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Coniferous wood quality in the future: concerns and strategies

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Summary As the raw material base for forest products manufacturing shifts from old-growth to short-rotation plantation stock, the wood from these younger trees will contain larger proportions of juvenile wood. This in turn will influence the quality of forest products obtained. The pattern of specific gravity variation in these trees, which varies among the five most important Pacific Northwest species groups, is reviewed, and the nature of their differences is related to growth habit. The shade intolerance of some species is speculated to manifest itself in an early culmination of annual height inrement, after which specific gravity increases rapidly to a maximum. This is contrasted to shade-tolerant species, in which specific gravity may take several decades to attain a minimum value, followed by only moderate increases thereafter. In addition, faster growth rates in widely spaced plantation trees tend to depress specific gravity and advance the age at which these trees reach their minimum value, thereby compounding the overall wood density of deficit of short-rotation trees.

Lower specific gravity, compounded with reduced lignin content in juvenile wood, negatively influences kraft pulp yield, but not pulp quality parameters such as sheet density, burst and tensile strength. Reduced wood density, coupled with larger fibril angles in juvenile wood, reduces average strength and stiffness of lumber from younger plantation trees. Mechanical stress rating needs to be adopted to segregate the strong, stiff material for engineered construction uses, because a large proportion of visually graded lumber from juvenile wood zones will not meet currently assigned stress values. Mechanical stress rating can ensure a continued stream of appropriate engineering grades from future tree supplies.

Introduction

This review examines some aspects of wood property variation existing within second-growth trees of the most important Pacific Northwest conifers used for general structural purposes. This subject becomes more timely as the available old-growth stock is depleted, and forest-products manufacturing shifts to a shorter-rotation, faster-grown, second-growth base. The cumulative amount of wood formed during the first 20

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to 40 years in the life of these fast-grown plantation trees represents a much larger proportion of usable fiber than the same years in slower-grown, appreciably older trees.

There are a host of properties that determine the quality of wood for different purposes, but the single most important characteristic is wood specific gravity or relative density. Much has been written about variation in this property, but perhaps there is still reason to review it, because the degree and form by which it varies in a tree differs with species. This review considers variation in relative density within trees from pith to bark at lower stem heights ranging from breast height to the ten percent level. Vertical variation in properties can largely be estimated by recognizing that the wood at higher positions has fewer rings and therefore has properties similar to previously formed wood at lower levels in the tree. The review continues with a summary of how differences in relative density may interact with patterns of cellulose and lignin distribution within a tree to produce different amounts and qualities of pulp. It also shows how relative density, acting together with microfibril angle, can affect strength and stiffness of wood. The practical significance of this variation on properties of pulp and lumber from young second-growth trees concludes the review.

Central to this subject of wood property variation within a tree is the concept of juvenile wood, for it is in this zone where wood characteristics are constantly changing prior to becoming more stable in mature wood. Zobel and van Buijtenen (1989) define juvenile wood as that first laid down by the cambium near the center of the tree. It is formed in the precence of abundant photosynthate and growth hormones, both produced in the tree crown; consequently it is often termed crown-formed wood, with the transition to more mature wood occurring some distance below the base of the live crown. A specific demarcation between juvenile and mature wood defies description, not only because of differences among species and growing conditions, but also because individual wood properties become more or less stable at different ages, and with different degrees of abruptness. Most authorities have used relative density stability as the criterion to mark the boundary between juvenile and mature wood, but this can range from ring number 8 to 35 years, or even more. Others have used the age at which tracheid length or fibril angle appears to stabilize as the dividing point between the two wood zones. Barbour and Charet (1988) suggested a rather elaborate boundary for spruce as the point where the weight of earlywood and latewood contributed equally to the annual ring mass. I have chosen to use the term juvenile wood in a general sense to comprise the first 20 to 30 annual rings in a log cross-section, and to emphasize the properties of this zone in comparison to subsequently formed wood. To be more specific, the average number of annual rings counted from the pith ("age from pith") which comprise the juvenile zone, will often be quoted.

The following species or species groups from the Pacific Northwest are considered:

Douglas fir, *Pseudotsuga menziesii* (Mirb.) Franco
Lodgepole pine, *Pinus contorta* Dougl.
Western hemlock, *Tsuga heterophylla* (Raf.) Sarg.
Spruce: (white), *Picea glauca* (Moench.) Voss; (Engelmann)
    P. engelmanni Parry ex Engelm; (Sitka) *P. sitchensis*
    (Bong.) Carr; (black) *P. mariana* (Mill.) B.S.P.
True fir: (alpine) *Abies lasiocarpa* (Hook.) Nutt; (amabilis)
    A. amabilis (Dougl.) Forbes; (grand) *A. grandis* (Dougl.)
    Lind; (noble) *A. nobilis* (Dougl.) Lind.

Specific gravity (relative density) variation in individual species

Relative density or specific gravity is a concise measure of the ratio of cell wall substance to lumen volume in wood. It can be visually estimated most accurately by considering

