Effect of growth rate on the anatomy, specific gravity, and bending properties of wood from 7-year-old red alder (*Alnus rubra*)[1]

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Abstract: Understanding the association between growth rate and wood properties is of practical importance to maximizing and sustaining wood and fiber production. Anatomical characteristics, specific gravity, and bending properties were determined at breast height for thirty 7-year-old trees with varying growth rates, from a red alder (*Alnus rubra* Bong.) plantation. Wood was sampled from the growth ring with a cambial age of 5 years. Growth varied from 2.0 to 9.3 mm/year (ring width), or 264 to 3350 mm^2/year (ring area). We analyzed the relationship between growth rate, in terms of both annual ring width and area, and each wood property. Because both measures of growth rate yielded the same qualitative results, we only used ring width in our analyses. Regression analysis showed that growth rate had no effect on specific gravity, the modulus of elasticity in bending, the modulus of rupture in bending, fiber diameter, or the proportion of growth ring that was fiber or vessel. Fiber length, vessel diameter, and ray proportion, however, were positively correlated with growth rate. Fiber-wall thickness and axial parenchyma proportion decreased slightly with growth rate. The results indicate that the growth rate of *A. rubra* trees can be increased through silvicultural practices with few negative effects on wood and fiber quality, at least in the juvenile wood zone of the stem.

Résumé : La compréhension de la relation entre le taux de croissance et les propriétés du bois est importante pour maximiser et maintenir la production de bois massif et de fibres. Les caractéristiques anatomiques, la densité et les propriétés en flexion ont été déterminées pour du bois échantillonné à hauteur de poitrine sur 30 arbres âgés de 7 ans, de taux de croissance variables, provenant d'une plantation d'aulne de l'Orégon (*Alnus rubra* Bong.). Le bois a été échantillonné dans le cerne annuel de la cinquième année de croissance du cambium. La croissance variait de 2,0 à 9,3 mm par année (largeur des cernes) ou de 264 à 3350 mm^2 par année (surface des cernes). Nous avons analysé la relation entre le taux de croissance, exprimé en termes de largeur et de surface des cernes annuels, et chaque propriété du bois. Puisque les deux mesures du taux de croissance ont donné les mêmes résultats qualitatifs, nous avons utilisé seulement la largeur des cernes dans nos analyses. L'analyse de régression a démontré que le taux de croissance n'avait pas d'effet sur la densité, le module d'élasticité en flexion, le module de rupture en flexion, le diamètre des fibres ou la proportion des cernes constitués de fibres ou de vaisseaux. Cependant, la longueur des fibres, le diamètre des vaisseaux et la proportion des rayons étaient corrélés positivement avec le taux de croissance. L'épaisseur des parois des fibres et la proportion de parenchyme axial diminuaient légèrement avec le taux de croissance. Les résultats indiquent que le taux de croissance des tiges d'*A. rubra* peut être augmenté par des traitements sylvicoles avec peu d'effets négatifs sur la qualité du bois massif et des fibres, du moins dans la zone de bois juvénile de la tige.
[Traduit par la Rédaction]

Introduction

Red alder (*Alnus rubra* Bong.) is the most important hardwood for the forest-products industry in the Pacific Northwest of the United States (Harrington and DeBell 1980). Interest in its management and utilization is at an all-time high (Hibbs et al. 1994). In Oregon, the 1991 hardwood harvest was 28% greater than that in 1987; 76% of the 1991 hardwood harvest was *A. rubra* (Ahrens 1994). This diffuse-porous species is used to make pulp, furniture, cabinets, and pallets and is also satisfactory for oriented strandboard (Murad 1984), studs (Layton et al. 1986), and turned products. Because of its favorable wood properties, there is great potential for increasing use of this hardwood resource (Briggs and Bethel 1978; Resch 1988; Plank et al. 1990).

DeBell et al. (1992) reported that intensive management of *A. rubra* plantations greatly influenced the growth rate of *A. rubra* trees. It is not known, however, how accelerated growth affects its wood and fiber properties. Understanding this relationship is of practical importance in attempting to maximize fiber production without lowering wood and fiber quality.

