

JUVENILE WOOD EFFECT IN RED ALDER: ANALYSIS OF PHYSICAL AND MECHANICAL DATA TO DELINEATE JUVENILE AND MATURE WOOD ZONES

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ABSTRACT

The objective of this study was to investigate the influence of juvenile wood on the mechanical and physical properties of red alder. Tree growth in the first 10 to 20 years, usually referred to as juvenile wood, often influences wood quality by adversely affecting mechanical strength properties. Strength can be reduced up to 50 percent by the presence of juvenile wood. More knowledge of juvenile/mature wood properties will provide practical information for silviculturists and processors of red alder, leading to a more appropriate usage of this species. Six red alder trees were used in this investigation and a collaborative anatomical study by Oregon State University (OSU). The three-point-bending test mini-specimens were taken from a pith-centered, radially oriented slab in the green condition. Sample material was taken at breast height and below the first major branch for height comparison. Measured variables for the Purdue study were modulus of elasticity (MOE), modulus of rupture (MOR), specific gravity (SG), and work-to-failure (Work). MOE in red alder was found to have a mean join point (end of juvenility) of approximately 16 years and 10 years for the bottom and the top sections, respectively. The variability of MOR, SG, and apparent Work property values over time rendered them unsuitable for indicating a juvenile-mature wood join point.

World population is projected to more than double by the end of the 21st century, with a commensurate increase in demand for forest products (13). Old-growth forests are finite, and when harvested, are effectively lost for decades. An additional pressure on the current timber resource is increased governmental regulation of harvest on publicly held timberland in response to environmental concerns.

The combination of diminished harvest during an era of constant/increased demand has created both problems and opportunities for the Pacific Northwest wood products industry. Problems caused by having less material for harvest include industry down-sizing, employee layoffs, and inability to meet market demand. However, with a market shortfall, new opportunities arise for nontra-

ditional resources. One potential area for alternative species use is partial substitution in the traditional resource market.

Red alder (*Alnus rubra*) is an alternative species that could potentially fill some of the market opportunities created by the decreased softwood harvest in the Pacific Northwest. Red alder is the most common hardwood in the Pacific Northwest (2,25), with a growing stock

volume of 7,436 million cubic feet (MMCF) (19). Uses for red alder include face veneer, furniture, core-stock and cross bands in plywood, and chips for waferboard and pulpwood (19). Also, red alder has been shown to have potential for use as stud material (16) and oriented strandboard (18).

Increased utilization, both in hardwood and softwood markets, will place

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Forest Prod. J. 50(7/8):75-87.

a greater demand on the available alder resource. Initially, movement into new markets, e.g., softwood-dominated structural arenas, requires an extensive examination of the species' mechanical behavior and variability. Only after a sufficient testing database is established can the species be accepted for structural use. Currently, baseline strength data for clear red alder has been established (19), with some additional information on red alder's stud use potential (16). Red alder's pioneer nature, rapid growth, and genetic variation show potential for improvement in growth and quality through breeding (19), implying potential shifts in wood quality.

There is a relatively unexplored factor that could greatly affect wood quality in both current and future timber resources (particularly fast-grown material). This factor is juvenile wood, and its effects on wood quality in southern and western softwoods are well known. But for hardwoods, research in this area is limited.

The tree stem can be classified as two regions, juvenile (core) and mature (outer), based on fundamental differences in the structure and properties of the wood (21). Juvenile wood is found in both softwoods and hardwoods, and is usually of lower quality (particularly in conifers) than mature wood (12). Juvenile wood is formed in a cylindrical column about the pith, following the crown as it grows (21). As shown in **Figures 1 and 2**, which are adapted from diagrams in previous reports (5,26), when measured outward from the pith, properties

of juvenile wood make a gradual transition toward those of mature wood (5). The boundary of this zone, while dependent upon the property measured, occurs on the average at 5 to 20 rings from the pith (although there can be wide variations) (12).