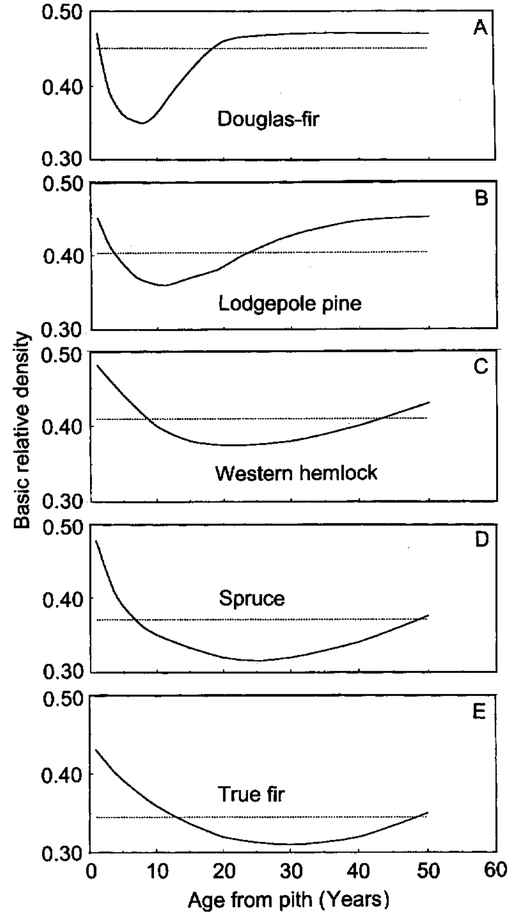

Fig. 1A–E. Patterns of relative density for young second-growth trees (breast height) of five western species groups. The curves represent the typical relationships reported in the literature (see text). The horizontal dashed lines represent the average values for relative density reported by Jessome (1977) for old-growth trees of the species

the percentage of latewood within individual annual increments. In most conifers, the relationship between radial position (age, or ring number from pith) and relative density has been employed to describe patterns of its variation. However, ring width also varies with age, leading to confusion and contradiction in deciding which is the prime variable related to density, because age and ring width are so often confounded. From the viewpoint of tree physiology, age of ring governs density variation to an important degree, because of the proximity of the juvenile core to the live crown of the tree, the source of growth-regulating hormones and photosynthetic products. The following profiles of radial density variation emphasize this relationship.

Douglas-fir

The radial density profile has been described by many workers (e.g. Wellwood and Smith 1962; Kennedy and Warren 1969; Megraw 1986; Zobel and van Buijtenen 1989; Jozsa et al. 1989). Density is invariably high in the first few rings from the pith, after which it plummets steeply to about ring 6 to 10. It then begins a steady climb until it reaches a relatively constant value at about age 20 to 25 (Fig. 1A). According to Megraw (1986), the high density wood adjacent to the pith is the result of exceptionally high earlywood specific gravity, a general phenomenon pointed out by Elliott (1970) for most coniferous species.

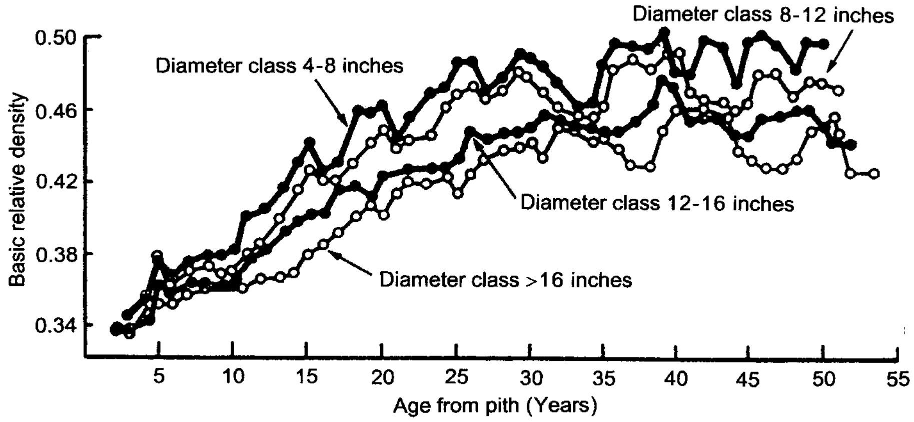

Fig. 2. Horizontal variation in basic relative density in 96 even-aged Douglas-fir trees of 4 different classes

The variation in density between trees of different growth rate can be seen in Fig. 2, which shows average curves for an even-aged stand of Douglas-fir (Kennedy and Warren 1969). Average ring widths ranged from 1–2 mm (diameter class 4–8 inches), through more than 4 mm (diameter class > 16 inches). The original dependent variable – latewood percentage – was converted to basic specific gravity units by assigning values of 0.3 and 0.7 respectively, to earlywood and latewood (Ifju and Kennedy 1962). Fig. 2 shows specific gravity varying from 0.34 in rings near the pith to an average value of about 0.46 at age 25, an increase of 35 percent. Ring width between trees also exerts an influence on density; for example at any given age from 20 to 50, the slowest-growing trees (ring width 1–2 mm) have a density about 0.04 units higher than comparable values of the wider-ringed trees (>4 mm.) This difference of less than 10 percent indicates the smaller consequence of growth rate between trees, compared to the major importance of age within a tree in controlling density variation in Douglas-fir.

Fast-grown wood can have high specific gravity, but an increased proportion of latewood is required to achieve this, because relative density of earlywood and/or latewood fractions is reduced as rings become wider (Smith and Kennedy 1983). In fact, Megraw (1986) and Jozsa and Middleton (1995) are emphatic in stating that growth rate per se is inconsequential in influencing relative density. In summary, the control exerted by rate of growth on density appears to be minor when compared to the age effect.

Lodgepole pine

Much less is known about the density patterns in this species than in Douglas-fir. Zobel and van Buijtenen (1989) have concluded that the hard pines in general show a rapid increase in wood density from the pith outward and level off at some relatively early age, after passing through a short transition period. The extensive data of Koch (1987) did not specifically address itself to the radial variation in density within trees, but his analysis shows that stem specific gravity decreases from an average value of 0.46 at stump height to about 0.40 at the base of the live crown, above which it remains constant, thereby implying an age effect. His data also show density decreasing by about 0.01 unit between faster and slower-growing mature trees, implying a minor negative growth rate effect between trees. Taylor et al. (1982) noted that at most sampling heights, specific gravity of lodgepole pine decreased from a relative high in rings 1 to 5, to a minimum in rings 6–10, after which there was a slow increase to a maximum some 30 to 50 rings from the pith. In the very closely related jack pine (*Pinus banksiana* Lamb.), Villeneuve et al. (1987) noted a regular pattern of density decrease to the ninth ring, after which it increased particularly rapidly to age 15, when it began to level off. Most recently, Jozsa and Middleton (1995) have reported a radial density pattern that is high near the pith, reaching a minimum at about age 10, and then increasing slowly to reach its initial high value only after ring 40.