Previous investigations of the effect of growth rate on hardwood properties have focused almost exclusively on specific gravity and fiber length (synthesized in Zobel and van Buijtenen 1989). The results of these studies are often contradictory for diffuse-porous species. In several studies, specific gravity and fiber length had a significant relationship to growth rate (Scaramuzzi 1956, as cited in Zobel and van Buijtenen

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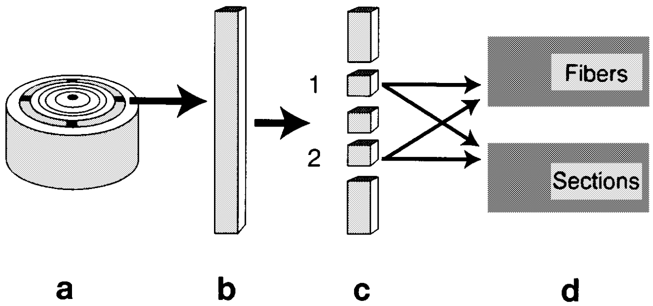
Fig. 1. Diagram of sample preparation from a disk of *A. rubra* wood. (*a*) Disk. (*b*) Bending and specific gravity sample. (*c*) Two locations (1 and 2) from which anatomical materials were cut after the bending test. (*d*) Slides from macerations and microtome section.



1989; Malan 1991; Peszlen 1994), but in two studies on this taxon, specific gravity was not related to growth rate (Parker et al. 1978; Lowell and Krahmer 1993).

A serious and common error in evaluating the relationship between growth rate and wood properties is confounding growth rate and cambial age (Zobel and van Buijtenen 1989): a comparison of the difference between the wood properties of fast-grown and slow-grown trees would be incorrect if samples were not taken 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 7-year-old *A. rubra* trees, with cambial age held constant. The trees were grown in a variety of silvicultural regimes that resulted in different growth rates.

Materials and methods

Materials

Wood samples of *A. rubra* from an intensively managed plantation were provided by the U.S. Department of Agriculture Forest Service Research Station in Olympia, Washington. The plantation was originally designed to study biomass production of cottonwood (*Populus* spp.) and *A. rubra* (DeBell et al. 1991, 1992) under different silvicultural regimes by varying the following treatments (12 treatment combinations): irrigation (no irrigation), fertilization (no fertilization), and spacing (three levels). Each treatment combination was replicated three times. A total of 300 trees were in each treatment combination. The silvicultural treatments resulted in plant materials with different growth rates. The effects of these treatments on wood properties are addressed in Lei (1995).

When trees were 7 years old, we took one small, one medium, and one large tree (judged by diameter at breast height) from three different plots for each treatment combination, for a total of 36 trees. Six of the 36 trees were excluded from the study because they had fewer than five growth rings at breast height. A 25 cm thick disk was removed from each tree at breast height (1.3 m), kiln dried to a target moisture content of 12%, then stored in a room with a 12% equilibrium moisture content. Our study focused on the growth ring 5 years from the pith (referred to here as having a cambial age of 5) at breast height, which in most samples was the growth ring formed during the 1991 calendar year.

Sample preparation

Four samples that were centered on the middle of the fifth growth ring were removed from each disk (Fig. 1*a*). Aggregate rays were avoided because they are absent or rare in material of this age (Noskowiak 1978). We measured the width of the fifth growth ring at four compass points on the disk. The first point was a random location, and the others were taken at points 90°, 180°, and 270° from the first one. We also measured the radius from the pith to the beginning of the fifth growth ring at each point. We calculated the average area of the fifth growth ring from these measurements. Samples 0.51 cm (0.20 in) in the tangential direction, 0.64 cm (0.25 in) in the radial direction, and 8.26 cm (3.25 in) in the longitudinal direction (Fig. 1*b*) were taken from the same points where growth ring width was measured. Samples were centered on the fifth growth ring, but if that ring was narrower than 0.64 cm, samples included wood from other years as well.

