatomical characteristics and specific gravity among and within Oregon white oak trees.

Source of variation	DF	Fiber length	Vessel Diameter	Percent fiber	Percent vessel	Percent ray	Percent parenchyma	Specific gravity
Tree	5	0.15	0.14	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

Table IV.3 Results of linear regression analyses for wood properties (Y) versus cambial age (X) at breast height and the upper height.

UPPER HEIGHT (n=48)

Regression parameters[a]	Fiber length	Vessel diameter	Fiber %	Vessel %	Ray[b] %	Parenchyma[b] %	Specific gravity[b]
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 two-segment regression function.

b Data only fit simple regression function.

Table IV.3 (continued)

BREAST HEIGHT (n=60)

Regression parameters[a]	Fiber length	Vessel diameter	Fiber %	Vessel %	Ray[c] %	Parenchyma[b] %	Specific gravity[b]
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			

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 two-segment regression function.

b Data only fit simple regression function.

c Property is not a function of age.

for the first 15 years and then decreased toward the bark. Average growth ring width was 2.2 mm ranging from 0.6 to 3.3 mm and latewood percentage was 63% varying from 34% to 71% at breast height for six trees. Growth ring width averaged 2.6 mm for the first 10 rings from the pith, 2.9 mm between the 11th and 20th rings, 2.3 mm from the 21st to 30th rings, and only 1.1 mm after 30 years. Both ring width and latewood percentage dropped rapidly after 25-30 years. Douglas-fir trees overtopping and dominating the oak trees after about 30 years may be responsible for the extremely slow growth of Oregon white oak trees during these late years.

Reduction of latewood width but fairly constant earlywood width (Figure IV.1) resulted in decreasing latewood percentage with age. Because earlywood width remained about constant, the latewood percentage changed from 70%, 69%, 64%, to 38% from pith to bark for the four periods of 0-10, 11-20, 21-30, and after 30 years of cambial age. A decrease in latewood percentage due to narrower ring width but constant earlywood width was also noted by other researchers (Panshin and deZeeuw, 1980; Zhang and Zhong, 1990; Zhang et al., 1993). The outer wood with narrow growth rings the near bark was mainly composed of earlywood pores, which results in a lower latewood percentage, fiber proportion, and specific gravity than the core wood near pith.

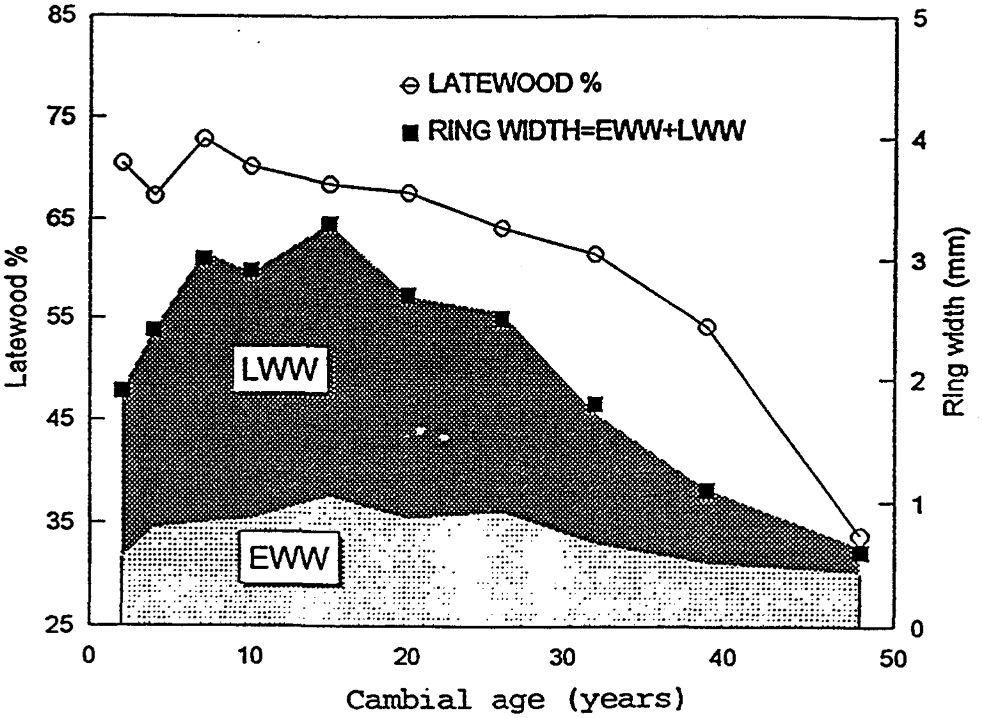


Figure IV.1 Radial profiles of ring width and percentage of latewood from pith to bark at breast height in Oregon white oak. Ring width is composed of earlywood width (EWW) and latewood width (LWW).

<u>Fiber length</u>

Fiber length increases rapidly during the early years, then levels off after about 10 or 15 years (Figure IV.2). This radial profile shows a transition pattern from juvenile to mature wood. Figure IV.3 shows an example of fitting the data (fiber length vs. cambial age) into a two-segment linear regression model. In this case, the demarcation age from juvenile to mature wood was determined to be 10 years at the upper height (R^2=0.74). Similarly the demarcation age was determined to be 15 years at breast height (R^2=0.44). The pattern of radial variation of fiber

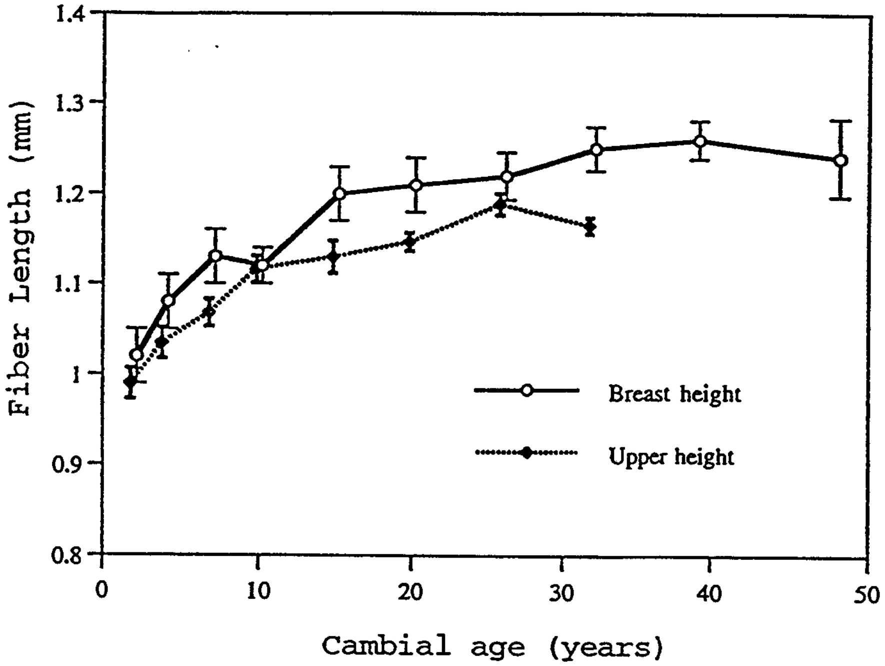


Figure IV.2 Average radial profiles of fiber length at breast height and the upper height of six Oregon white oak trees. Standard error bars show the variation among trees.

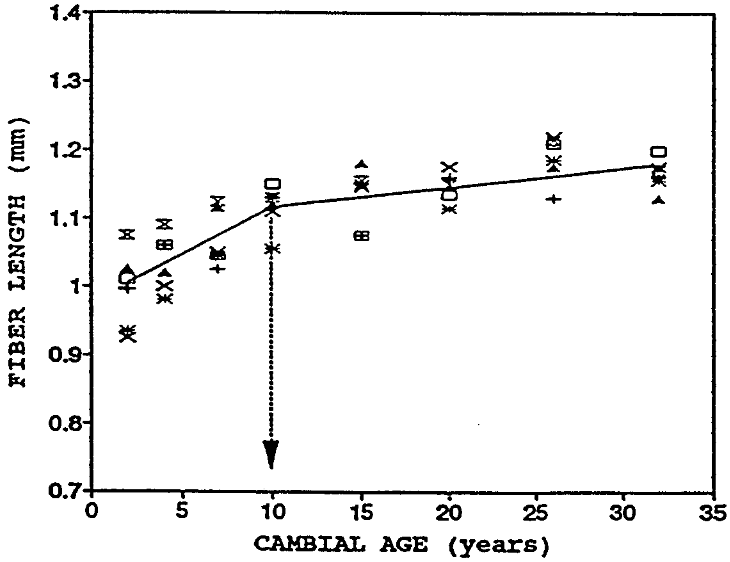


Figure IV.3 An example of fitting a piecewise regression model on the data of fiber length versus cambial age at upper height.

length in Oregon white oak is consistent with many ring-porous and diffuse-porous hardwoods, showing an apparent juvenile-mature transition in cell length from pith to bark (Dinwoodie, 1961; Panshin and deZeeuw, 1980; Robinson and Mize, 1987; Zobel and van Buijtenen, 1989; Helinska-Raczkowaska and Fabisiak, 1991; Peszlen, 1993).

Vessel diameter

Earlywood vessel diameter at both heights increases rapidly during the early years of growth and then levels off toward the bark (Figure IV.4). The results (Table IV.3) of the two-segment linear regression of vessel diameter on cambial age showed fairly high coefficients of determination at upper height (R^2=0.90) and breast height (R^2=0.71). This indicates that the effect of cambial age could adequately explain the variation for the vessel diameter at both heights. The demarcation age for vessel diameter between juvenile and mature wood was 15 years for both heights.

The pattern of radial variation in vessel diameter of Oregon white oak conforms to the results of previous studies for other ring-porous as well as diffuse-porous species (Taylor and Wooten, 1973; Fukazawa and Ohtani, 1982; Dodd, 1984; Furukawa and Hashizume, 1987; Peszlen, 1993; Butterfield et al., 1993). Vessel diameter appears

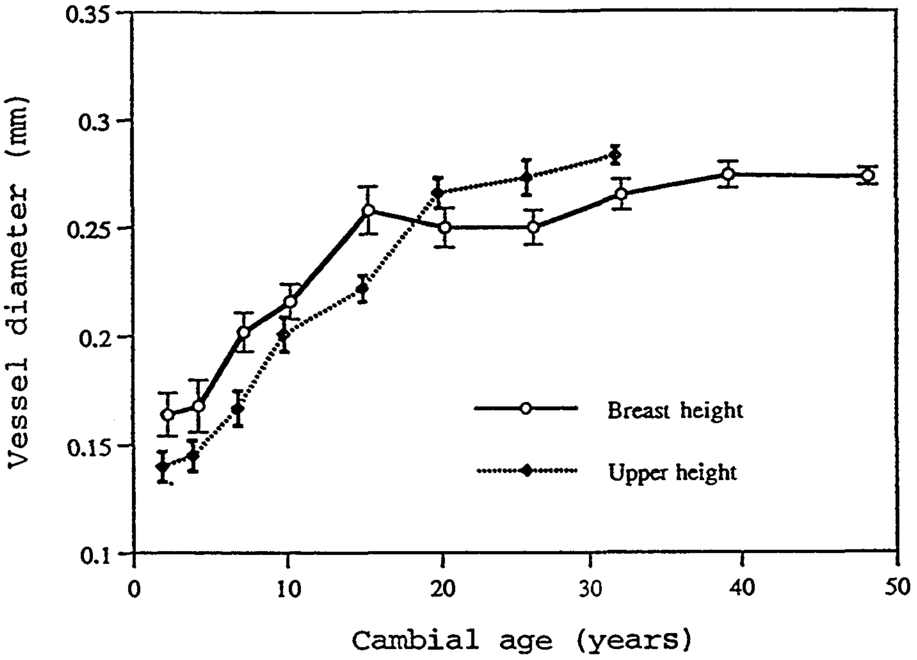


Figure IV.4 Average radial profiles of vessel diameter at breast height and the upper height of six Oregon white oak trees. Standard error bars show the variation among trees.

to be another anatomical feature, along with fiber length, that consistently shows a juvenile-mature transition from pith to bark in both ring-porous and diffuse-porous.