In summary, while the density pattern in lodgepole is similar to Douglas-fir, the difference between the low juvenile value and the mature wood value may not be as great in lodgepole pine, and the number of years to reach a mature value probably exceeds that of Douglas-fir. The similarities and differences between the two species are shown in Fig. 1A and B.

Western hemlock

The two species previously discussed are both "abrupt transition" conifers, i.e., they both display an abrupt intra-increment transition from earlywood to latewood, particularly beyond the juvenile core. Western hemlock, and the two species groups to follow, have a more gradual transition to latewood within an annual ring, and this appears to lead to a somewhat different pattern of radial density variation.

The earliest systematic radial density data was collected by Wellwood and Smith on 94 young fast-grown hemlock trees, with rather uniform annual rings averaging about 5 mm in width from pith to bark. They noted the greatest density in rings 1–5 (0.471), with a steep decline by rings 16–20 (0.373). This trend was gradually reversed, but the oldest wood of age 26–29 still had recovered to only 0.417. Another sample of 22 older trees yielded a minimum relative density (0.409) in a broad band from age 21 to 50, after which density increased to 0.446 by 80 years.

Krahmer (1966) found the highest specific gravity (slightly greater than 0.50) in ring 1, with a subsequent decrease through a radial distance of 5 cm (age not specified), after which it leveled off to slightly less than 0.40, with little subsequent change. He noted that beyond the juvenile core zone (radius 5 cm), there was a significant negative relationship with rate of growth ($R^2 = 0.23$). Megraw (1986) showed a similar pattern in a sample of 24 year old western hemlock. It had highest density (0.46) at ring 2, with a broad low point (0.36) from age 6 to about 20, with only a small recovery to about 0.38 in the oldest wood.

Wellwood (1960), Kennedy and Swann (1969) and De Bell et al. (1994) all have shown density to be negatively correlated with growth rate. However, the two earlier studies did not examine the independent effect of age, which was confounded with ring width. The latest study, however, compared trees within the confines of a similar age cohort (rings 20–24) and found a significant relation between density and growth rate ($R^2 = 0.39$) due largely to decreasing latewood percentage in wider rings. They found that latewood width was relatively constant regardless of growth rate, resulting in smaller latewood percentages and lower density in the wider rings. However, Jozsa and Middleton (1995) were unable to confirm these results when they examined between-tree density variation in wood at a number of specific ages from the pith, but they did find the typical age-related radial density variation pattern within trees.

If the hemlock pattern (Fig. 1C) is compared to Douglas-fir and lodgepole pine (Fig. 1A and B), it is evident that each species has a high relative density in the first few rings, but in western hemlock, the decline to a minimum value continues for a greater number of years. Furthermore, nearly constant minimum values persist for several years in hemlock. This delays the onset of density recovery, which is more gradual and modest than the other two species.

Spruce

Since several species of spruce with similar wood properties grow in the Pacific Northwest, apparent differences reported among them probably are due to limited sampling, rather than the species themselves. It will be assumed that various species within the genus respond similarly, even when a species may be grown in plantations outside its natural range (i.e. Sitka spruce in the British Isles).

Bryan and Pearson (1955), Jeffers (1959) and Brazier (1967) all have noted that young Sitka spruce grown in Britain has a high initial density, which decreases to a minimum at about age 10–20, and then increases somewhat thereafter. Jeffers found that the narrowest rings within a stem generally had the highest density, but statistical analysis of the independent effect of age and ring width showed age to be the paramount factor. Taylor et al. (1982) found in white spruce that very early rings had a density of 0.39, while a minimum value of about 0.32 was attained between 10 and 25 years, followed by a small increase to about 0.34 by age 40. They also noted that fast growth was associated with lower specific gravity, but in general the age effect was the variable more strongly associated with density variation.

Wang and Micko (1984) and Savill and Sandels (1983), working respectively with white and Sitka spruce, both found relatively high density prior to age 5, a minimum value around 10–15 years, and a gradual increase to a maximum of about 40 years. The Sitka spruce was sampled from a spacing experiment, and represented growth rings averaging in width from 3.4 mm (close stocking) to 7.9 mm (widest spacing). Accompanying the faster growth, there was a corresponding reduction in average relative density of whole stems from 0.42 to 0.38. Petty et al. (1990) also dealt with two different spacings of Sitka spruce trees, and found that the closer spacing produced higher density wood. The typical pattern in individual stems was one of high density near the pith, falling to a minimum at 11–25 years followed by some recovery. Within stems, growth rate showed only a slight negative correlation with density.

Villeneuve et al. (1987) studied wood density patterns with age in several families of young black spruce. Without exception, relative density decreased linearly from their first measurement at age 8 to their final data at age 20. The decrease was significant – from 0.47 to 0.36 – and showed no indication of having reached a minimum after 20 years. Barbour and Charet (1988) also found a maximum density in black spruce near the pith, but little change after minimum had been reached at age 10.