Bending tests

A Universal Instron Testing Machine (Canton, Mass.) and an electronic automatic data-acquisition system were used to determine modulus of elasticity (MOE) and modulus of rupture (MOR). 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 minibending samples based on the ASTM D 143-83 (American Society for Testing and Materials (ASTM) 1986). The 0.51-cm depth of samples and the 7.1-cm span provided the recommended span-to-depth ratio of 14:1 (ASTM).

Loading was applied to the radial rather than the tangential surface to reduce the effect of earlywood and latewood orientation in the top and bottom layers of the sample. We chose to make specimens narrower in the tangential than radial direction. This geometry increased the specimens' stability in bending (important in such small specimens) and allowed the two "radial" faces of the beams to be more radial in orientation (important for small-diameter trees). Before the bending test, each sample was weighed; the weight and subsequent ovendry weight were used to calculate the moisture content of the sample.

Specific gravity

Volume was the product of the length, width, and depth of each sample (measured with electronic calipers) at a known moisture content and adjusted to expected values at a 12% moisture content. Specific gravity was calculated as sample ovendry weight divided by sample volume at 12% moisture content, divided by 1 g/cm^3 (the density of water).

Anatomical characteristics

After the bending tests were completed, pieces were removed from each end of the sample for the measurement of anatomical characteristics; each block was both sectioned and macerated, and all anatomical data per sample are means from the two blocks (Figs. 1*c* and 1*d*). We cut 20 μm thick transverse and radial sections from each block after soaking them in water for several minutes to become softened. The transverse sections were stained in aqueous safranin and mounted permanently. Two defect-free transverse sections were made for each sample. Temporary slides of two radial sections per sample were also made.

To prepare macerated-fiber slides, several match-sized sticks were boiled in water for 15 min and then heated in a solution (20 mL 20% nitric acid and 0.5 g sodium chloride) at 85°C for 20 min. The acid was replaced by water and the fibers were boiled for 10 min more. The water was exchanged several times to completely remove excess acid for better staining, and fibers were stained in aqueous safranin overnight. Temporary slides of the macerated fibers were made with glycerin as the mounting medium.

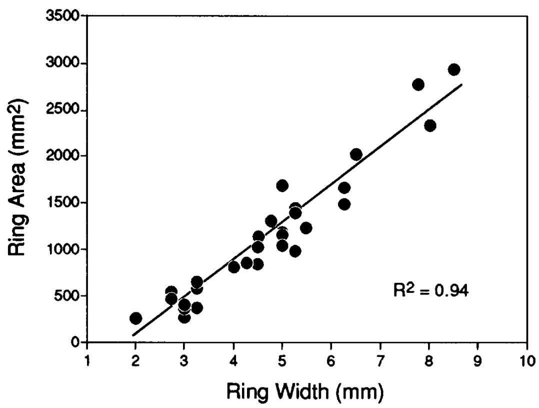
We used an image-analysis system for anatomical measurements. The images of the microscope slides were captured through a CCD video camera attached to a stereomicroscope (for low magnification) or a compound microscope (for high magnification). Images were processed and analyzed with the public-domain software program NIH Image (version 1.47; Rasband 1992). In this procedure, one first

Table 1. Fitted regression equations for wood properties (y) related to growth rate (x; annual ring width).

	Independent variable		
Dependent variable (y)	Ring width (mm)	SE	R^2
Fiber length (mm)	y=0.93+0.013x	0.032, 0.006	0.13
Double thickness of fiber wall (μm)	y=3.75−0.048x	0.115, 0.022	0.14
Vessel diameter (μm)	y=56.8+1.02x	1.96, 0.38	0.21
Ray proportion (%)	y=11.1+0.69x	0.73, 0.14	0.47
Axial parenchyma proportion (%)	y=1.33−0.077x	0.11, 0.021	0.33

Note: Only the significant relationships are shown ($P < 0.05$). The standard error for each regression coefficient (SE) and the R^2 value for each regression equation are listed.