<u>Tissue proportions</u>

The percentages of fibers and vessels showed much variability from pith to bark at both heights. The percentage of fibers shows a slow decrease for the early years and then a rapid decrease toward bark (Figure IV.5). In contrast, the percentage of vessels shows an opposite trend, a slow increase for the first few years followed by a rapid increase at late years (Figure IV.6). The percentage of axial parenchyma shows nearly a linear increase at upper height and a small increase with fluctuations at breast height (Figure IV.7). The percentage of ray tissue remains about constant from pith to bark at both heights (Figure IV.8).

The demarcation age for percentage of fibers changing in the radial direction from a slow decrease to rapid decrease was about 15 years at both heights, with determination coefficients R^2=0.86 at breast height and R^2=0.76 at the upper height. The demarcation age for the percentage of vessels changing from a slow increase to a rapid increase was 26 years at breast height (R^2=0.91) and

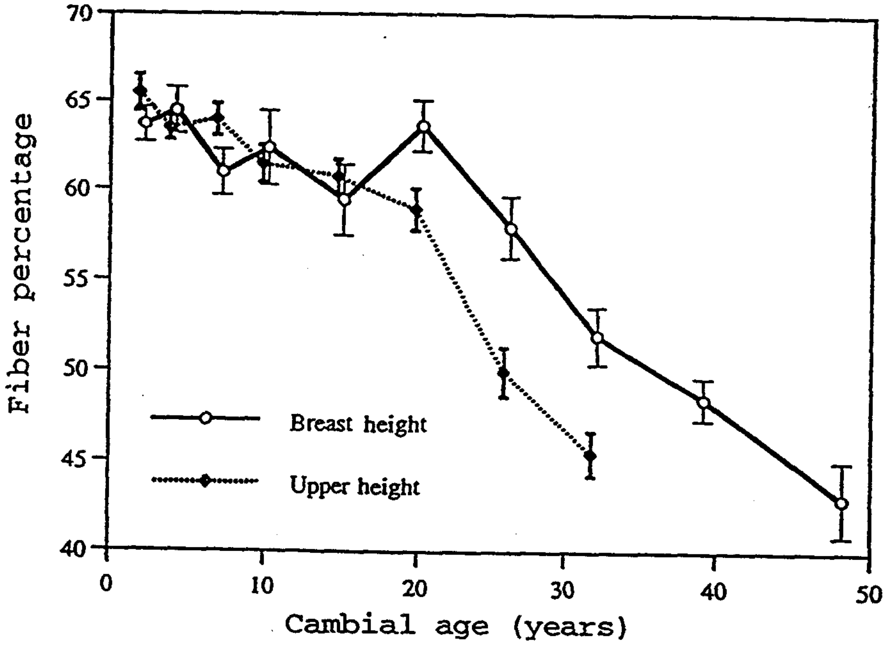


Figure IV.5 Average radial profiles of the percentage of fibers at breast height and the upper height of six Oregon white oak trees. Standard error bars show the variation among trees.

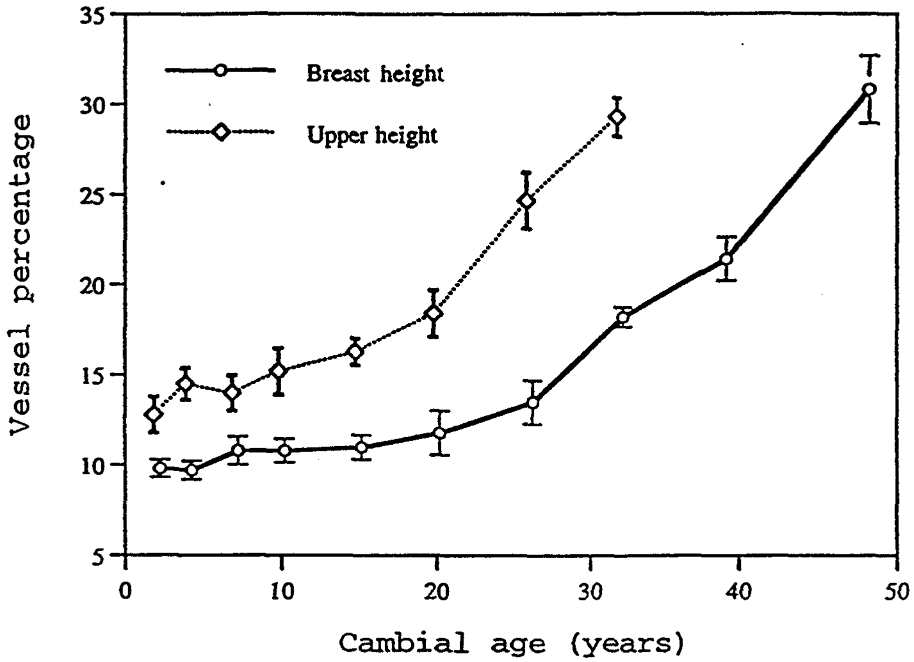


Figure IV.6 Average radial profiles of the percentage of vessels at breast height and the upper height of six Oregon white oak trees. Standard error bars show the variation among trees.

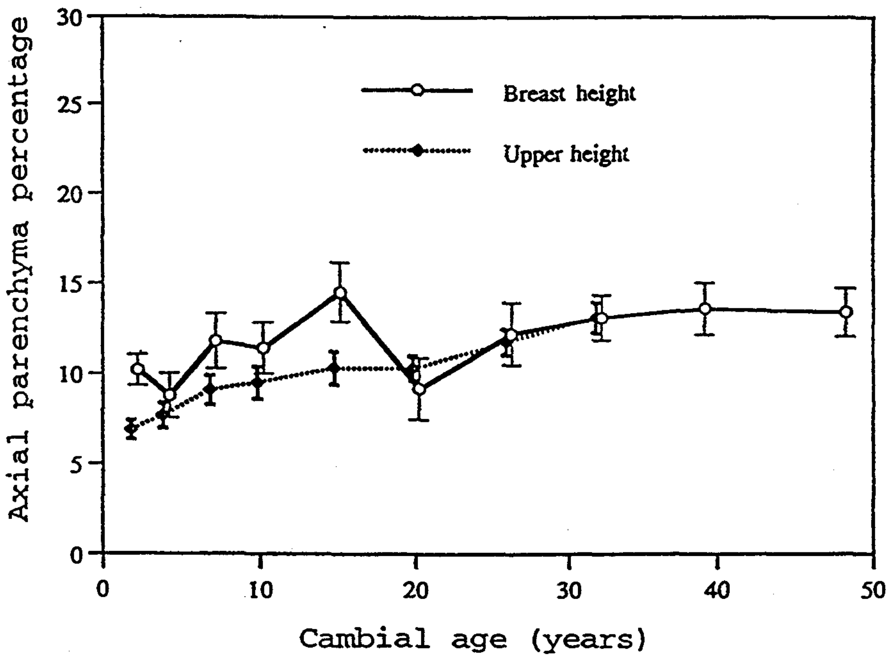


Figure IV.7 Average radial profiles of the percentage of axial parenchyma at breast height and the upper height of six Oregon white oak trees. Standard error bars show the variation among trees.

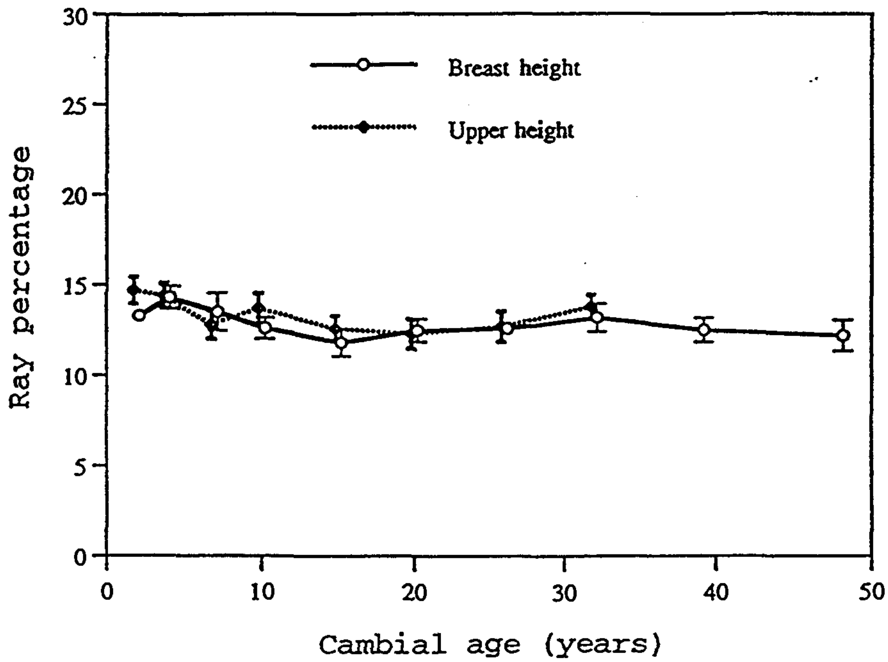


Figure IV.8 Average radial profiles of the percentage of ray at breast height and the upper height of six Oregon white oak trees. Standard error bars show the variation among trees.

20 years at the upper height (R^2=0.66). The percentage of ray tissue is not a function of cambial age at both heights ($R^2 \leq$ 0.08). The effect of cambial age could explain 51% of variation in axial parenchyma at upper height, but explain little (9%) at breast height.

The results of the analyses of radial profiles in tissue proportions in this study agreed well with the conclusions by Taylor and Wooten (1973) and Ezell (1979) that fiber and vessel proportions were more variable than parenchyma and ray proportions, and that the percentage of fibers increased with the decrease in percentage of vessels from pith to bark. With regard to the juvenile-mature profile, Bendtsen (1978) and Zobel and van Buijtenen (1989) indicated that wood properties are very variable within the juvenile zone and much more constant within the mature zone. However, the radial profiles of percentages of fibers and vessels in Oregon white oak showed a reverse trend, a minor change in the core wood and rapid change in the outer wood with cambial age. Large variability in fiber and vessel proportions with cambial age, especially during the period of slow growth, may have major effects on the yield of fibers when the loads of Oregon white oak logs with different size and age are used as raw material for fiber products. Constant value in ray tissue through the radius and relative small variation in the percentage of axial parenchyma from pith to bark may not affect the use of fiber and wood as far as their variation is concerned. In addition, broad rays are evenly spaced by several narrow rays on tangential surface. This pattern is also consistent from pith to bark. This means that the appearance of wood due to the broad rays on the tangential surface is consistent regardless of age.