In summary, wood density within spruces is generally highest in the first few rings near the pith, reaching a minimum within 20 years, and then rising slowly to an intermediate value. This pattern (Fig. 1D) most closely resembles western hemlock (Fig. 1C). Between stems, there is evidence of a negative relationship between ring width and specific gravity. This is further exemplified by results of Chang and Kennedy (1967) from 232 plantation white spruce trees from Ontario averaging 30 years of age. Growth rate was negatively correlated with specific gravity, and was responsible for one-third of the total relative density variation noted. Corriveau and Beulieu (1987) also reached this conclusion after surveying white spruce populations in Quebec. They found that growth rate was negatively correlated with relative density in mature wood (>15 years old), explaining some 39 percent of density variation.

True fir

Surprisingly little is known about the relative density variations within the several species growing in the Pacific Northwest, perhaps because they have not been as widely replanted as the previous genera mentioned. Kennedy and Wilson (1954) found that alpine fir had its highest average relative density (0.44) close to the pith, while a minimum value (0.33) was not reached until age 70. Density only increased slightly thereafter, to about 0.36 by age 110. The faster grown trees were consistently about 0.10 units lower in relative density when wood of two growth-rate classes of trees was compared at equivalent ages, pointing to an important between-tree relationship with ring width. Dodd and Power (1986) noted that 15-year-old trees of white fir showed a trend of decreasing value toward the bark, but owing to the youth of the trees, there was no indication that a minimum value had yet been reached. Jozsa and Middleton (1995) found relatively little variation in alpine fir with age, but nonetheless recorded a decrease from 0.35 near the pith to a flat minimum value of 0.30 between ages 20 to 40, and a slight recovery thereafter to age 60.

From the few studies available, it appears that it may take an extraordinary number of years to reach a minimum value, after which there is little sign of upturn as age increases. This genus therefore may be the most extreme case among the gradual transition conifers (see Fig. 1E). Between trees, there seems to be the usual negative relationship with growth rate, explaining some 29 percent of the relative density variation in amabilis fir (Kennedy and Swann 1969).

Discussion and general conclusions regarding relative density

Several questions come to mind from the foregoing review:

1. What is responsible for the universal observation that wood closest to the pith has high relative density?
2. Why do some species (Douglas-fir and lodgepole pine) reach a minimum density at a relatively young age, and recover to produce a reasonably constant, mature wood earlier than others (spruces, hemlock and true firs)?
3. What effect does tree spacing and its rate of growth response have on the radial pattern of density variation in stems?

One answer to the first question is related to the well-known distribution of tracheid lengths in the earliest juvenile wood, where individual cells may be only 25–35 percent of the length of mature wood tracheids. These first-formed cells also generally have small diameters, thereby providing a constricted periphery around which the secondary wall can form. The short tracheids result in an increased number of cross-walls per unit of wood (Elliott 1970), which would tend to increase density, just as small diameters would relate to thicker cell walls in the abundant but somewhat atypical earlywood (Elliott 1960; Megraw 1986). Mild compression wood can also be particularly prevalent in the core wood close to the pith, since the small-diameter stem can be easily subjected to wind and snow-load stresses.

Prior to discussing the second question, the general assertion of Zobel and van Buijitenen (1989) that "··· species of *Abies*, *Picea* and *Tsuga* do not have severe juvenile wood, so that the age of ring is not as critical as it is in the hard pines ···" might be reconsidered. It could be argued that juvenile wood is more severe in these genera, because of the greater number of years required to reach a minimum density value, coupled with only a slow, moderate increase in density of older wood.

The mechanism responsible for different density patterns inherent in the second question may be related to the relative shade tolerance of various species, and the cumulative vegetative activities of their tree crowns. Larson (1963) has indicated that the physiology of wood formation and resulting wood quality is regulated by changes occurring in the crown. Kucera (1994) has shown a close relationship in Norway spruce between the time at which the annual height increment culminates, and the age at which density reaches a minimum at stump height. The culmination of annual height increment represents the first point of infection on a sigmoid tree height/age curve when the current annual height increment first slows down, (as opposed to the more widely interpreted point later on the height/age curve where mean annual height growth culminates). In two different sites, Kucera (1994) found current annual height growth to culminate at 18 and 28 years, corresponding precisely to the ages at which relative density reached a minimum, prior to recovering somewhat.

In contrast, Kucera (1994) suggested that more light-demanding species than spruce are characterized by exponential height growth and rapid crown expansion. This growth habit ceases within a relatively few years when the annual height increment culminates, and he speculated that this event signals the formation of the annual increment of minimum density at the stump level. As tree development continues transition wood is formed, followed by a more or less uniform, higher density mature wood below the base of the live crown as it migrates up the stem. Such is the case for Douglas-fir (Di Lucca 1989) and lodgepole pine.

More shade tolerant trees such as spruces, western hemlock, and particularly the true firs (Burns 1989) have relatively slow height growth in early years, with a consequent delay in culmination of annual height increments (Kucera 1994). This matches the observation of a prolonged decrease in wood density in annual rings further from the pith in these species. The ranking by shade intolerance of the Pacific Northwest species reviewed in this paper is: lodgepole pine (most intolerant), Douglas-fir, spruces, western hemlock and true firs. This rank order is about the same as that age at which wood density reaches a minimum (earliest in the first two species, and latest in the true firs). The ranking is also reasonably related to the degree to which mature wood density meets or exceeds original juvenile density.

An observed association between shade tolerance and years required to reach minimum density does not equate to a cause-and-effect mechanism. Nonetheless, the longer time required for incremental height growth to culminate in shade tolerant species could be taken as a measure of the greater number of years over which terminal meristematic activity proceeds to its maximum. This would provide an abundant flow of growth hormones to the cambium of the bole for a greater number of years. It is generally assumed that an abundance of these growth-promoting substances encourages earlywood production and leads to relatively low density wood.