Fig. 2. Linear relationship between ring width and ring area of the fifth growth ring from the pith at breast height (1.3 m) in *A. rubra*.



digitizes the microscope image, digitizes a stage micrometer at the same magnification (to get a pixel/μm conversion), then calibrates the screen.

Fiber length

Fiber lengths were determined on digitized images of the macerated wood using the image analysis system described above with the dissecting microscope. We used a mouse to designate the ends of each fiber, insuring that only entire fibers were measured. We measured 40 fibers from each block, giving 80 fibers per sample.

Vessel and fiber diameters, fiber-wall thickness

Transverse-section slides were used for determinations of vessel diameter, fiber diameter, and double thickness of fiber walls. Slides were digitized and measured as for fiber lengths, but using the compound microscope. All measurements were in the tangential direction.

Tissue proportions

The proportion of tissue in different cell types was estimated for two sections (almost duplicates of one another) from each block (so four sections per sample) of about 10–45 mm^2 each, depending on ring width. Vessels were distinguished from fibers and axial parenchyma by defining 620 mm^2 as the smallest vessel area, based on preliminary measurements. The axial parenchyma cells of each cross section were “painted” on the computer screen by the computer operator, and their area relative to the whole section was measured. Ray proportion was measured by the same method, but on radial sections. The fiber proportion was obtained by subtracting proportional areas of vessel, ray, and axial parenchyma from unity (100%).

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.

Results and discussion

Growth rate

At the cambial age of 5 years, there was more than a 4-fold difference between the smallest and largest annual growth rate of sample trees in terms of ring width (2.0 to 9.3 mm/year), and more than a 12-fold difference in terms of ring area (264 to 3350 mm^2/year).

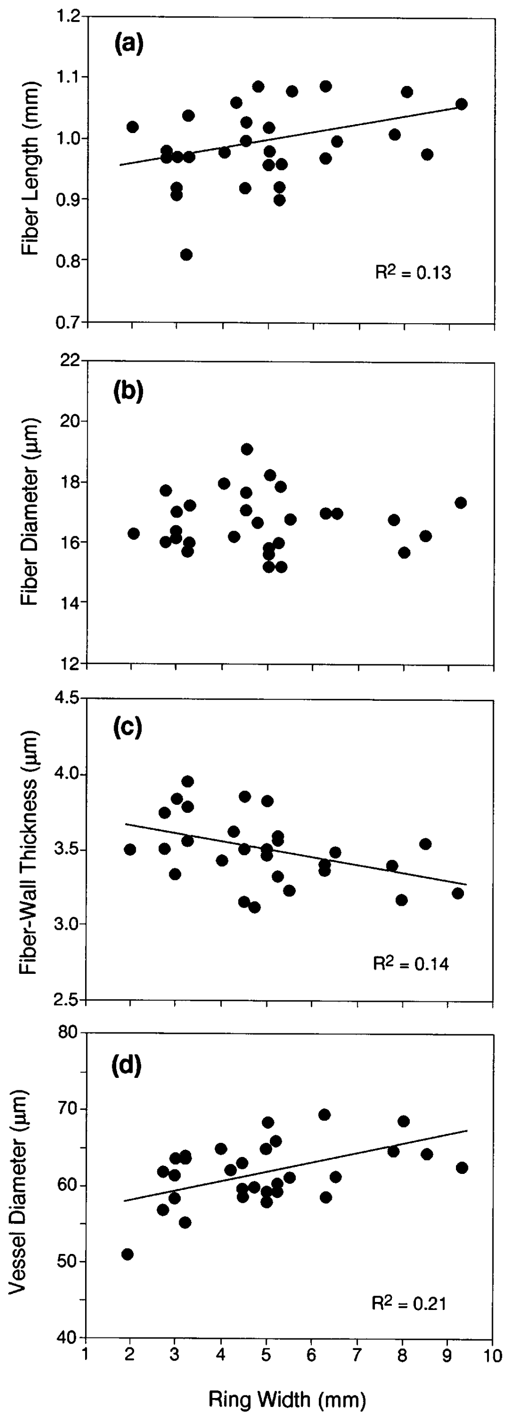
From the standpoint of plant development, ring width and area have different meanings. In the wood industry, growth ring width, often referred to as the growth rate, is largely a measure of the periclinal division of cells. When the diameter of a tree increases, anticlinal division of cells, and resulting tangential growth, is required to keep up with the increase in tree circumference. Ring area includes both radial and tangential expansion and is probably a better indicator of growth rate. The data from 30 trees, however, show that ring width and area have a strong linear relationship (Fig. 2); only the results from the ring-width analysis are reported (see Lei 1995 for the same analyses presented here but on a ring-area basis).