Specific gravity

Specific gravity shows a nearly linear decline with cambial age (Figure IV.9), decreasing almost 27% from pith to bark at both heights. Wood from breast height has a higher specific gravity than that from the upper height at a given cambial age across the radius. The variation in specific gravity between two heights is due to the differences in the percentages of fibers and vessels between two heights.

The results of the simple linear regression analysis showed that the cambial age could account for most of the variation in specific gravity (76% at breast height and 65% at upper height). Obviously no demarcation age between juvenile and mature wood could be determined from the specific gravity. This radial variation in specific gravity of Oregon white oak falls in the Type III pattern

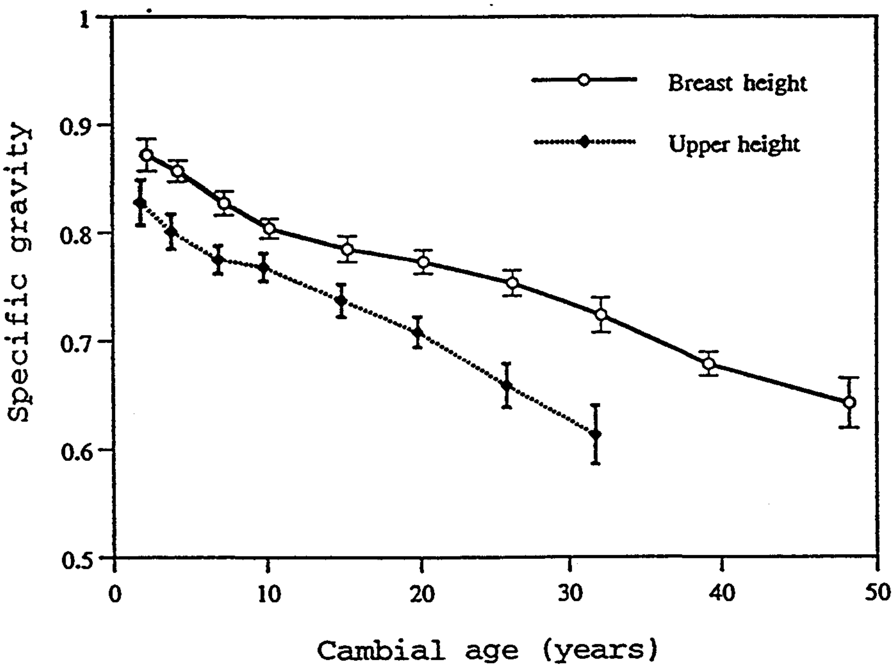


Figure IV.9 Average radial profiles of specific gravity at breast height and the upper height of six Oregon white oak trees. Standard error bars show the variation among trees.

of many ring-porous species (Panshin and deZeeuw, 1980). Similarly, a significant and negative relationship between specific gravity and cambial age was also reported for *Quercus petraea* and *Quercus robur* (Zhang et al., 1993). However, the linear decrease in specific gravity from pith to bark could not be justified by the radial variation in latewood percentage, fiber and vessel proportions because they did not follow a simple linear variation. Other factors such as fiber wall thickness and proportion of gross cell wall might also affect specific gravity.

Juvenile and mature wood

After the demarcation ages were determined between juvenile and mature wood for the anatomical characteristics, the wood properties of juvenile and mature wood were calculated and compared. Table IV.4 shows the results of the comparison between the juvenile wood (before 10 years) and mature wood (after 30 years) for each measured wood characteristic. The results of the t-test show that the differences between juvenile and mature wood are highly significant at the 0.01 level for most of the anatomical characteristics and specific gravity except for the percentage of ray tissue. Juvenile wood had 113% more vessel volume, vessels 65% larger in diameter, 49% more axial parenchyma, 28% fewer fibers, and was 20%

Table IV.4 Comparison of various wood characteristics between juvenile wood (<10 years) and mature wood (>30 years) in Oregon white oak.

Property	Juvenile wood n=72	Mature wood n=60	difference %
Fiber length (mm)	1.06 (0.10)	1.20 (0.11)	+ 13 **
Vessel diameter(mm)	0.164 (0.04)	0.272 (0.02)	+ 65 **
Fiber %	63.7 (3.8)	45.6 (6.7)	- 28 **
Vessel %	12.4 (3.1)	26.5 (6.2)	+ 113 **
Ray %	14.4 (2.6)	13.7 (2.5)	- 7 n.s.
Parenchyma %	9.5 (3.9)	14.2 (4.1)	+ 49 **
Specific gravity	0.827 (0.06)	0.664 (0.08)	- 20 **

** Significant different by T-test at 0.01 level.
n.s. Not significant different by T-test at 0.05 level.
+/- increase/decrease from juvenile to mature wood.

lower specific gravity than the mature wood. The percentage of ray tissue showed little difference between the juvenile and mature wood.

Significant differences in anatomical characteristics and specific gravity between juvenile and mature wood means a lack of uniformity in wood quality within a tree. It also must be noted that using the term 'juvenile wood' may be misleading in ring-porous species like Oregon white oak because there are higher specific gravity and fiber percentage in the core wood near pith than in outer wood in Oregon white oak. Therefore, core wood has higher wood strength and fiber yield, which are not characteristics of 'juvenile wood'. On the other hand, higher specific gravity and fiber percentage may lead to greater shrinkage and more drying defects in core wood.

Comparison to red alder

From the study on red alder in chapter III of this dissertation and the present study on Oregon white oak, it was found that fiber length and vessel diameter change greatly from pith to bark for both species. However, red alder is quite uniform in tissue composition and specific gravity from pith to bark. In contrast, Oregon white oak showed much greater radial variation in fiber and vessel proportions and specific gravity than red alder. This discrepancy is due to the factor that Oregon white oak is ring-porous, whereas red alder is diffuse-porous. As expected based on previous research on ring-porous hardwoods (Haygreen and Bowyer, 1989; Phelps and Workman, 1994) and the present study on Oregon white oak, the amount of earlywood remains relative constant regardless of the ring width, whereas the amount of latewood is directly affected by growth rate. Consequently, the radial variation of wood properties is greatly affected by both the growth rate and cambial age in ring-porous hardwoods. It is expected that growth rate or ring width, latewood percentage, and tissue composition in ring-porous hardwoods will be highly correlated to each other, which in turn will greatly affect physical and mechanical properties such as specific gravity, MOE, and MOR. However, wood properties of diffuse-porous species such as red alder are expected to be less affected by growth rate and cambial age than those of ring-porous species.

Conclusions

Based on the results of this study, the cambial age or radial position is a key factor determining most of the wood properties at both breast height and upper height in the tree. Radial variation shows a demarcation age between juvenile and mature wood of 10 to 26 years, depending on anatomical characteristics. There are significant differences between the core wood and the outer wood in most of the anatomical characteristics and specific gravity, but the core wood is not necessarily of low quality. Using the term 'juvenile wood' to refer to wood that is variable in its properties and quality may be misleading for ring-porous hardwoods like Oregon white oak. Effects of the tree-to-tree variation and the slight lean in the tree are minor.

CHAPTER V

RELATIONSHIPS BETWEEN ANATOMICAL CHARACTERISTICS, SPECIFIC GRAVITY, AND BENDING PROPERTIES IN RED ALDER (*Alnus rubra* Bong.) AND OREGON WHITE OAK (*Quercus garryana* Dougl.)

Abstract

Anatomical characteristics, specific gravity, and bending properties were determined from mini-samples for red alder (*Alnus rubra* Bong.) and Oregon white oak (*Quercus garryana* Dougl.). The relationships among these properties by radial position were analyzed for each species.

In red alder, the correlations between anatomical characteristics were weak except for a strong and negative relationship between percentages of fiber and vessel tissues. Specific gravity showed stronger relationships with bending properties than did any of the anatomical characteristics.

In Oregon white oak, ring width, latewood percentage, percentage of fiber and vessel tissue were significantly correlated to each other in outer wood, but not in core wood. Ring width and tissue proportions, rather than specific gravity, were better correlated to the bending properties. MOR was more associated with anatomy and specific gravity than was MOE, and this relationship was stronger in outer wood than in core wood.

A positive correlation between MOE and MOR was significant and consistent in core and outer wood for both species. Canonical correlation analyses revealed that percentage of fiber and vessel tissues were more related to specific gravity, MOE and MOR than were other anatomical characteristics for the two species.

Introduction

Explaining variable properties and performance of wood by its structure has long been an interest of wood scientists (Dinwoodie, 1975; Bodig and Jayne, 1982; Boyd, 1982; Burley and Miller, 1982; Beery et. al., 1983; Ifju, 1983; Zhang and Zhong, 1992). Understanding the relationships among various wood characteristics allows not only a more efficient, but also a wider use of different wood resources for particular applications, thereby reducing dependence on old-growth forest resources. If significant relationships among anatomical, physical, and mechanical properties can be established, the information about these relationships can be used by foresters and the wood industry to evaluate the quality of wood supply even before the trees are harvested. For example, mechanical properties can be estimated by analyzing the anatomical and physical data collected from living trees through nondestructive techniques, such as increment core sampling.

One of the most studied relationships among various wood properties has been the association between specific gravity and mechanical properties because specific gravity has been well documented as the most important parameter influencing the strength of wood (Ifju et al., 1965; Armstrong et al., 1984; USDA, 1987; Dinwoodie, 1989).

Maeglin (1976) indicated that specific gravity can serve as a good indicator of strength for softwoods which are simple in their tissue composition.

However, specific gravity as an index of strength for hardwoods is not as good as it is for softwoods because of the diversity of species and their complex structure (Hillis, 1989). An inconsistent relationship between strength and specific gravity was found especially in hardwoods (Bendtsen, 1978; Onilude, 1982). Studies also showed that specific gravity was not the most important factor influencing strength properties of wood in *Populus x euramericana* (Peszlen, 1993), *Liquidambar styraciflura* and *Liriodendron tulipifera* (Faust, 1989). Other anatomical characteristics, such as tissue proportions (Hill, 1954 and Leclercq, 1980), and microfibril angle (Zhang and Zhong, 1992) were the better estimators of the strength properties than was specific gravity for a number of hardwoods. From the study of eight species of hardwoods, Beery et. al. (1983) concluded that elastic behavior (i.e. modulus of elasticity, MOE) was more dependent on specific gravity than the anatomical characteristics, but failure property (strength) was attributable to anatomical features. Bendtsen and Senft (1986) found that fiber length accounted for 25% and 43% of the variations in stiffness (MOE) and strength (modulus of rupture, MOR), and microfibril angle explained 38% of variation in both MOE and MOR for eastern cottonwood (*Populus deltoides*) in bending. Therefore, mechanical properties of hardwoods are not solely determined by the amount of wood substance (specific gravity), but are also affected by many previously mentioned factors such as tissue proportions, microfibril angle in the cell wall, fiber length, and others.

Considering the large number of important hardwood species, studies on the structure-property relationships are still limited. Moreover, the effect on strength due to differences in wood structure between ring-porous and diffuse-porous species needs to be investigated.