The third question is a practical one borne from recent trends which favor relatively sparse plantation spacing over a short rotation in order to achieve maximum stand value in the form of large-diameter sawlogs. Young, widely spaced plantation trees will have large active crowns, leading to a prolongation of juvenile growth prior to transition to more mature wood (Di Lucca 1989; Briggs and Smith 1986). This greater number of growth rings in the juvenile zone shifts the curves of Fig. 1 to the right, with the effect that low-density wood will be produced for a longer time in the life of the tree. The initially fast growth rate of these young vigorous trees has a compounding effect which may result in a high proportion of juvenile wood in stems harvested over short rotations.

Smith (1980) found that initially wide spacing in young 20-year old Douglas-fir and western hemlock increased ring width and decreased percentage of latewood significantly. Savill and Sandels (1983) found that early respacing of 10-year old Sitka spruce delayed the onset of minimum density wood by as much as 8 years, so that the specific gravity of whole stems after 40 years was 10 percent less in the most widely spaced stems compared to unspaced controls. Petty et al. (1990) also found that closer spacing produced higher density wood in Sitka spruce. All of this is further evidence of a negative ring width-wood density relationship, at least in more mature wood, among

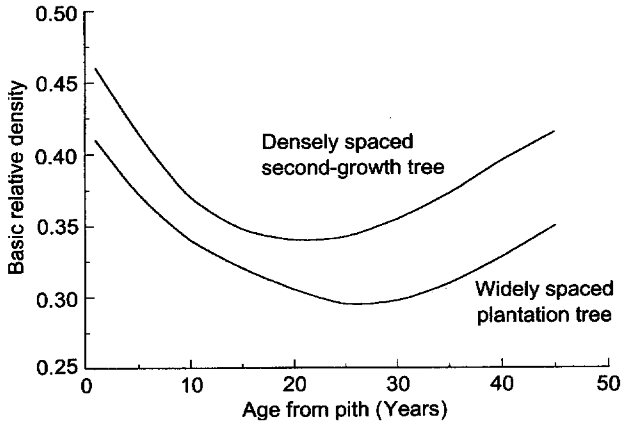

Fig. 3. Trend of relative density variation with age in variously spaced second-growth trees

trees of comparable ages. The cumulative effect of continued fast growth rates in widely spaced plantation stems is summarized in Fig. 3, which compares the relative density pattern of hypothetical closely spaced trees with those more widely spaced. The curve of the widely spaced plantation tree has shifted to the right because of a longer period of juvenile wood formation, and downward because of accelerated incremental growth.

There still will be individual trees that defy these trends, and proceed to form mature, relatively dense wood early in spite of accelerated growth. These are the individuals that should be selected for the breeding programs, under the assumption that at least some of this favorably errant behavior is heritable.

Influence of basic property variation on product characteristics

Pulp yield and quality

Relative density, in combination with other wood quality attributes, particularly tracheid length and cellulose/lignin ratio, influences both the yield and quality of pulp that may be produced by wood of a single tree. Sanio's law governs the increase in cell length from the pith outward, such that increasing tracheid length with age, up to a more or less steady state at 30 to 50 years, has been well documented.

Somewhat higher cellulose contents and lower lignin concentrations have been observed regularly in mature wood as compared to its juvenile counterpart. For example, Kennedy and Jaworsky (1960) found (Cross and Bevan) cellulose content of 58.1 percent in the first 15 years of Douglas-fir, compared with 62.0 percent in the remaining rings (16–81). In this same species, Erickson and Arima (1974) noted comparable values of 58 percent (ring 2) and 65 percent in the first 25 years of growth, and a corresponding decrease in lignin content from 25.8 to 24.3 percent. Swan et al. (1989) also showed a regular decrease in lignin content in Douglas-fir at breast height from 31.5 percent in the first 5 rings to 28.5 percent at ages greater than 30 years.

Western hemlock likewise shows the same trends. Keays and Hatton (1971a) found a difference of about one percent between the lignin content of rings 1–20 (31.2%), and more mature wood (30.3%). Wellwood and Smith (1962) found a much smaller difference in alpha cellulose between rings 11–20 and 41–50 in western hemlock (54.8% vs. 55.1%) than in Douglas-fir (50.1% vs. 54.7%).

Table 1. Comparative yields and strength of kraft pulps from juvenile and mature wood

Species	Reference	Kraft Yield (percent)	Basic density	Yield × density	Juvenile/mature pulp strength ratios		
					(tear)	(tensile)	(burst)
Douglas-fir	Hatton/Keays 1972				0.70	1.10	1.07
• Juvenile Wood (tree top diam. 2.5 to 10 cm)		45.5					
• Mature Wood		47.0					
Douglas-fir	Hatton/Cook 1992				0.71	1.15	1.17
• Juvenile Wood (rings 1–20)		45.6	0.411	0.84			
• Mature wood		47.2	0.473	1.00			
Douglas-fir	Jackson/Megraw 1986				0.70		1.0
• Juvenile wood (rings 1–15)		2 percentage points less than mature wood					
Lodgepole pine	Hatton/Gee 1994				0.71	1.06	1.05
• Juvenile wood (rings 1–20)		45.0	0.363	0.87			
• Mature wood		47.5	0.393	1.00			
Western hemlock	Keays/Hatton 1971a				0.85	0.84	0.96
• Juvenile wood (rings 1–20)		44.1					
• Mature wood		45.9					
White spruce	Keays/Hatton 1971b				0.83	0.97	0.94
• Juvenile wood (tree top diam. 2.5 to 10 cm)		44.8					
• Mature wood		46.5					

While Hatton and Hunt (1992) found no significant difference in lignin content between the first 25 years of lodgepole pine and the wood formed thereafter, they did find that cellulose (determined as glucose residues) was higher in mature wood (42.9%) than in juvenile wood (41.4%).