Anatomical properties

The statistically significant regression equations between anatomical properties and ring width are shown in Table 1. Properties not in the table did not have a consistent relationship with growth rate.

Fiber length was positively but weakly correlated with ring width ($R^2 = 0.13$; Table 1; Fig. 3*a*). The results show that fiber length was not depressed by increased growth rate, as also shown for *Populus* (Holt and Murphey 1978) and other hardwoods (synthesized in Zobel and van Buijtenen 1989). However, this finding is in contrast with other observations that at high rates of diametric growth, cambial initials become smaller (Bannan 1967), and that at higher growth rates fibers are longer (e.g., Cech et al. 1960). Fiber diameter did not vary significantly with ring width (Fig. 3*b*). The thickness of the fiber wall tended to decrease slightly as growth rate increased, but the relationship was weak ($R^2 = 0.14$; Table 1; Fig. 3*c*).

Fig. 3. The relationships between ring width for the fifth growth ring from the pith at breast height (1.3 m) of *A. rubra* and (*a*) fiber length, (*b*) fiber diameter, (*c*) fiber-wall thickness, and (*d*) vessel diameter. Lines show statistically significant relationships ($P < 0.05$).



The combination of a slight increase in fiber length and a decrease in fiber-wall thickness with growth rate raised the ratio of fiber length to cell wall thickness (*L*/*T*). A higher *L*/*T* ratio is an indicator of higher tensile strength, tensile MOE, and burst factor in paper (Horn 1978), so accelerating growth of *A. rubra* should increase rather than decrease the fiber quality of paper.

Vessel diameter was significantly and positively correlated with growth rate ($R^2 = 0.21$; Table 1; Fig. 3*d*). Fast-grown *A. rubra* trees will produce wood with slightly wider vessels, which is unfavorable for paper making and solid-wood products; large vessel diameter leads to problems in refining and printing processes and difficulties in the finishing of solid wood. In contrast with our results, vessel diameter and growth rate were negatively correlated in other diffuse-porous species such as *Populus* spp. (Peszlen 1994) and *Fagus* spp. (Koltzenburg 1966, as cited in Zobel and van Buijtenen).

The proportion of wood tissue present as fibers and vessels showed no apparent change with growth rate (Figs. 4*a* and 4*b*). The ray proportion, however, increased from about 10 to 17% as the growth rate increased from 2.0 to 9.3 mm/year ($R^2 = 0.47$; Table 1; Fig. 4*c*). Although the proportion of axial parenchyma tended to decrease with growth rate (Table 1; Fig. 4*d*), the small amount of axial parenchyma in wood (1 to 2% proportional area) should have little effect on wood and fiber properties.

Small changes in the fiber and vessel proportions with growth rate will have only a small effect on the wood's specific gravity, machinability, or mechanical properties, or on the fiber yield of the pulp. A higher ray proportion at faster growth may increase the wood drying rate and affect anisotropy in shrinkage, and it will increase the fines component in pulp, which will slow the pulping process.

Specific gravity and bending properties

Specific gravity was not related to growth rate (Fig. 5*a*), corroborating the observations of Leney et al. (1978) for the same species. Specific gravity did not decrease in spite of a slight decrease in fiber wall thickness with growth rate. One explanation is that the increase in the proportional volume of higher specific gravity ray tissue offsets the effect of fiber-wall thickness on specific gravity; a higher ray proportion has been associated with higher specific gravity in many species of hardwoods (Taylor 1969; Fujiwara 1992). With little change in fiber and vessel proportions, the combined effect of the increase in ray-tissue proportion and the decrease in fiber-wall thickness led to little overall change in the specific gravity with growth rate.