The objective of this study was to explore the relationships among anatomical characteristics, specific gravity and bending properties for one ring-porous and one diffuse-porous species. Mini-samples from different radial positions were used for determining anatomical characteristics, specific gravity, and bending properties, which allowed the separate studies of core wood (the wood near the pith) and outer wood (the wood near the bark).

Materials and Methods

Materials

Six 40-year-old red alder (*Alnus rubra* Bong.) trees and six Oregon white oak (*Quercus garryana* Dougl.) trees older than 50 years, were sampled from Coast Range of Western Oregon. These represent the diffuse- and ring-porous species, respectively. Details of sample sites and trees for these two species are presented in Appendix E and H.

From each tree, a 25-cm thick disk was removed at breast height (1.3 m). A 2.5-cm wide radial slab was cut from each disk across the diameter from the lower to the upper side of the lean in the tree. All slabs were dried to 12% moisture content (see Chapter III and IV for details). Samples centered on rings 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 23, 26, 30, 34 in red alder and 2, 4, 7, 10, 15, 20, 26, 32, 39, and 48 in Oregon white oak were cut from both sides of each slab. The samples were 0.51 cm (0.20 inches) in the radial direction, 0.64 cm (0.25 inches) in tangential direction and 8.26 cm (3.25 inches) along the grain. Specific gravity, modulus of elasticity and modulus of rupture in bending, and anatomical characteristics were determined for each sample.

Test and measurements

Prior to strength testing, each sample was weighed to 0.001 g and measured to 0.01 mm in length, width, and depth. The data were subsequently used for calculation of specific gravity, moisture content, modulus of elasticity (MOE), and modulus of rupture (MOR) in bending. A three-point bending test with loading through the radial surface was performed over a 7.1 (2.80 inches) cm span with a crosshead speed of 1.17 mm/min on an Instron Universal Testing Machine.

After bending failure, samples were ovendried and weighed again. Then, one subsample was cut from each side of the failure region of each sample. Two cross sections and two tangential sections were made from each subsample by microtome. Two temporary fiber slides were made by maceration from the same subsample.

Ring width, latewood percentage[a], and the percentages of fiber, vessel, and axial parenchyma[a] tissues were determined for each sample from the four cross sections. Percentage of ray tissue[b] was determined from the four tangential sections. Tangential vessel diameter was determined from 80 vessel elements on cross sections for each sample. Fiber length was determined from 80 individual fibers for each sample.

Detailed procedures used for the test of bending and the measurements of specific gravity and anatomical characteristics are given in chapter II.

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[a] Measured only in Oregon white oak.

[b] Aggregate rays were not included in any sample of red alder.

Data analysis

Data analyses were conducted for each species separately. Within each species, data were organized into three groups representing core wood, outer wood, and mixed wood. Core wood contained the first three samples from pith (with cambial ages of 2, 4, 6 years for red alder and 2, 4, 7 years for Oregon white oak). Outer wood consisted of five outermost samples near bark (with cambial age > 20 years for red alder and > 32 years for Oregon white oak). Mixed wood included all the samples from pith to bark.

Correlation analysis

Relationships among anatomical, physical and bending properties were analyzed using both multivariate and univariate methods. Simple correlation analysis was conducted to determine the relationship between two wood characteristics. Canonical correlation is a statistical procedure for analyzing the relationship between two sets of variables (Lindeman et al., 1980). In this study, one set of variables was composed of anatomical characteristics and another set was composed of physical-mechanical properties. Linear combinations of anatomical variables that were most highly correlated to linear combinations of physical-mechanical properties could be identified by canonical correlation analysis. Although canonical correlation involves more complicated relationships and the results are difficult to interpret, the weights of each variable for a canonical variate can show which variables in one set of variables are more important in relation to another set of variables. Anatomical characteristics included growth ring width (RW), latewood percentage[a] (LW), fiber length (FL), vessel diameter (VD), percentage of fiber tissue (PF), percentage of vessel tissue (PV), percentage ray tissue (PR) and percentage of axial parenchyma[a] (PP). Physical-mechanical properties were specific gravity (SG), MOE and MOR. Canonical correlation analyses were performed using the statistical analysis package SAS (SAS Inst., 1988). Mathematics of canonical correlation and SAS procedure are included in Appendix I.

Regression analysis

Stepwise regression analysis procedure (SAS Inst., 1988) was applied to determine the relationship between anatomical characteristics, specific gravity, MOE, and MOR. Stepwise regression is a statistical search method to select the 'best' subset of independent variables for a multiple regression equation (Neter et al., 1989). The

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[a] Only for Oregon white oak.

independent variables enter the equation based on their respective contribution to the dependent variable's variance. The independent variable that accounts for the greatest amount of variation in the dependent variable enters the equation first. With the first independent variable in the equation, the variable that explains the greatest amount of variation in the dependent variable is entered second, and so on.

First, the anatomical characteristics and specific gravity were used as the independent variables to regress against the dependent variable (MOE or MOR) to determine which independent variables were more closely associated with MOE or MOR:

$$MOE = f(RW, LW, FL, VD, PF, PV, PR, PP, SG) \quad (V\text{-}1)$$

$$MOR = f(RW, LW, FL, VD, PF, PV, PR, PP, SG) \quad (V\text{-}2)$$

Then the specific gravity as a dependent variable was regressed on the anatomical characteristics (independent variables) to learn which anatomical characteristics were most closely associated with specific gravity:

$$SG = f(RW, LW, FL, VD, PF, PV, PR, PP) \quad (V\text{-}3)$$

Independent variables were selected based on the 0.10 significant level for entering and staying in the regression models.

Results and Discussion

Averages for properties

Average values for anatomical measurements, specific gravity, and bending stiffness and strength for mixed wood, core wood, and outer wood are given in Table V.1 for red alder and Oregon white oak. Narrower ring widths, longer fibers, and larger vessel diameters in outer wood than in core wood are common for the two species. There is little difference in percentage of ray tissue between core wood and outer wood for either species. There are large differences in specific gravity between core wood and outer wood in Oregon white oak because of the differences in percentages of fiber and vessel tissue. Red alder is very uniform in the percentages of wood tissues and specific gravity, although very different in ring width, between core wood and outer wood. MOE and MOR are higher in core wood than in outer wood for red alder, but lower for Oregon white oak.

Correlations among anatomical characteristics

Red alder

The results of simple correlation analysis for red alder are shown in Table V.2. Ring width was

Table V.1 Mean properties (standard deviations) for mixed wood, core wood, and outer wood in red alder and Oregon white oak.

Properties	Red alder			Oregon white oak		
	Mixed wood (n=168)	Core wood (n=36)	Outer wood (n=36)	Mixed wood (n=120)	Core wood (n=36)	Outer wood (n=36)
Ring width (mm)	4.2 (2.1)	6.6 (2.0)	2.4 (0.8)	2.2 (1.0)	2.5 (0.8)	1.2 (0.6)
Percent latewood	Not applicable			65 (9)	70 (7)	54 (7)
Fiber length (mm)	1.10 (0.12)	0.93 (0.09)	1.20 (0.06)	1.16 (0.12)	1.08 (0.12)	1.22 (0.12)
Vessel diameter (μm)	61.8 (13.1)	53.6 (13.2)	67.1 (10.7)	232 (45)	178 (52)	271 (33)
Percent fiber	58.4 (4.0)	60.2 (4.3)	56.4 (3.9)	57.4 (10.1)	63.1 (4.3)	46.4 (7.9)
Percent vessel	26.2 (4.5)	24.1 (4.5)	28.3 (4.4)	16.2 (8.3)	11.7 (2.5)	25 (7.4)
Percent ray	14.3 (2.2)	14.1 (2.2)	14.5 (2.0)	14.3 (2.4)	15.1 (2.3)	14.5 (3.0)
Percent parenchyma	1.1 (0.4)	1.6 (0.5)	0.8 (0.2)	13 (5.1)	11.3 (4.2)	13.6 (5.2)
Specific gravity	0.468 (0.028)	0.468 (0.033)	0.461 (0.019)	0.771 (0.084)	0.852 (0.045)	0.681 (0.067)
MOE (MPa)	8340 (931)	7898 (651)	8494 (777)	8853 (1463)	8549 (1184)	8257 (1685)
MOR (MPa)	80.69 (8.76)	77.61 (7.82)	81.78 (7.24)	85.27 (15.18)	84.88 (13.75)	76.21 (13.72)

significantly correlated to fiber length in mixed wood ($r=-0.68$) and outer wood ($r=-0.36$), but these relationships were not significant at the 0.05 level in core wood. The correlation between ring width and the percentage of fiber or vessel tissue was statistically significant in outer wood but not in core wood. The discrepancy of the correlations in core and outer wood might be due to the fact that fiber length and the percentages of fibers and vessels are more variable in core wood than in outer wood. Lack of relationships between ring width and anatomical characteristics in core wood is in agreement with previous study for young red alder (Chapter II). Even in outer wood, correlation of ring width to other anatomical characteristics is not strong ($r \leq 0.36$). This is important that the change of growth rate (ring width) will not substantially affect wood properties.

A positive relationship between fiber length and vessel diameter was significant (at the 0.05 level) in mixed wood and core wood, but not significant in outer wood ($P=0.06$), which agrees with the result that both the fiber length and vessel diameter increased rapidly with age (Chapter III) near the pith, but changed little near the bark.

The percentages of fiber and vessel tissues showed a strong and consistent negative correlation in mixed wood, core woods, and outer wood ($-0.88 < r < -0.86$). This

Table V.2 Correlation coefficient matrix of anatomical characteristics for red alder. The first line (M) of any triplet is for mixed wood (M)(n=168), the second (C) is for core wood (n=36), and the third (O) is for outer wood (O)(n=36).

	FIBER LENGTH	VESSEL DIAMETER	PERCENT FIBER	PERCENT VESSEL	PERCENT RAY	
RING WIDTH	-0.68 (0.00)*	-0.24 (0.00)	0.32 (0.00)	-0.25 (0.00)	-0.05 (0.53)	(M)
	-0.11 (0.53)	0.26 (0.13)	0.08 (0.66)	-0.12 (0.49)	0.10 (0.57)	(C)
	-0.36 (0.00)	-0.13 (0.24)	0.32 (0.00)	-0.22 (0.04)	-0.13 (0.21)	(O)
FIBER LENGTH		0.34 (0.00)	-0.25 (0.00)	0.17 (0.03)	0.13 (0.09)	(M)
		0.36 (0.03)	-0.17 (0.31)	0.13 (0.44)	0.06 (0.73)	(C)
		0.21 (0.06)	-0.07 (0.55)	-0.19 (0.09)	0.25 (0.02)	(O)
VESSEL DIAMETER			-0.26 (0.00)	0.15 (0.05)	0.22 (0.00)	(M)
			-0.20 (0.24)	0.06 (0.73)	0.26 (0.13)	(C)
			-0.16 (0.16)	0.01 (0.94)	0.26 (0.02)	(O)
PERCENT FIBERS				-0.87 (0.00)	-0.08 (0.30)	(M)
				-0.88 (0.00)	-0.15 (0.39)	(C)
				-0.86 (0.00)	-0.10 (0.38)	(O)
PERCENT VESSEL					-0.42 (0.00)	(M)
					-0.34 (0.04)	(C)
					-0.43 (0.00)	(O)

* Inside parentheses is the P-value.

negative relationship is expected because the increase in one type of cell must necessarily result in the decrease in at least one other type of cell for all species of hardwoods. The percentage of vessel tissue was also negatively correlated with that of ray tissue in core, outer, and mixed woods, although the correlation coefficients were low ($-0.43 < r < -0.34$).