The effect of juvenile wood on softwoods has been extensively explored. However, comparatively little research of juvenile effects on hardwoods has been done. To compete with softwoods and/or be managed effectively, greater knowledge of both juvenile and mature wood properties in red alder is needed. This study examined the behavior of selected wood properties for red alder by exploring radial variation from pith to bark at two heights within each tree on a growth increment basis. There were two specific objectives:

1. Create and evaluate pith-to-bark profiles of red alder for juvenile wood effect on the properties of specific gravity (SG), modulus of rupture (MOR), modulus of elasticity (MOE), ring width, and work-to-failure (Work).
2. Determine statistically if an "age of maturity" or "juvenile wood zone" based on each tested property can be assigned.

LITERATURE REVIEW

In large stem, old-growth timber, the proportion of juvenile wood is relatively small and its effects are confined to the material taken from the center of the tree (often largely contained within one piece). With large stems, one piece is a small portion of the total yield, and has little effect on the average behavior of

the whole. With the advent of plantation-grown timber, and the increased harvesting of younger, smaller-diameter stems, the proportion of juvenile wood in the resource became greater (5).

On the West Coast, softwoods have traditionally been the species of choice for timber harvesting and use in structural lumber. The diminishment of the old-growth resource, the increased use of fast-growth, early-harvest softwoods, and the advent of environmental pressures have forced consideration of alternate timber sources in the structural marketplace (13). The potential exists for underutilized hardwoods to provide this alternative lumber source. However, competition with traditional softwood sources will be extremely difficult if the properties affecting the desired structural performance within this new market are unknown. One very important contributor to wood behavior is the effect of juvenile wood. The relevant previous studies of juvenile wood effects on hardwoods are reviewed with a specific focus on the characteristics of red alder (*Alnus rubra*), a diffuse-porous species.

Although researched less extensively than those of softwoods, some general qualities of juvenile wood in hardwoods are known. Juvenile wood cells in hardwoods are shorter than mature wood cells (12). The mature fibers are approximately twice as long as the juvenile fibers (7). There is more spiral grain found in juvenile wood (20). Juvenile wood in hardwoods occurs in a core and

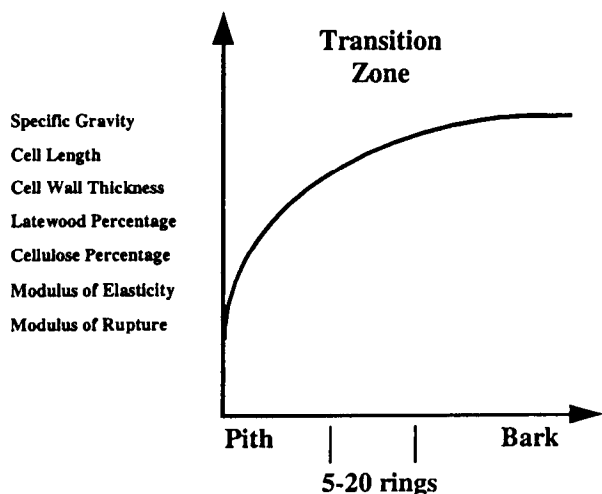


Figure 1. — Graphical representation of an increasing trend for wood property changes from pith to bark.

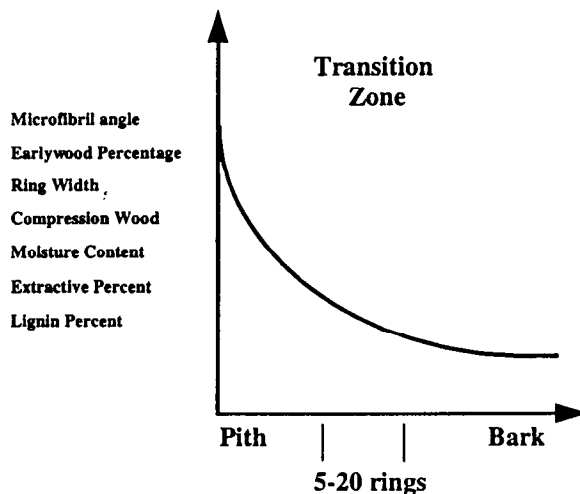


Figure 2. — Graphical representation of a decreasing trend for wood property changes from pith to bark.

the characteristics for the most part make a gradual transition to some steady, mature state (12,26). There does not seem to be an exact demarcation where juvenile effects end and mature wood begins, but rather there is a property-dependent transition zone (5,12,26).