From these results, and data on other species, a small reduction in pulp yield can be anticipated when pulping juvenile wood. Results of comparative kraft pulping studies in Douglas-fir, lodgepole pine, western hemlock and white spruce are shown in Table 1, along with average values for relative densities for the two wood zones. Inclusion of relative density figures allows the calculation of pulp yield on the basis of volume of wood input into digesters. The full effect of juvenile wood is to depress pulp yield by some 15 percent, compared to yields expected from an equal volume of mature wood.

Table 1 also compares the quality of pulp from juvenile and mature wood. In all species, tear strength is lower in juvenile wood pulp, owing in part to the well-known dependence of tear on tracheid length. It is also generally accepted that thicker cell walls contribute to higher tear strength of pulps. Consequently, hemlock and spruce appear to be less disadvantaged than Douglas-fir or lodgepole pine, because hemlock and spruce have thicker cell walls in their early juvenile wood, as indicated by the high wood density in this zone.

In Douglas-fir and lodgepole pine, the appreciably lower density of juvenile wood allows the individual tracheids from this region to collapse and form interfiber bonds more readily during sheet formation, leading to sheets of stronger burst and tensile strength. The smaller density differential between juvenile and mature wood in spruce and hemlock seems to result in a slightly lower burst and tensile strength in juvenile wood of these species.

Less is known about the effect of juvenile wood on mechanical pulp properties. Hatton and Johal (1994) have found that in refiner and chemithermomechanical pulps of Douglas-fir, lodgepole pine and its closely related jack pine, mature wood consistently gave greater tear and tensile strengths at comparable freeness levels. This was attributed to significantly longer fibers in the mature wood. In spite of its higher density, the specific energy to produce refiner pulps was lower in mature wood. The greater fraction of fines in juvenile wood pulp increased its light-scattering coefficient, of particular benefit in printing grades.

Strength and stiffness of sawn wood

Among the very first studies relating within-tree variation to strength in any species was that of Kraemer (1950) in red pine (*Pinus resinosa* Ait). He found that considerable variation in strength and stiffness remained between inner and outer locations across the stem, after using covariance analysis to remove the effect of specific gravity and growth rate. He ascribed the poorer mechanical properties of young trees (compared with old growth) as a function of rapid growth in plantation trees. The concept of juvenile wood had not yet been introduced; otherwise Kraemer probably would have related the generally low strength of young plantation trees to their large volume of juvenile wood. Consistent with our present knowledge of juvenile wood, he observed significant variation in microfibril angle, ranging from 56° in rings near the pith, to 8° in older wood, and he concluded that this could be the main factor influencing variation in mechanical properties.

There have been a number of more recent studies relating strength properties of plantation trees of southern pines (Pearson and Gilmore 1971, 1980; Biblis 1990; MacPeak et al. 1990; Kretschmann and Bendtsen 1992; Biblis et al. 1993) and radiata pine (Cave and Walker 1994). The general conclusion drawn from these studies has been that juvenile wood has significantly less strength and stiffness than more mature wood, and that the discrepancy between the two zones is greater than expected simply by differences in relative density. The juvenile wood may be so impaired in mechanical properties that the lumber product does not meet the design code specifications for its visual grade.

An early study on within-tree variation in rapid second growth Douglas-fir was initiated by Littleford (1961), who found that small clear samples cut within 15 rings from the pith had lower strength and stiffness than outer wood. When specific gravity variation was statistically eliminated, differences in modulus of rupture were slight, but maximum crushing strength still varied significantly between the two zones, and modulus of elasticity behavior was intermediate between the two strength properties.

Kennedy and Warren (1969) analyzed the results of standard ASTM small clear tests made on 78 large old growth Douglas-fir. They found a significant increase in bending and maximum crushing strength from the pith outward through a radius of 30 cm. This increase was not due to radial specific gravity variation alone, because specific strength (strength/specific gravity) still showed a regular outward increase. Again with clear Douglas fir, Senft et al. (1986) found that modulus of elasticity was very sensitive to radial position, virtually doubling in value from pith to bark, while relative density increased by only one-third.

Bendtsen et al. (1988) were the first to study the influence of juvenile wood on full-sized (2 inch × 4 inch) lumber cut from Douglas-fir plantation trees 75 years old. The parallel-to-grain tensile strength of the 2 × 4 pieces composed entirely of juvenile wood (rings 1–18) was only 59 percent of mature wood strength, while modulus of elasticity was 72 percent as great. The relative density of the juvenile wood was 78 percent of the mature wood. Analysis of a similar study by Barrett and Kellogg (1991) indicated that while juvenile wood had an average relative density equal to 85 percent of that of mature wood, modulus of repture of juvenile wood was only 69 percent of mature wood, and modulus of elasticity was 79 percent. These results again point to some other factor in addition to density that is regulating mechanical properties, and both studies indicate that strength is more severely impacted by juvenile wood than stiffness in this species.