Other correlations between anatomical characteristics in red alder except those mentioned above were either weak ($|r| < 0.26$) or not statistically significant at the 0.05 level.

<u>Oregon white oak</u>

The results of correlation analyses are presented in Table V.3. Mixed wood and outer wood showed significant correlations between ring width and latewood percentage ($r= 0.64$ and 0.57), between ring width and percentage of fiber tissue ($r= 0.56$ and 0.39), between ring width and percentage of vessel tissue ($r= -0.61$ and -0.47), between latewood percentage and percentage of fiber tissue ($r= 0.78$ and 0.55), and between percentage of latewood and percentage of vessel tissue ($r=-0.84$ and -0.59). In contrast, all these relationships were not significant at the 0.05 level in core wood. A significant and strong correlation between fiber and percentage of vessel tissue

Table V.3 Correlation coefficient matrix of anatomical characteristics for Oregon white oak. The first line (M) of any triplet is for mixed wood (n=120), the second (C) is for core wood (n=36), and the third (O) is for outer wood (n=36).

	LATEWOOD (%)	FIBER LENGTH	VESSEL DIAMETER	PERCENT FIBER	PERCENT VESSEL	PERCENT RAY	PERCENT PARENCHYMA	
RING WIDTH	0.64 (0.00)*	-0.10 (0.28)	-0.29 (0.00)	0.56 (0.00)	-0.61 (0.00)	0.01 (0.93)	-0.11 (0.25)	(M)
	0.02 (0.09)	-0.05 (0.77)	0.07 (0.67)	-0.02 (0.90)	0.07 (0.70)	0.04 (0.82)	-0.04 (0.83)	(C)
	0.57 (0.00)	0.25 (0.14)	-0.08 (0.63)	0.39 (0.02)	-0.47 (0.00)	-0.03 (0.85)	0.12 (0.48)	(O)
LATEWOOD (%)		-0.15 (0.11)	-0.48 (0.00)	0.78 (0.00)	-0.84 (0.00)	0.05 (0.59)	-0.18 (0.05)	(M)
		0.03 (0.87)	0.12 (0.47)	-0.32 (0.06)	0.06 (0.73)	0.05 (0.77)	0.26 (0.03)	(C)
		0.48 (0.00)	-0.18 (0.29)	0.55 (0.00)	-0.59 (0.00)	-0.08 (0.65)	0.14 (0.43)	(O)
FIBER LENGTH			0.53 (0.00)	-0.18 (0.05)	0.19 (0.04)	-0.04 (0.68)	0.06 (0.55)	(M)
			0.70 (0.00)	-0.06 (0.71)	0.14 (0.43)	0.08 (0.62)	-0.05 (0.77)	(C)
			-0.11 (0.51)	0.36 (0.03)	-0.31 (0.06)	0.18 (0.30)	-0.19 (0.27)	(O)
VESSEL DIAMETER				-0.42 (0.00)	0.52 (0.00)	-0.13 (0.16)	0.04 (0.67)	(M)
				0.13 (0.45)	0.05 (0.75)	0.23 (0.18)	-0.29 (0.09)	(C)
				-0.07 (0.70)	0.07 (0.69)	-0.11 (0.52)	0.06 (0.71)	(O)
PERCENT FIBER					-0.87 (0.00)	0.00 (0.97)	-0.55 (0.00)	(M)
					-0.37 (0.03)	-0.14 (0.42)	-0.74 (0.00)	(C)
					-0.72 (0.00)	-0.08 (0.64)	-0.40 (0.02)	(O)
PERCENT VESSEL						-0.12 (0.18)	0.14 (0.13)	(M)
						-0.07 (0.68)	-0.08 (0.64)	(C)
						-0.23 (0.17)	-0.24 (0.17)	(O)
PERCENT RAY							-0.26 (0.00)	(M)
							-0.40 (0.02)	(C)
							-0.11 (0.51)	(O)

* Inside parentheses is the P-value.

was found in mixed (r=-0.87) and outer wood (r=-0.72), but the correlation was weak, though significant, in core wood (r=-0.37). These results correspond well with the finding from the previous study (Chapter IV) that ring width and latewood percentage consistently deceased with age after 15 years while the change in ring width was inconsistent with that in latewood percentage before 15 years. Lack of relationship in core wood but consistent relationship in outer and mixed wood suggest that it is more reliable to estimate the variation in tissue proportions by ring width or latewood percentage from outer wood than from core wood.

Correlation among SG, MOE, and MOR

In red alder (Table V.4.A), significant correlations (at the 0.01 level) were consistently found between specific gravity and MOR (r=0.61, 0.48, and 0.62) and between MOE and MOR (r=0.84, 0.58, and 0.87) in mixed wood, core wood, and outer wood, respectively. The correlation between specific gravity and MOE was significant at the 0.05 level in mixed wood and outer wood but not significant in core wood (P=0.13). It appeared that specific gravity was a better indicator of strength (MOR) than of stiffness (MOE) in bending. The relationship between specific gravity and MOE or MOR was stronger in outer wood than in core wood.

For Oregon white oak (Table V.4.B), the relationships between specific gravity and bending properties were very different for core wood and outer wood. Specific gravity was positively correlated to MOE and MOR in outer wood. In contrast, negative relationships between specific gravity and bending properties was found in core wood. Mixed wood exhibited little correlation between specific gravity and bending properties because the opposite sign of correlation coefficients in core wood and outer wood offset the relationships. The results indicate that specific gravity is a poor indicator of strength and stiffness of bending in Oregon white oak and even a misleading criterion for bending properties in core wood. Specific gravity as an inaccurate estimator of mechanical properties was also reported for ring-porous species such as *Fagus grandifolia* (Leclercq, 1980) and *Quercus liaoningensis* (Zhang et al., 1993). Although both the bending strength (MOR) and stiffness (MOE) were poorly correlated to specific gravity, MOE and MOR were positively and significantly correlated to each other in mixed wood (r=0.67), core wood (r=0.60) and outer wood (r=0.67).

Although red alder and Oregon white oak are very different in their structure, it is consistent that a positive and significant relationship between MOE and MOR was found in both species and also found separately in mixed wood, core wood, and outer wood.

Table V.4 Correlation coefficients (P-value) between specific gravity (SG), modulus of elasticity (MOE) and modulus of rupture (MOR) for red alder (A) and Oregon white oak (B). The first line (M) of any triplet is for mixed wood (all samples combined), the second (C) is for core wood, and the third (O) is for outer wood.

(A) Red alder

	MOE	MOR	
	0.33 (0.00)	0.61 (0.00)	(M)
SG	0.26 (0.13)	0.48 (0.00)	(C)
	0.36 (0.00)	0.62 (0.00)	(O)
		0.84 (0.00)	(M)
MOE		0.58 (0.00)	(C)
		0.87 (0.00)	(O)

(B) Oregon white oak

	MOE	MOR	
	0.19 (0.03)	0.18(0.05)	(M)
SG	-0.30 (0.08)	-0.41(0.01)	(C)
	0.49 (0.00)	0.36(0.03)	(O)
		0.67(0.00)	(M)
MOE		0.60(0.00)	(C)
		0.67(0.00)	(O)

Correlation of anatomy with SG, MOE and MOR

In red alder, vessel diameter was significantly and negatively correlated to specific gravity, MOE and MOR in mixed wood, core wood, and outer wood (Table V.5). It is obvious that wood with large vessels is low in specific gravity and weak in strength. Specific gravity was negatively correlated to percentage of vessels and positively correlated to percentage of fibers in mixed wood and core wood, but these relationships were not significant at the 0.05 level in outer wood. Correlation between individual anatomical characteristic and MOE or MOR was either weak or not significant at 0.05 level. There was no single anatomical characteristic that was a better indicator of bending strength and stiffness than specific gravity. Lack of relationship between ring width and physical-mechanical properties is important for increasing the growth rate without lowering the specific gravity and strength of wood.

The results of canonical correlation analyses for red alder (Table V.6) showed that the first canonical correlations for mixed wood, core wood, and outer wood were 0.57 and 0.78 and 0.65, respectively. These values were significant at 0.01 level and larger than any simple correlation coefficients between anatomical characteristics and physical-mechanical properties. These

Table V.5 Correlation coefficients of anatomical characteristics with specific gravity (SG), modulus of elasticity (MOE) and modulus of rupture (MOR) for red alder. The first line (M) of any triplet is for mixed wood (all samples combined), the second (C) is for core wood, and the third (O) is for outer wood.

	SG	MOE	MOR	
RING WIDTH	0.03 (0.74)	0.21 (0.01)	-0.18 (0.02)	(M)
	-0.09 (0.59)	-0.31 (0.07)	-0.22 (0.20)	(C)
	0.06 (0.60)	0.08 (0.48)	0.11 (0.32)	(O)
FIBER LENGTH	-0.07 (0.40)	0.26 (0.00)	0.22 (0.01)	(M)
	-0.18 (0.31)	0.01 (0.94)	0.11 (0.52)	(C)
	0.13 (0.25)	0.16 (0.15)	0.12 (0.26)	(O)
VESSEL DIAMETER	-0.40 (0.00)	-0.27 (0.00)	-0.33 (0.00)	(M)
	-0.31 (0.06)	-0.39 (0.02)	-0.38 (0.02)	(C)
	-0.44 (0.00)	-0.51 (0.00)	-0.53 (0.00)	(O)
PERCENT FIBER	0.24 (0.00)	0.07 (0.37)	0.10 (0.20)	(M)
	0.33 (0.05)	0.14 (0.42)	0.12 (0.49)	(C)
	0.13 (0.24)	0.02 (0.83)	0.08 (0.47)	(O)
PERCENT VESSEL	-0.29 (0.00)	0.01 (0.95)	-0.11 (0.16)	(M)
	-0.47 (0.00)	0.00 (0.99)	-0.20 (0.24)	(C)
	-0.16 (0.16)	0.08 (0.49)	-0.05 (0.68)	(O)
PERCENT RAY	0.15 (0.04)	-0.14 (0.07)	0.04 (0.64)	(M)
	0.32 (0.06)	-0.28 (0.10)	0.17 (0.31)	(C)
	0.07 (0.54)	-0.19 (0.08)	-0.05 (0.64)	(O)

* Inside parentheses is the P-value.

squared values mean that the anatomical variables accounted for 32%, 61% and 42% of the variations in physical-mechanical variables in mixed, core, and outer wood. Because the variables in either set were measured in different units, the standardized canonical coefficients rather than the raw coefficients are interpreted. Only the standardized canonical coefficients are provided in the table. The standardized canonical coefficients for

Table V.6 The results of canonical correlation analyses between anatomical characteristics and physical-mechanical properties in red alder.