There was no correlation between growth rate and either of the bending properties, MOE or MOR (Figs. 5*b* and 5*c*). This result indicates that increasing growth rate by silvicultural practices neither reduces specific gravity nor lowers the bending strength and stiffness of *A. rubra* wood, at least in the juvenile wood zone. Other research on specific gravity of *A. rubra* found no significant radial (Harrington and DeBell 1980; Gartner et al. 1997) or longitudinal (Gartner et al. 1997) variation within older trees. These results and those presented in this paper indicate that within the bole of one tree, specific gravity is relatively constant. This information is useful because a tree with uniform specific gravity will be easier to process and use than one with variable specific gravity.

The results from this study should not be used to explain the relationship between growth rate and wood properties in mature wood because all samples are from the fifth ring and only include juvenile wood. The relationship between growth rate and wood properties in mature wood needs to be investigated.

Fig. 4. The relationship for the fifth growth ring at breast height (1.3 m) of *A. rubra* between tissue proportions and ring width. (*a*) Fiber proportion. (*b*) Vessel proportion. (*c*) Ray proportion. (*d*) Axial parenchyma proportion. Lines show statistically significant relationships ($P < 0.05$).

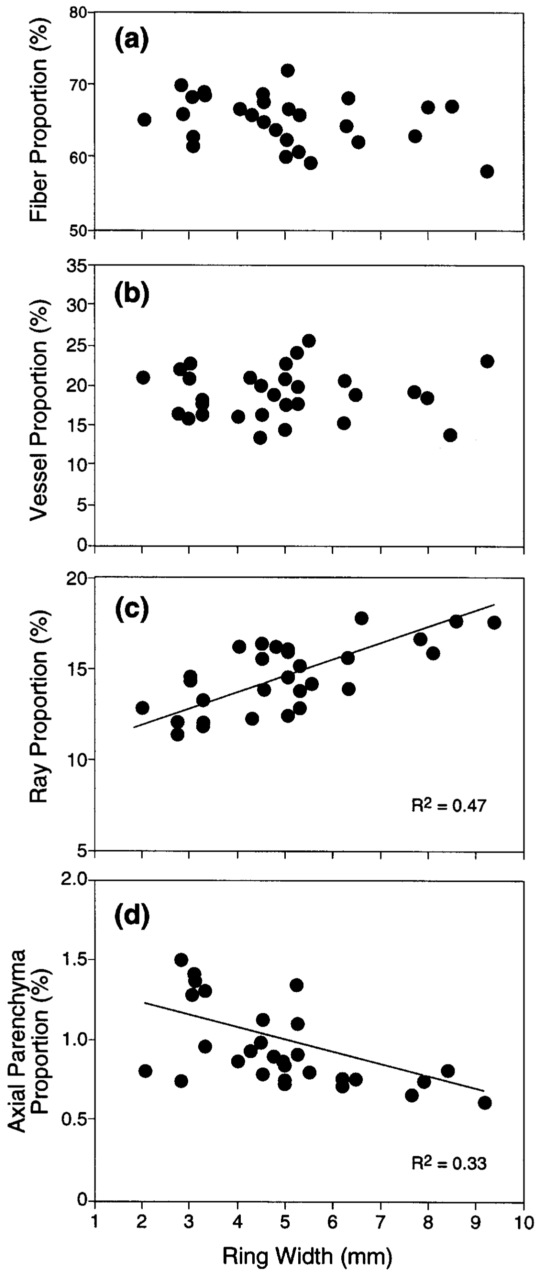
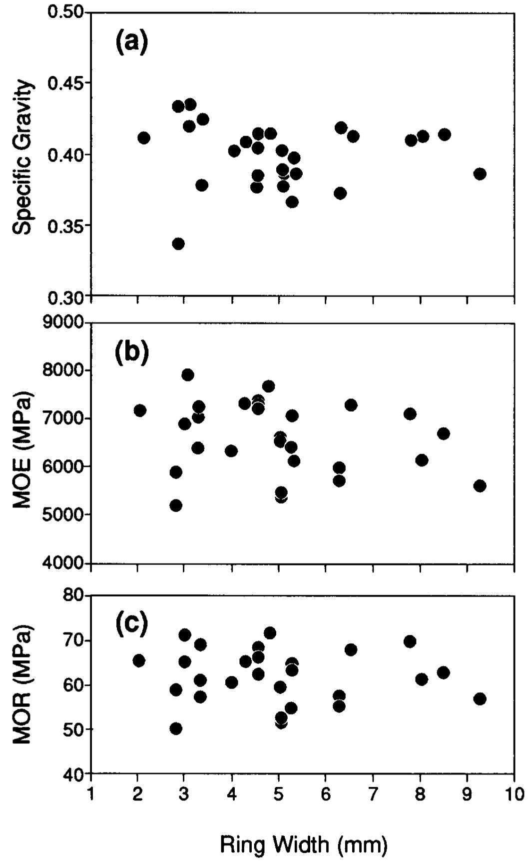