Much less information relating within-tree variation to strength is available for other western conifers. Pellerin et al. (1989) noted that several strength properties of old-growth lodgepole pine were greater in material sampled 9 cm from the pith, compared to material closer to the stem center. However, no corresponding density figures were available to assess the significance of this difference. Bryan and Pearson (1955) measured maximum crushing stress in clear samples of Sitka spruce from pith to bark. They found that specific strength increased with rings from pith, i.e., the increase in strength was more than proportional to the change in specific gravity. In young, fast-grown trees of this species, Schaible and Gawn (1989) found a reduced yield of high strength lumber, owing to a high percentage of juvenile wood in all samples. Likewise, Zhou and Smith (1991) found a yield of low-grade lumber (reject and structural light framing No. 3) amounting to 63 percent of total output from 55 year old white spruce trees. They associated this preponderance of low value lumber to the presence of juvenile wood (first 15 rings), which accounted for up to 55% of the total timber volume at this rotation age. Pieces having more than 76 percent juvenile wood content had only three-quarters of the bending strength and stiffness of more mature wood. Relative density was not a major contributing factor, since the juvenile wood was nearly as dense (94 percent) as the mature wood. However, knot area was greater in the juvenile wood, and could have accounted for about half of the differential between juvenile and mature wood. Nevertheless, juvenile wood per se was significantly weak to prompt the authors to recommend that the presence/absence of pith in lumber be recognized as an indicator of juvenile wood, and be applied as a criterion in visual lumber grading.

Work in progress by Ellis[1] is examining bending strength and stiffness of small clear pieces of second growth western hemlock in relation to their radial position from pith to bark. Fig. 4 shows that both of these mechanical properties increased significantly through the first 40 years from the pith in spite of a drop in initial density and only a modest recovery by age 40. The increase in stiffness is quite remarkable, since

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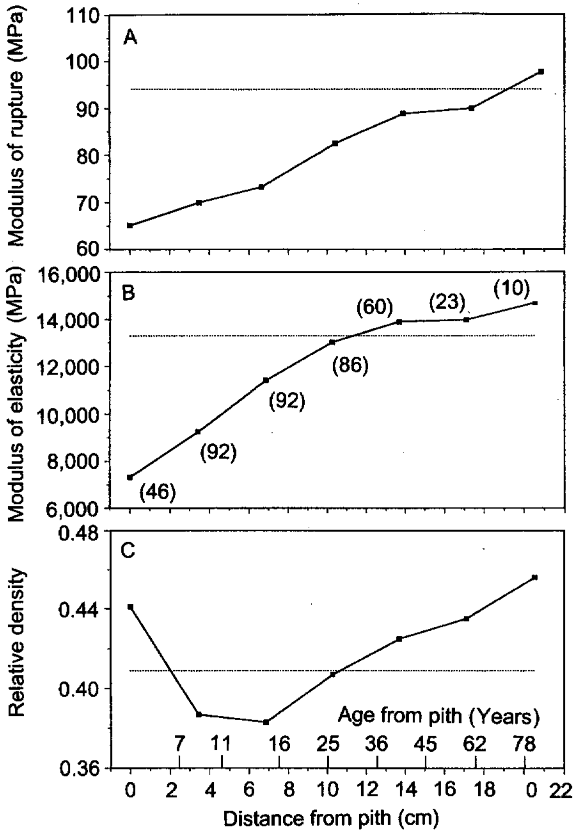

Fig. 4A–C. Relationship of bending strength, stiffness and relative density with age and distance from pith in clear second-growth western hemlock tested at 8% m.c. Horizontal dotted lines represent average values for old-growth wood corrected to 8% m.c. (A and B), and average basic density for old-growth hemlock (C). Numbers next to points represent number of individual tests

modulus of elasticity nearly doubled from 7200 to 14000 MPa over the first 40 years. Over the same age span, modulus of rupture increased by a smaller (38 percent) but nonetheless noteworthy degree, considering the minor fluctuations in density over that period. Fig. 4 also shows the age which these second growth hemlock trees must reach before producing wood considered average for the species (Jessome 1977). It appears that it would take about 70, 30 and 23 years to reach expected average values for bending strength (Fig. 4A), stiffness (Fig. 4B) and density (Fig. 4C), respectively.

The question that emerges from all these studies is why strength and stiffness generally increase from the pith outward a faster rate than relative density. Obviously there are qualitative changes in tracheid walls in addition to just increases in wall thickness that manifest themselves in improved mechanical properties. There is ample evidence in the literature that fibril angle decreases from the pith outward, following closely the pattern of tracheid length increase (Echols 1955; Erickson and Arima 1974). For example, Wellwood (1962) reported fibril angles of 22° and 19° respectively for western hemlock earlywood (EW) and latewood (LW) in ring 1, and a subsequent decrease to 11° and 8° by 27. This paralleled a tracheid length increase of 1.21 mm (EW) and 1.34 mm (LW) in ring 1 to 2.84 mm (EW) and 3.11 (LW) by ring 27. The decrease in fibril angle accounted for about 29 percent of the increase in micro-tensile strength of latewood from these rings. Even within mature wood (rings 36–45) of Douglas-fir, Ifju and Kennedy (1962) found mean fibril angles of 33° (EW) and 11° (LW), and a strong relationship between these angles and micro-tensile strength, accounting for 77 percent of the strength variation. Both Ifju and Kennedy (1962) and Kennedy (1966) found specific tensile strength and stiffness of latewood of Douglas-fir and Norway spruce to be at least 50 percent greater than earlywood.

Cave and Walker (1994) recently have concluded that "… cellulose orientation in the S_2 layer is a principal predictor of timber quality, with density behaving as an auxiliary variable." They note that the effect of density on strength and modulus of elasticity may be largely through microfibril angle, because as relative density increases, so does the proportion of highly oriented (small fibril angle) latewood.

Practical implications and strategies for best use of short rotation plantation trees

These specific Northwest conifers will have different overall qualities in second-growth plantations, owing to their shorter rotations and more rapid growth. Figs. 1–3 show that average relative densities will be lower, and Table 1 indicates the lower yields to be expected in pulping an increased proportion of juvenile wood. However, with the exception of tear strength, the quality of pulp from this zone is not affected, and may even be enhanced to a certain degree. Strength and stiffness of clear wood and lumber products will be adversely affected through a combination of lower densities and larger fibril angles in the juvenile and transition zones.