	Canonical correlations					
	First			Second		
	MIXED WOOD	CORE WOOD	OUTER WOOD	MIXED WOOD	CORE WOOD	OUTER WOOD
	0.57**	0.78**	0.65**	0.42**	0.65**	0.45 n.s.
	Standardized canonical coefficients for anatomical variables					
RING WIDTH	-0.067	0.115	0.243	0.067	0.065	0.018
FIBER LENGTH	0.672	0.600	0.584	0.715	0.320	-0.258
VESSEL DIAMETER	-1.016	-0.718	-0.963	0.022	0.333	-0.287
FIBER (%)	-15.040	-29.593	-14.789	12.738	8.209	62.004
VESSEL (%)	-16.771	-30.866	-16.130	14.198	9.263	68.005
RAY (%)	-8.045	-14.588	-8.340	6.252	3.742	35.776
	Standardized canonical coefficients for physical-mechanical variables					
SG	0.456	-1.170	0.468	-0.711	-1.347	0.183
MOE	0.262	-0.668	-0.106	1.105	0.011	-1.846
MOR	0.448	2.027	0.749	-0.309	0.497	1.747

** significant at 0.01 level.
n.s. not significant at 0.05 level.

anatomical variables showed that more weights were given to vessel and fiber proportions. This means that vessel and fiber proportions were the most important variables among anatomical characteristics in relation to the physical-mechanical properties in mixed, core, and outer woods. MOE was the least favored among physical-mechanical variables. Therefore, MOE was less influenced by anatomical properties than specific gravity or MOR. The second canonical correlations were either much weaker than the first ones or not significant.

For Oregon white oak (Table V.7), specific gravities were positively correlated to ring width, latewood percentage, and fiber and vessel proportions in mixed wood and outer wood. In contrast, these relationships were not significant in core wood at the 0.05 significant level. Lack of correlation between ring width and latewood percentage in the first few years around the pith has also been shown for white oak (*Quercus alba*) (Phelps and Workman, 1994). MOE and MOR were both positively correlated to the fiber proportion in mixed wood and outer wood, but negatively correlated to vessel proportion in mixed wood, core wood, and outer wood. The results showed that outer wood was consistent with mixed wood but different from core wood in regard to the correlations between individual physical-mechanical properties and

Table V.7 Correlation coefficients of anatomical characteristics with specific gravity, modulus of elasticity (MOE), modulus of rupture (MOR) for Oregon white oak. The first line (M) of any triplet is for mixed wood (all samples combined), the second (C) is for core wood, and the third (O) is for outer wood.

	SG	MOE	MOR	
RING WIDTH	0.53 (0.00)*	0.18 (0.06)	0.12 (0.20)	(M)
	-0.21 (0.22)	-0.16 (0.35)	-0.21 (0.23)	(C)
	0.58 (0.00)	0.06 (0.73)	0.04 (0.81)	(O)
LATEWOOD (%)	0.71 (0.00)	0.27 (0.00)	0.37 (0.00)	(M)
	-0.01 (0.96)	-0.16 (0.37)	-0.05 (0.76)	(C)
	0.39 (0.02)	0.23 (0.18)	0.20 (0.24)	(O)
FIBER LENGTH	-0.33 (0.00)	0.16 (0.09)	0.13 (0.16)	(M)
	-0.44 (0.01)	-0.04 (0.80)	0.20 (0.24)	(C)
	0.27 (0.11)	-0.32 (0.06)	0.48 (0.00)	(O)
VESSEL DIAMETER	-0.67 (0.00)	-0.04 (0.69)	-0.07 (0.43)	(M)
	-0.39 (0.02)	-0.21 (0.22)	0.02 (0.89)	(C)
	0.03 (0.87)	-0.05 (0.78)	0.01 (0.96)	(O)
FIBER (%)	0.70 (0.00)	0.30 (0.00)	0.37 (0.00)	(M)
	0.22 (0.20)	-0.15 (0.37)	-0.15 (0.38)	(C)
	0.52 (0.00)	0.43 (0.01)	0.48 (0.00)	(O)
VESSEL (%)	-0.77 (0.00)	-0.35 (0.00)	-0.44 (0.00)	(M)
	0.22 (0.10)	-0.40 (0.02)	-0.34 (0.04)	(C)
	-0.55 (0.00)	-0.38 (0.02)	-0.45 (0.01)	(O)
RAY (%)	0.10 (0.26)	-0.03 (0.75)	-0.01 (0.89)	(M)
	-0.18 (0.29)	0.02 (0.92)	0.08 (0.66)	(C)
	-0.08 (0.66)	0.21 (0.23)	0.20 (0.23)	(O)
PARENCHYMA (%)	-0.18 (0.04)	-0.01 (0.93)	0.01 (0.95)	(M)
	-0.22 (0.20)	0.34 (0.04)	0.27 (0.11)	(C)
	0.06 (0.74)	-0.21 (0.23)	-0.17 (0.32)	(O)

* Inside parentheses is the P-value

anatomical characteristics. In addition, correlations are stronger in outer wood than in core wood. Therefore, predicting physical-mechanical properties by anatomical characteristics from core wood or juvenile wood may not be as reliable or accurate as from outer wood or mature wood.

Results of canonical correlation analyses for Oregon white oak in Table V.8 showed strong and significant correlations between anatomical characteristics and physical-mechanical properties at the 0.01 level. The canonical correlation coefficients were 0.86, 0.71, and 0.79 in mixed wood, core wood, and outer wood, respectively. The standardized canonical coefficients most favored fiber proportion. Vessel proportion was slightly less weighted than fiber proportion, but more weighted than other characteristics in outer wood and mixed wood. In core wood, the parenchyma proportion was less weighted than the percentage of fibers but more weighted than the percentage of vessels because of relative less amount of vessel tissue in core wood. The canonical coefficients of the first canonical variate for physical-mechanical variables were obviously more weighted on specific gravity than on MOE and MOR in mixed wood, core wood and outer wood. This indicates that specific gravity was more related to anatomical characteristics than was either MOE or MOR. The second canonical correlation variate was not worth considering because it was not significant at the 0.05 level for any of wood zones.

Regression analysis

In red alder, the results of stepwise regression analyses showed that multiple anatomical variables together

Table V.8 The results of canonical correlation analysis between anatomical characteristics and physical-mechanical properties in Oregon white oak.

	Canonical correlations					
	First			Second		
	MIXED WOOD	CORE WOOD	OUTER WOOD	MIXED WOOD	CORE WOOD	OUTER WOOD
	0.86 **	0.71 n.s.	0.79 **	0.46 **	0.59 n.s.	0.70 n.s.
	Standardized canonical coefficients for anatomical variables					
RING WIDTH	0.004	-0.176	0.843	-0.593	0.429	-0.311
LATEWOOD (%)	0.158	0.292	-0.538	0.078	0.206	-0.110
FIBER LENGTH	0.010	-0.494	0.080	0.423	-0.016	-0.549
VESSEL DIAMETER	-0.335	-0.226	0.128	0.667	0.517	0.026
FIBER (%)	8.834	19.387	-137.510	66.243	-10.676	95.484
VESSEL (%)	6.771	9.976	-133.880	54.101	-4.853	91.851
RAY (%)	1.995	10.684	-52.933	15.152	-8.226	36.452
PARENCHYMA(%)	4.321	18.765	-92.215	33.107	-11.024	63.789
	Standardized canonical coefficients for physical-mechanical variables					
SG	0.923	0.855	1.148	-0.438	0.573	0.026
MOE	-0.049	-0.060	-0.545	0.215	-0.859	0.141
MOR	0.293	-0.235	-0.070	0.830	-0.267	0.890

** significant at 0.05 level.
n.s. not significant at 0.05 level.

were not more effective than individual characteristics in predicting the specific gravity because of low determination coefficients (Table V.9.a). No single or multiple anatomical characteristics could adequately predict specific gravity.

Anatomical characteristics and specific gravity could explain less than 33% of the variation of MOE in mixed or outer wood and only 15% in core wood (Table V.9.b). However, it appears that specific gravity and anatomical characteristics explained much more variation (>59%) in MOR (Table V.9.c) than in MOE. In addition, MOR can be better predicted by specific gravity and anatomical characteristics in outer wood (R^2=0.74) than in core wood (R^2=0.59). Furthermore, MOR was not only correlated to similar variables such as specific gravity, fiber length and vessel diameter, but also that these variables entered the regression model in the same order for mixed wood, core wood, and outer wood. Specific gravity was the first and dominant variable in the equation for explaining the variation in MOR. Adding anatomical variables to the regression equation did not explain much more variation in MOE or MOR than did the specific gravity alone. These results suggest that bending strength (MOR) is more dependent on specific gravity and anatomical features than is bending stiffness (MOE). Stiffness could not be

Table V.9 Variables* selected by stepwise regression analyses to predict (a) specific gravity, (b) modulus of elasticity and (c) modulus of rupture in mixed wood, core wood, and outer wood of red alder.

(a) SPECIFIC GRAVITY

Mixed wood	Core wood	Outer wood
VD (0.16)	PV (0.18)	VD (0.24)
PR (0.22)	VD (0.22)	FL (0.28)
PV (0.24)	PF (0.24)	PF (0.31)
FL (0.26)		

(b) MODULUS OF ELASTICITY

Mixed wood	Core wood	Outer wood
SG (0.11)	VD (0.15)	VD (0.15)
FL (0.23)		FL (0.33)
VD (0.29)		
PR (0.31)		

(c) MODULUS OF RUPTURE

Mixed wood	Core wood	Outer wood
SG (0.61)	SG (0.48)	SG (0.62)
FL (0.66)	FL (0.54)	FL (0.69)
VD (0.68)	VD (0.57)	VD (0.74)
	PV (0.59)	

predicted well by specific gravity and anatomical characteristics. Specific gravity is the most important indicator of bending strength in red alder. Ring width as a

* Inside parentheses is the coefficient of determination for the equation with the addition of the variable above it.

measure of growth rate was not an important factor inpredicting specific gravity, MOE or MOR because ring width as an independent variable never entered any of the fitted regression equations.

The results of stepwise regression analyses for Oregon white oak are presented in Table V.10. The regression of specific gravity on anatomical characteristics (Table V.10.a) showed that fiber length was the first variable entering the equation for core wood while the ring width was the first one for outer wood. Fiber and vessel proportions were the other two variables consistently added to the prediction equation of specific gravity in core wood, outer wood, and mixed wood. However, less than 50% of the variation in specific gravity could be accounted for by measured anatomical variables in core wood and outer wood. For all samples combined (mixed wood), almost 70% of the variation in specific gravity could be accounted for by anatomical characteristics. The regression of bending properties on anatomical properties and specific gravity (Table V.10.b and c) shows lower determination coefficients ($R^2 \leq 0.33$) in core and mixed wood and higher coefficients ($R^2 = 0.45$ for MOE, $R^2 = 0.69$ for MOR) in outer wood. In core wood, the favored independent variables for MOE were fiber length, vessel and fiber proportions, which differed from ring width and specific gravity for MOR. In outer wood, ring width was the first entered variable in the regression equations for predicting MOE and MOR. Fiber proportion was included in the regression equations for MOE and MOR. These results showed ring width was an important factor for predicting specific gravity, MOE and MOR. Specific gravity as a last-entered or absent variable in the regression equations is not an important factor for predicting MOE and MOR in Oregon white oak. Specific gravity, MOE and MOR could be predicted better in outer wood than in core wood.