Fig. 5. (*a*) Specific gravity, (*b*) modulus of elasticity (MOE), and (*c*) modulus of rupture (MOR) show no relationships with ring width for samples from the fifth growth ring at breast height (1.3 m) in *A. rubra*.



Only clear wood samples (those without knots) were used in this study. The relationship between growth rate and other wood-quality features such as size and number of knots, proportion of juvenile wood, and taper of logs also needs to be investigated.

Another important aspect that needs to be explored is the fiber yield per hectare. Silvicultural practices such as spacing can greatly increase growth of individual trees, but do not necessarily raise the unit area yield. Although individual trees grew faster in the wider than the narrower spacing, total woody yield remained lower than that of the two narrower spacings (DeBell et al. 1992). 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.

Conclusions

Silvicultural treatments applied to *A. rubra* plantation trees during their early years greatly changed the growth rates but had little effect on wood and fiber properties. Whether ring width or area is used to measure growth rate has little effect on the relationship between growth rate and wood properties. Silvicultural practices can increase the radial growth rate of *A. rubra* trees with few effects on wood processing and utilization due to the anatomical characteristics, specific gravity, and bending properties of the wood.

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References

Ahrens, G.R. 1994. Hardwood resource management and future hardwood timber supplies in the Pacific Northwest. *In* A Symposium on Western Hardwoods: Policy, Products and the Future, 12 Oct. 1994, College of Forestry, Oregon State University, Corvallis, Oreg.

American Society for Testing and Materials (ASTM). 1986. Annual book of ASTM standards. Vol. 04.09. Wood. D 143-83. American Society for Testing and Materials, Philadelphia, Pa.

Bannan, M.W. 1967. Anticlinal divisions and cell length in conifer cambium. For. Prod. J. **17**(6): 63–69.

Briggs, D.G., and Bethel, J.S. 1978. The potential for integrated utilization of alder. *In* Utilization and management of alder. *Edited by* D.G. Briggs, D.S. DeBell, and W.A. Atkinson. USDA For. Serv. Gen. Tech. Rep. PNW-70. pp. 163–173.

Cech, M.Y., Kennedy, R.W., and Smith, J.H.G. 1960. Variation in some wood quality attributes of one-year-old black cottonwood. Tappi, **43**: 857–859.

DeBell, D.S., Harrington, C.A., and Clendenen, G.W. 1991. Increasing the productivity of biomass plantations of cottonwood and alder in the Pacific Northwest. Annual report for the period 1 Mar. 1989 to 15 Dec. 1990. USDA Forest Service, Forest Sciences Laboratory, Olympia, Wash.

DeBell, D.S., Harrington, C.A., Clendenen, G.W., Zasada, J.C., Harms, W.R., and McKevlin, M.R. 1992. Increasing the productivity of biomass plantations of cottonwood and alder in the Pacific Northwest. Annual report for the period 1 Jan. 1991 to 30 Dec. 1991. USDA Forest Service, Forest Sciences Laboratory, Olympia, Wash.