The present practice in structural lumber production is to grade the lumber visually, and assign an appropriate stress value to it which is consistent with the characteristics of the grade. However, these stress values have been determined from testing wood from old-growth forests, which yields large logs having a higher proportion of mature wood. There is increasing evidence that visual grade stresses applied to lumber from short-rotation plantation trees are in many instances too high, because of the preponderance of juvenile wood. For example, Barrett and Kellogg (1991) found that Select Structural (visual) grade lumber from the juvenile zone of butt logs from second-growth Douglas-fir did not have the bending or stiffness properties normally associated with that grade. Instead, it was the equivalent of only No. 2 grade. Similarly, Select Structural lumber sawn from the juvenile wood of upper logs had the mechanical characteristics of only No. 3 or Economy grades. Bendsten et al. (1988) also concluded for 50-year rotations of Douglas-fir, that an unacceptably large proportion of visually graded lumber would not meet structural design stresses. Fahey et al. (1991) found that Douglas-fir lumber containing large amounts of juvenile wood could only carry stress values of 1450f or be downgraded to No. 3 lumber, compared with similar visual quality containing largely mature wood, which could be stress-rated at 1650f or better. Although specific testing of commercial structural lumber from juvenile vs. mature zones has so far largely been limited to Douglas-fir and the southern pines, a similar pattern is suggested in white spruce (Zhou and Smith 1991) and by the clear wood figures reported for western hemlock in Fig. 4.

The legitimate stress values to assign to juvenile wood lumber are thus of increasing concern. One alternative would be to identify lumber containing juvenile wood by colorcoding the zone on ends of logs before sawing, and to then assign lower grades to the juvenile wood lumber developed which would match its lower strength and stiffness characteristics. However, not all juvenile lumber needs to suffer this falldown in grade, because some proportion of it actually has properties appropriate to its visual grade. In fact Barrett and Kellogg (1991) found that about half of the potential loss in value due to indiscriminate property downgrading of juvenile wood could be avoided by machine stress rating (MSR). This system measures the stiffness of every piece passing through it, thereby segregating the non-conforming portion of the population, while preserving the grade of those boards displaying adequate performance.

In order to optimize the allocation of lumber to appropriate stress grades and general appearance grades in the future, the quantitative values of that MSR grading can supply are required. However, even MSR is not without its problems; Kretschmann and Bendtsen (1992) noted a change in the slope of the strength-stiffness relationship with increasing amounts of juvenile wood in loblolly pine lumber. Improved mechanical grading techniques employing measures of density, slope or grain and moisture content in addition to stiffness are being researched, and probably will be developed commercially in some combination. A large proportion of juvenile wood consequently may be assessed for uses where strength is not as important as appearance; the rather small, tight knots within the juvenile wood zone may even have positive value. Special care during drying of juvenile lumber, such as applying weight restraints on the top of kiln loads may be necessary. Otherwise, warping degrade may result from excessive longitudinal shrinkage of the first-formed juvenile wood, which is characterized by large fibril angles.

Most of the lumber produced from the mature zone of logs will develop structural grades identified by MSR, and some smaller amounts of juvenile wood will also qualify. Since the engineering performance of the MSR grades is clearly indicated, species preferences may be secondary to obtaining the appropriate strength and stiffness grade for specific structural requirements.

The practice of using strong and stiff material for upper and lower flanges of I-beams, for outer laminations in glued-laminated lumber and laminated veneer lumber, and for tension chords of roof trusses will accelerate and become more widespread as more sophisticated engineered wood products are developed. Juvenile wood can still be quite acceptable in locations within these products where they are needed only to carry horizontal shear stresses. In summary, lumber from various wood zones should be marketed less as a homogeneous commodity and more as specialty products having properties to meet the end use intended.

Wood supply is a tightening constraint on producers' ability to supply all wood products, including pulp. As sawmills increase their efficiency of solid wood recovery through better sawing and end-and edge-gluing techniques, the quantity of available pulp chips in the form of mature wood will diminish. More of the pulp raw material will come from previously unmerchantable tops of harvested trees, i.e., that length of the crown and upper stem from 10 cm to 3 cm in diameter. Virtually all of this wood will be juvenile; this pulpwood supply will be augmented by more early plantation thinnings that will also be overwhelmingly juvenile. Owing to the reduced yield from juvenile wood, and more importantly, the extra handling cost of this small material, it will certainly be more expensive than present sources that include sawmill residual chips and pulp-grade logs. The cost of using such material to produce a ton of pulp has been estimated to be 65 percent more than using traditional mature wood supplies (Kirk et al. 1972).

Since the quality of kraft pulp from juvenile wood can be significantly different from mature wood (Table 1), the manufacturer has an opportunity to produce pulps with specific properties; for example, if achieving a high sheet density, as well as good burst and tensile strength is required, juvenile wood serves admirably. If high tear strength is required, Douglas-fir mature wood, with its large proportion of thick-walled latewood tracheids, is ideal. If a pulp of balanced properties is required, than a measured ratio of juvenile wood to mature wood should supply the furnish. Furthermore, it should be noted that although mechanical pulps of juvenile wood of Douglas-fir, lodgepole and jack pines are weaker than mature wood pulps in tearing and tensile strength, they are superior in light-scattering capability (Hatton and Johal 1994). This would make juvenile wood mechanical pulp attractive for printing grades. In the future, it may be more critical to store pulp chips by juvenile and mature wood categories, as well as by species, in order to optimize the quality of pulp for identified customers.

More attention paid to the origin of the wood entering mills, better segregation and grading, and a greater array of grades and products to meet specific end uses can assure quality wood products for expanding markets in the 21st century, regardless of the changing nature of the raw material base.

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