Table V.10 Variables* selected by stepwise regression to predict (a) specific gravity, (b) modulus of elasticity and (c) modulus of rupture in mixed wood, core wood and outer wood of Oregon white oak.

(a) SPECIFIC GRAVITY

Mixed wood	Core wood	Outer wood
PV (0.58)	FL (0.21)	RW (0.34)
RW (0.69)	PV (0.30)	PF (0.44)
PF (0.70)	PF (0.37)	PV (0.49)

* Inside parentheses is the coefficient of determination for the equation with the addition of the variable above it.

Table V.10 (continued)

(b) MODULUS OF ELASTICITY

Mixed wood	Core wood	Outer wood
VD (0.16)	FL (0.16)	RW (0.24)
PR (0.22)	PV (0.27)	PF (0.32)
PV (0.24)	PF (0.33)	PR (0.38)
FL (0.26)		SG (0.45)

(c) MODULUS OF RUPTURE

Mixed wood	Core wood	Outer wood
PV (0.20)	RW (0.16)	RW (0.48)
FL (0.24)	SG (0.25)	FL (0.57)
		PF (0.64)
		SG (0.69)

Summary and Conclusions

Although red alder and Oregon white oak represent two very different categories of hardwoods, a strong and negative relationship between fiber and vessel proportions and a significant and positive correlation between MOE and MOR in bending are common for the two species. Bending strength (MOR) was more dependent on the anatomical characteristics and specific gravity than was the bending stiffness (MOE) in both species. In addition, the bending strength (MOR) could be better predicted by anatomical characteristics and specific gravity in outer wood than in core wood.

In Oregon white oak, there is an apparent effect of growth zone (core vs. outer wood) on the relationships among anatomical, physical, and mechanical properties. These relationships were significant in outer wood but not in core wood. Therefore, it is not reliable to predict the properties of outer wood from core wood. In particular, specific gravity is a misleading indicator of bending properties in core wood.

In contrast, the effect of growth zone is not evident in red alder. Specific gravity was better than any other anatomical properties in explaining the variation in bending properties. Stiffness cannot be predicted well by anatomical characteristics and specific gravity.

CHAPTER VI

DISSERTATION CONCLUSIONS

This dissertation presented an opportunity to investigate: (1) the effect of growth on anatomical, physical, and mechanical properties in young red alder trees; (2) anatomical characteristic and specific gravity variations from pith to bark for mature red alder and Oregon white oak trees; (3) relationships among anatomical, physical, and mechanical properties for both species. Based on the results of the investigation, the following conclusions were reached for each species separately:

Red Alder

1. Wide spacing and/or irrigation treatments can greatly increase radial growth of young trees in red alder plantations without much influence on anatomical characteristics or modulus of elasticity and modulus of rupture in bending except that irrigation may slightly reduce the specific gravity.

2. Fertilization is not effective in increasing growth rate or in changing the wood and fiber properties.

3. Either annual ring width or ring area may be used as a measure of growth rate and the same results in the analysis of the relationship between growth rate and wood properties will be obtained.

4. There was significant variation among red alder trees in specific gravity and vessel diameter. This offers the possibility of selecting individual trees for better quality. Tree-to-tree variations in other anatomical characteristics were small or not significant.

5. Variation in anatomical properties and specific gravity between heights and between the lower and upper sides of the lean in the tree were small and probably negligible from a practical standpoint.

6. Variation from pith to bark were not the same for all wood properties. Fiber length and vessel diameter at both heights increased rapidly in the early years and became constant at an estimated 8 to 12 years. Fiber proportion demonstrated a three-segment profile of decrease-increase-decrease radial variation at breast height and a simple decreasing radial profile at the upper height. Vessel proportion at each height was inversely related to fiber proportion.

7. The specific gravity is particularly uniform from pith to bark at both heights.

8. The relationships between anatomical characteristics were weak except for a strong and negative correlation between fiber and vessel proportions. Specific gravity was better than any anatomical characteristics in predicting

bending strength. Stiffness had a strong and positive correlation with strength but could not be well predicted by anatomical properties and specific gravity.

Oregon White Oak

1. Variation among trees, between two heights, and between the lower and upper sides of the lean in the tree accounted for only a small portion of the total variation in anatomical characteristics or specific gravity. This indicates that other important factors, such as cambial age and growth rate, may have a strong influence on the wood properties.

2. Fiber length and vessel diameter at first showed a rapid increase, followed by leveling off toward the bark at both heights. In contrast, fiber/vessel proportion at both heights decreased/increased slightly in the first few years and then decreased/increased rapidly toward bark. Transition age from core wood to outer wood was estimated by piecewise regression analysis to be around 10 to 26 years, depending on anatomical characteristics. The ray tissue proportion showed little change across the radius.

3. Specific gravity showed a simple linear decrease from pith to bark at both heights.

4. There was an apparent effect of growth zone (core vs.

outer wood) on the relationship among wood properties. Ring width, latewood percentage, and fiber and vessel proportions were closely correlated to each other in outer wood, but not in core wood. MOR was better correlated with anatomical characteristics and specific gravity than was MOE, and this relationship was stronger in outer wood than in core wood.

5. Specific gravity was a poor, even a misleading indicator of stiffness and strength in bending.

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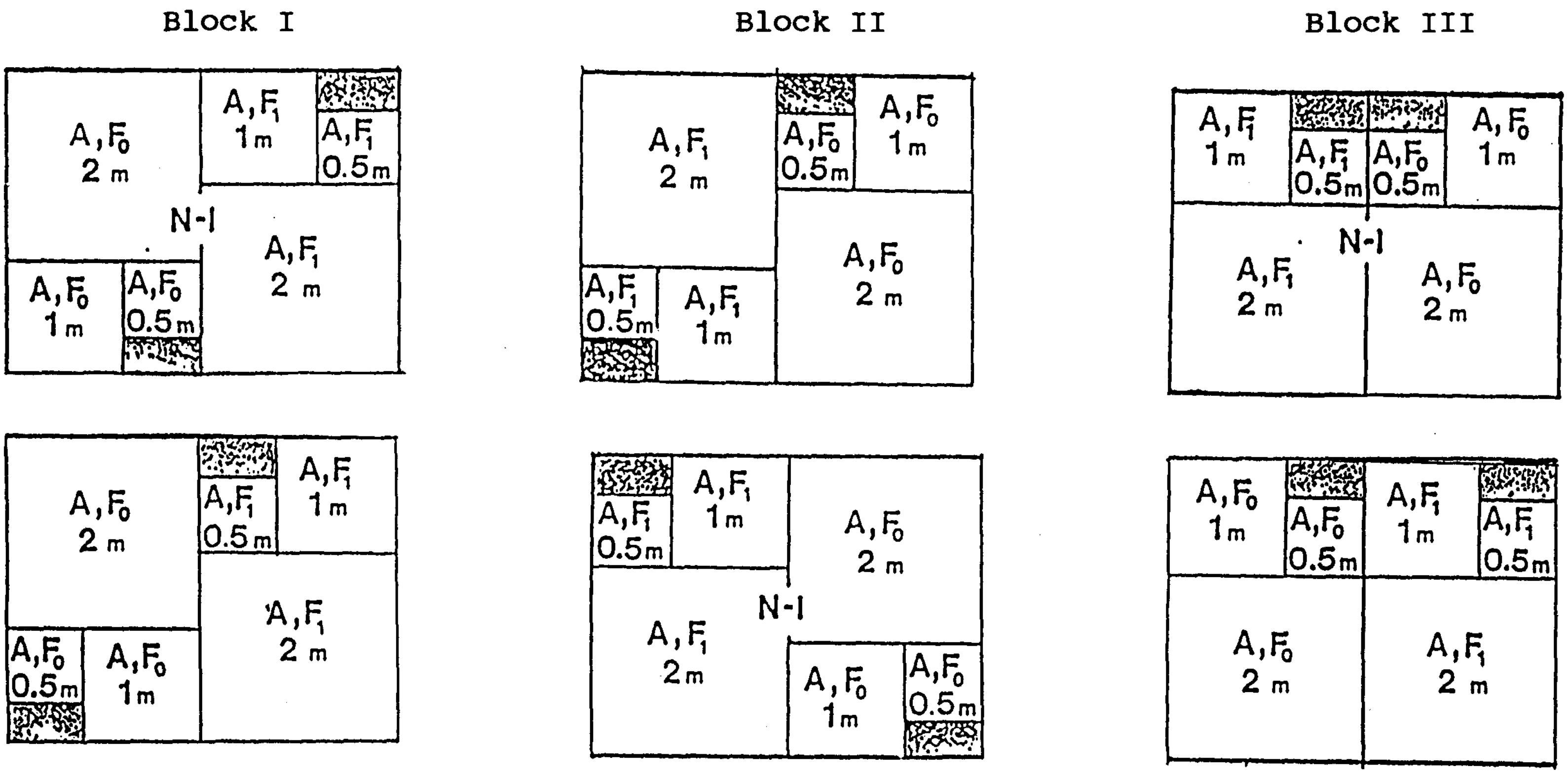
APPENDICES

Appendix A Layout of split-split-plot experimental design of red alder plantation (DeBell et al. 1991).



Spacings

0.5m = 0.5m X 0.5m
1m = 1m X 1m
2m = 2m X 2m

Fertilization

F_0 = non-fertilized (control)
F_1 = Fertilized

Irrigation

N-I = no irrigation
Otherwise, irrigated

Appendix B The height and diameter at breast height (DBH), and the silvicultural treatments applied to sample trees in this study.

Tree #	Height (m)	DBH (cm)	Spacing code*	Irrigation code**	Fertilization code***
51	5.65	3.9	0.5	0	1
50	7.35	4.7	1	0	1
49	5.5	4.9	2	0	0
63	6.6	5.3	0.5	0	1
56	10.1	5.4	0.5	1	1
46	9.85	6.4	1	0	1
65	7.6	6.5	1	0	0
66	7.75	6.8	0.5	0	0
47	9	7.2	2	1	0
64	7.25	7.3	2	0	1
39	8.7	7.3	0.5	0	1
68	10.55	7.5	0.5	1	0
38	8.95	8.1	0.5	0	0
62	8.45	8.5	1	0	1
45	11.25	8.6	0.5	1	0
42	7.85	8.7	2	0	0
59	9.8	8.9	1	1	0
40	8.2	9.3	1	0	1
41	8.25	9.7	2	0	1
37	9.75	9.8	1	0	0
48	11.5	9.9	2	1	1
43	9.55	10.0	0.5	1	1
61	7.75	10.4	2	0	0
72	11.6	10.4	0.5	1	1
71	12.05	10.8	1	1	1
70	10.2	12.0	2	1	0
44	11.3	12.3	1	1	1
67	12.1	13.9	2	1	1
69	12.35	14.2	1	1	0
58	10.75	15.5	2	1	1

* 0.5---0.5 x 0.5 m; 1---1 x 1 m; 2---2 x 2 m.
** 0---control; 1---irrigated.
*** 0---control; 1---fertilized.