Additionally, some specific research has been done concerning juvenile effects in hardwoods. Bendtsen and Senft (6) examined plantation-grown cottonwood for juvenile wood effects. Foster and Thor (10) recorded juvenile wood variation for SG and fiber length in American sycamore. Harrington and DeBell (11) explored SG variation from the pith to the bark in red alder. Quanci (26) examined juvenile wood effects on MOE, MOR, SG, microfibril angle, cell length, ring number, and average ring width in white ash. Roos et al. (29) researched juvenile wood effects on MOE, MOR, and SG in quaking aspen. Taylor and Wooten (35) looked at variation from pith to bark for SG, fiber length, fiber dimensions, and volumetric composition in black willow, willow oak, sycamore, pecan, and sugarberry. Taylor (34) also investigated juvenile wood effects on SG and fiber length in blackgum, mockernut hickory, post oak, shagbark hickory, and southern red oak.

Examination of the available hardwood literature reveals that there are conflicting findings for variation within and between species. Comparison is difficult due to the wide variation of wood characteristics, different management practices, and the lack of a standard research method. A primary source of dispute, for example, is the effect of age versus growth rate. A succinct statement of this conflict was given by Quanci (26): "Each is purported to be the major or sole controlling factor for specific gravity, microfibril angle, and cell length, which in turn affects modulus of rupture and modulus of elasticity." The natural and continual confounding effect of these two properties on one another (15,33) makes it very difficult to perform a definitive study on their influence concerning mechanical properties. Therefore, the remainder of this review will examine the wood property patterns and relationships that industry investigators have commonly used to determine wood quality.

Basic wood quality research Uses three patterns for wood characteristics in

the standing tree: horizontal, vertical, and intra-ring (26). Only the horizontal (radial) pattern will be examined in this review, with emphasis on characteristics of diffuse-porous hardwoods. The direct relationship of SG to mechanical properties and the amount of wood fiber in the tree is the primary area of interest for exploration of wood property patterns (21,36). SG is statistically related to the mechanical strength of wood and is a good index of hardness, strength, and other mechanical properties. For hardwoods, SG has been found to increase from pith to bark in over half of the species studied (21). SG changes are also associated with the delineation of juvenile and mature wood zones (5). According to Panshin and de Zeeuw (21), softwoods have consistent (usually increasing) SG patterns from pith to bark, but hardwoods do not show the same definite trends.

Calculation of SG in wood can be critically influenced by individual growth ring composition. SG of an individual growth ring represents an average of the earlywood and latewood. However, earlywood and latewood can differ considerably in anatomical composition, depending on species, genetic variability, and environmental conditions. Consequently, determination of SG is often confounded by anatomical variation.

Three general trends (types 1, 2, and 3) can be used to describe radial SG patterns in hardwoods. For type 1, moving in a radial direction, SG increases from pith to bark in a curvilinear pattern (dropping off slightly toward the bark) (34). For type 2, there is a converse pattern where SG decreases moving in a radial direction from pith to bark (12,23, 34,35). For type 3, no significant change is seen in the uniformity of SG from pith to bark (17,22).

This variety of trends has been shown by various researchers. Ring-porous white ash (*Fraxinus americana*) was found by Paul (23) and Quanci (26) to exhibit both type 2 and type 3 patterns. A semi-ring-porous species, black walnut (*Juglans nigra*), showed a type 2 pattern (23,24). Diffuse-porous species exhibiting a type 1 pattern included quaking aspen (*Populus tremuloides*) (29), eastern cottonwood (*Populus deltoides*) (6), American sycamore (*Platanus occidentalis*) (10,35), black willow (*Salix nigra*), sweetgum (*Liquidambar styraciflua*),

and blackgum (*Nyssa sylvatica*) (34). Red alder (*Alnus rubra*) showed a type 3 pattern (11,17,22). The results of these studies reveal that there is considerable variation in hardwood SG from pith to bark among and, in many cases, within species. The considerable variation exhibited by these hardwood species strongly implies that SG cannot always be relied on as an indicator of juvenile wood presence in hardwoods. In the case of red alder, all research to this point indicates no discernible juvenile wood effect on SG. It should be pointed out that, particularly for diffuse-porous hardwoods, ring-to-ring variation in SG is often relatively small over a wide portion of a stem, making strong property relationships difficult to discern.