Fujiwara, S. 1992. Anatomy and properties of Japanese hardwoods II. Variation of dimensions of ray cells and their relation to basic density. IAWA (Int. Assoc. Wood Anat.) Bull. n.s. **3**(4): 397–402.

Gartner, B.L., Lei, H., and Milota, M.R. 1997. Variation in the anatomy and specific gravity of wood within and between trees of red alder (*Alnus rubra* Bong.). Wood Fiber Sci. **29**. In press.

Harrington, C.A., and DeBell, D.S. 1980. Variation in specific gravity of red alder (*Alnus rubra*). Can. J. For. Res. **10**: 293–299.

Hibbs, D.E., DeBell, D.S., and Tarrant, R.F. 1994. Biology and management of red alder. Oregon State University Press, Corvallis.

Holt, D.H., and Murphey, W.K. 1978. Properties of hybrid poplar juvenile wood affected by silvicultural treatments. Wood Sci. **10**: 198–203.

Horn, R.A. 1978. Morphology of pulp fiber from hardwoods and influence on paper strength. USDA For. Serv. Res. Pap. FPL-312.

Koltzenburg, C. 1966. Die Abhängigkeit der Holzeigenschaften der Rotbuche (*Fagus sylvatica*) von Lichtgenuss, sociologischer Stellung und anderen Wuchsbedingungen. Thesis, Forst Fak Univ. Göttingen, Hann Münden, Germany.

Layton, T.F., Smith, W.R., and Maeglin, R.R. 1986. An evaluation of the saw, dry, and rip process to convert red alder into studs. Wood Sci. Technol. **20**: 185–200.

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

Leney, L., Jackson, A., and Erickson, H.D. 1978. Properties of red alder (*Alnus rubra* Bong.) and its comparison to other hardwoods. *In* Utilization and management of alder. *Edited by* D.G. Briggs, D.S. DeBell, and W.A. Atkinson. USDA For. Serv. Gen. Tech. Rep. PNW-70. pp. 25–33.

Lowell, E., and Krahmer, R L. 1993. Effect of lean in red alder trees on wood shrinkage and density. Wood Fiber Sci. **25**: 2–7.

Malan, F.S. 1991. Variation, association and inheritance of juvenile wood properties of *Eucalyptus grandis* Hill ex Maiden with special reference to the effect of rate of growth. S. Afr. For. J. **157**: 16-27.

Murad, I. 1984. The feasibility of producing oriented strandboard (OSB) from alder in western Oregon. M.S. thesis, Oregon State University, Corvallis.

Noskowiak, A.F. 1978. Distribution of aggregate rays in red alder. Wood Fiber, **10**: 58–68.

Parker, M.L., Smith, J.H., and Johnson, S. 1978. Annual-ring width and density patterns in red alder. Wood Fiber, **10**: 120–130.

Peszlen, I. 1994. Influence of age on selected anatomical properties of *Populus* clones. IAWA (Int. Assoc. Wood Anat.) J. **15**: 311–321.

Plank, M.E., Snellgrove, T.A., and Willits, S. 1990. Product values dispel "weed species" myth of red alder. For. Prod. J. **40**(2): 120–130.

Rasband, W. 1992. NIH Image 1.47: an instruction manual. Public domain image processing and analysis program. National Institutes of Health, Bethesda, Md.

Resch, H. 1988. Red alder: opportunities for better utilization of a resource. Oreg. State Univ. For. Res. Lab. Spec. Publ. 16.

Scaramuzzi, G. 1956. Variation of the volume proportions of wood elements within the stem in *Populus* × *euramericana* (Dode.) Guinier cv. "1214." Twelfth Congress of the International Union of Forest Research Organization, Oxford, U.K. IUFRO 56/4175.

Taylor, F.W. 1969. The effect of ray tissue on the specific gravity of wood. Wood Fiber, **1**: 142–145.

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