Appendix C Red alder plantation background conditions (DeBell, 1995)

1. Precipitation and irrigation levels for seven growing seasons (May 1 to Oct.31)

Year	1986	1987	1988	1989	1990	1991	1992
Precipitation (cm)	30.0	19.4	25.7	16.2	27.6	18.7	14.4
Irrigation (cm)	26.3	48.3	39.3	40.8	57.5	79.1	119.8
Total (cm)	56.3	67.7	65.0	57.0	85.1	97.8	134.2

2. Nutrient conditions of the soil

PH=5-6

Total nitrogen	Total sulphur	Phosphorus	Calcium	Magnesium	Potassium
0.20%	0.02%	160 ppm	350 ppm	60 ppm	200 ppm

3. Application of fertilizer

Triple superphosphate (300 kg p/ha)

Appendix D Response* of height and diameter of 5-year-old red alder plantation trees to the treatments of spacing, irrigation and fertilization.

Spacing (m x m)	Irrigation				
	Low		High		
	Average tree height (m)				
	Non-fert.	Fert.	Non-fert.	Fert.	Means
0.5 x 0.5	3.7	3.8	5.9	5.8	4.8
1 x 1	4.2	4.8	6.7	6.5	5.6
2 x 2	4.7	5.0	6.7	6.9	5.8
Means	4.2	4.5	6.4	6.4	5.4
	Average breast height diameter (cm)				
0.5 x 0.5	2.7	2.9	4.2	4.3	3.5
1 x 1	3.8	4.3	6.0	5.7	5.0
2 x 2	6.2	6.3	8.3	8.3	7.3
Means	4.2	4.5	6.2	6.1	5.3

* The data were provided by DeBell, D. S. and C. A. Harrington, USDA Forest Service, Forestry Science Laboratory, 3626-93rd AV, SW Olympia, Washington 98502.

Appendix E Site description and sample tree record of six trees of red alder.

Species: Red alder (*Alnus rubra* Bong.)

Date collected: March 29, 1992

Location: McDonald-Dunn Forest, College of Forestry, Oregon State University, Corvallis, Oregon (longitude 123°19'30"; latitude 44°38'30"; elevation 190-210 m).

Site description:

Six sample trees were cut from a 45 year-old mixed stand of red alder and big-leaf maple. The slope of site surface is about 36% and faces north. The sampling locations were well above a nearby stream. The site has moist sandy loam soil.

Sample tree records:

Tree #	lean direction	lean angle	DBH* (cm)	BD** (cm)	Tree height (m)	Fork height (m)	2nd*** height (m)
1	210°	5°	35	37	23.8	9.8	6.0
2	19°	5°	32	35	20.4	10.1	5.9
3	20°	2°	33	36	20.7	6.2	6.1
4	340°	5°	32	35	18.3	6.0	5.6
5	30°	5°	36	38	21.6	9.8	6.1
6	29°	14°	30	33	20.1	8.5	5.8

* Diameter at breast height
** Basal diameter
*** Where the second section was cut

Appendix F. Analysis of variance for evaluating tree, height, lean effects and interaction between height and lean within trees.

factors: 6 trees---T
2 heights---H (2 disks/per tree)
2 Sides(lean)---L(Upper and lower sides/per disk)

Samples: 12 samples/ each side (red alder)
8 samples/ each side (Oregon white oak)

SAS procedure:

```
PROC GLM;
CLASS T H L;
MODEL
Y= T ¦ H ¦ L;
RANDOM T T*H T*S T*H*S / TEST;
```

SOURCE	DF
MODEL	23
ERROR	264
TOTAL	287

SOURCE	DF	
T	5	
H	1	
T*H	5	ERROR FOR HEIGHT EFFECT
L	1	
T*L	5	ERROR FOR LEAN EFFECT
H*L	1	
T*H*L	5	ERROR FOR (H*L) INTERACTION

Appendix G. A preliminary analysis of tree effect and its interactions with height and lean for regression analysis of data from 6 trees.

Dependent variables: Y (wood property)
Independent variable: X (age);
Indicator variable: Z (0 or 1);
Fit regression function for each height separately;

SAS PROCEDURE:

```
PROC REG;
MODEL Y=T X Z Z*X T*Z T*Z*X;
```

IF T, T*Z, and T*Z*X are not significant, regression analysis will be conducted on pooled data from the 6 trees. Otherwise, regression analysis will be done separately for each tree.

Red alder

Results (P-value) of preliminary analysis for red alder at breast height

	FL	VD	F%	V%	R%	SG	RW
Tree (T)	0.93	**0.0001**	0.21	0.10	**0.03**	**0.001**	0.35
Age (X)	**0.0002**	**0.02**	**0.001**	**0.002**	0.42	0.16	**0.0001**
Z	**0.017**	0.08	**0.03**	**0.01**	0.78	0.52	**0.02**
Z*X	**0.01**	0.10	**0.04**	**0.01**	0.12	0.31	**0.001**
T*X	0.22	0.09	0.41	0.10	0.35	0.52	0.53
T*Z*X	0.06	0.21	0.34	0.19	0.42	0.14	0.42

Results (P-value) of preliminary analysis for red alder at upper height

	FL	VD	F%	V%	R%	SG	RW
Tree (T)	0.18	**0.046**	0.12	0.31	**0.01**	**0.001**	0.18
Age (X)	**0.0001**	0.05	**0.001**	**0.02**	0.21	0.08	**0.03**
Z	**0.001**	**0.04**	0.08	0.12	0.13	0.13	**0.01**
Z*X	**0.0002**	0.08	0.41	0.06	0.35	0.52	0.13
T*X	0.50	0.10	0.34	0.31	0.41	0.24	0.08
T*Z*X	0.33	0.07	0.21	0.27	0.16	0.10	0.23

The above results show that the data of 6 trees can be pooled for FL, F%, V% and RW for regression analysis. Regression analysis for VD and SG need to be further conducted on each tree separately.

Oregon white oak

Results (P-value) of preliminary analysis for Oregon white oak at breast height

	FL	VD	F%	V%	R%	P%	SG
Tree (T)	0.62	0.25	0.58	0.61	0.12	0.14	0.13
Age (X)	**0.02**	**0.01**	**0.001**	**0.01**	0.44	**0.01**	**0.001**
Z	**0.01**	**0.001**	**0.03**	**0.02**	0.13	0.24	0.42
Z*X	**0.01**	**0.03**	**0.02**	**0.04**	0.14	0.34	0.14
T*X	0.32	0.13	0.06	0.24	0.35	0.14	0.10
T*Z*X	0.09	0.16	0.41	0.14	0.09	0.24	0.17

Results (P-value) of preliminary analysis for Oregon white oak at upper height

	FL	VD	F%	V%	R%	P%	SG
Tree (T)	0.11	0.46	0.18	0.12	**0.13**	0.21	0.08
Age (X)	**0.04**	**0.03**	**0.001**	**0.001**	**0.02**	**0.04**	**0.01**
Z	**0.01**	**0.01**	**0.02**	**0.01**	0.08	0.25	0.14
Z*X	**0.03**	**0.01**	**0.03**	**0.03**	0.16	0.13	0.22
T*X	0.32	0.09	0.14	0.09	0.05	0.08	0.10
T*Z*X	0.25	0.21	0.06	0.53	0.08	0.06	0.51

For Oregon white oak, tree effect and tree-related interaction are not significant. Regression analysis for all characteristics can be conducted on pooled data from 6 trees.

Appendix H Site description and records of six sample trees of Oregon white oak.

Species: Oregon white oak (*Quercus garryana* Dougl.)

Date collected: March 3, 1992

Location: McDonald-Dunn Forest, College of Forestry, Oregon State University, Corvallis, Oregon (longitude 123°17'30"; latitude 44°40'15"; elevation 180-190 m).

Site description:
Six sample trees were cut from an 80 year-old mixed stand of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and Oregon white oak. The slope of site surface is about 21% and faces east. The site has dry clay loam soil.

Sample tree records:

Tree #	lean direction	lean angle	DBH* (cm)	BD** (cm)	Tree height (m)	Fork height (m)	2nd*** height (m)
1	10°	5°	27	41	21.1	5.7	4.4
2	80°	2°	29	35	22	5.6	4.3
3	200°	12°	27	32	18.8	7.1	4.5
4	155°	2°	26	31	19.6	8.2	4.6
5	50°	2°	30	33	21.6	3.8	4.2
6	85°	2°	32	38	24	8.1	4.6

* Diameter at breast height
** Basal diameter
*** Where the second section was cut

Appendix I Canonical correlation analysis (Lindman, 1980)

Let X and Z be two data matrices. X has p columns and Z has q columns. X represents anatomical properties with p variables and n observations. Z represents physical-mechanical properties with q variables and n observations.

Let a and b be two vectors with p and q components that define two linear combinations a(i) and b(i).

$$a(i)= \sum_{j=1}^{p} a_j x_{ij}$$

$$b(i)= \sum_{j=1}^{q} b_j z_{ij}$$

The n values of a(i) for all observations are components of Xa. Similarly, the n values of b(i) are the components of Za.

Search for the two linear combinations a(i) and b(i) that are highly correlated over all the values of i. Each of these two linear combinations is called a canonical variate. Canonical correlations are products-moment correlations between two canonical variates. Each canonical correlation is a measure of the degree of linear relationship between two sets of variables.

The variance of all values in a(i) for i=1, 2, ..., n is written as:

$$Var(a)= \frac{1}{n} \sum_{i=1}^{n} a(i) = \frac{1}{n} (Xa)'Xa$$

$$= \frac{1}{n} a'X'Xa$$

Similarly,

$$Var(b)= \frac{1}{n} b'Z'Zb$$

The first canonical correlation is the maximum correlation between two canonical variates: Xa and Zb.

The correlation coefficient between the two linear combinations a(i) and b(i) is the covariance:

$$\mathrm{Cov}(a, b) = \frac{1}{n} a'X'Zb$$

To find a and b that maximize

$$a'X'Zb$$

with condition

$$a'X'Xa = b'Z'Zb = 1$$

Then the function F, to be maximized is

$$F = a'X'Zb - (\sqrt{\lambda}/2)a'X'Xa - (\sqrt{\gamma}/2)b'Z'Zb$$

where $\sqrt{\lambda}/2$ and $\sqrt{\gamma}/2$ are LaGrange multipliers.

By taking partial derivatives of F with respect to a and b, and setting each of these to zero:

$$X'Zb - \sqrt{\lambda}X'Xa = 0$$

$$a'X'Z - \sqrt{\gamma}b'Z'Z = 0$$

By solving above two equations, a number of non-zero roots (values of λ) will be obtained. $\sqrt{\lambda_1}$ is the first canonical correlation, $\sqrt{\lambda_2}$ is the second canonical correlation. Detail mathematics of computation see Lindeman (1980).

The SAS program statements required to run the program for analyzing canonical correlation between anatomical characteristics (RW FL, VD, V, R)and physical-mechanical properties (SG, MOE and MOR) were:

```
OPTIONS PS=60;
DATA ALDER;
     INPUT RW, FL, VD, F, V, R, SG, MOE, MOR;

     +----------------------------+
     |                            |
     |    DATA                    |
     |                            |
     +----------------------------+
;
CARDS;

PROC CANCORR DATA=ALDER;
     VAR RW FL VD F V R;
     WITH SG MOE MOR;
RUN;
```