Attempts to relate growth rate to SG in hardwoods have been contradictory. Paul (23) found the growth rate to be related to SG for a wide variety of species. Radcliffe (27) found that for sugar maple (*Acer saccharum*), the growth rate was not related to SG. SG of hardwoods depends on the types of tissues (vessel elements and fibers) and their relative proportions (26). Many studies fail to account for the different SG of earlywood and latewood.

In an extensive examination of the available literature, Dinwoodie (9) concluded that fiber length increased rapidly outward for the first few rings from the pith for every species studied. Fiber length was found to increase from pith to bark in ash (8), green ash (*Fraxinus pennsylvanica*) (31), and oak (*Quercus* spp.) (35). Saucier and Hamilton (31) concluded that age and tree height explained 85 percent of the fiber variation in green ash. Quanci (26) found cell length in white ash (*Fraxinus americana*) increased in a curvilinear pattern for one tree, but varied too much for a pattern to be discerned for the remaining three sample trees.

The effect of growth rate on cell length in hardwoods is basically unknown. One publication found no relationship between growth rate on fiber length in ash (*Fraxinus excelsior*) (8). Quanci (26) found that for specimens taken from three trees of white ash, cell length initially increased, but then was constant from pith to bark. However, specimens from the fourth tree showed a curvilinear increase from pith to bark.

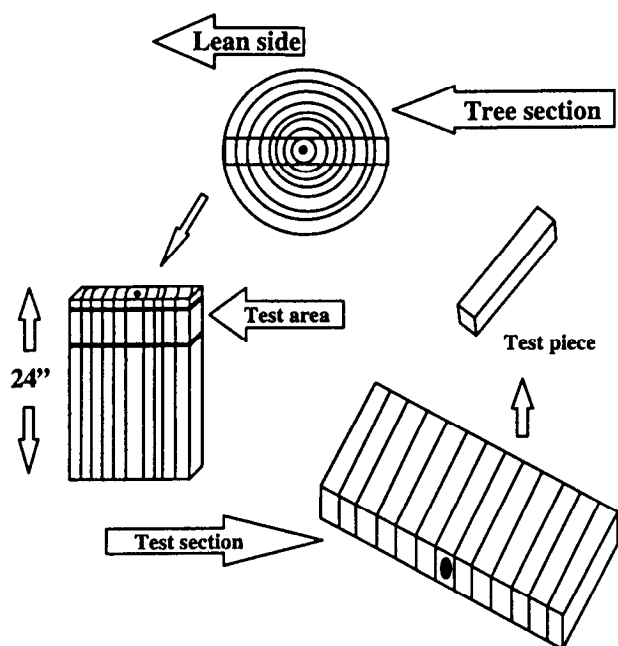


Figure 3. — From top, proceeding counter-clockwise, the schematic shows the general tree section, initial radial section, test section, and test piece.

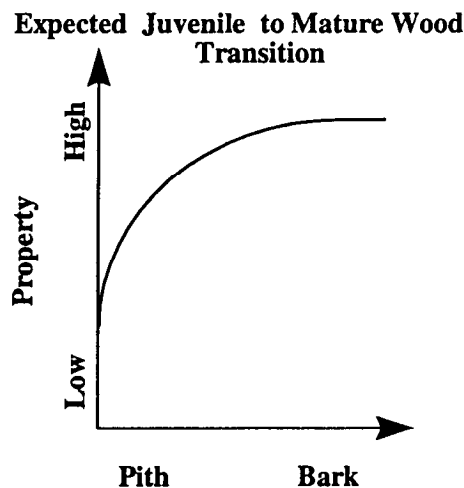


Figure 4. — Example of an increasing property curve over time.

The influence of cell length upon bending tests in eastern cottonwood was examined by Bendtsen and Senft (6), and the results showed that fiber length accounted for 25 percent and 43.5 percent of the variation of MOR and MOE, respectively. Results of regression analysis by Quanci (26) using cell length, SG, ring width, MOE, and MOR showed that inclusion of cell length did not significantly improve the model. Therefore, there was no statistical evidence that cell length contributed to MOR and MOE variation in white ash (26).

Ring width in all trees normally follows a general pattern of decrease as age increases (26). Ring number counted outward from the pith is used to indicate tree age. Growth rate, which is expressed by ring width, is controlled by a variety of environmental factors and is highly variable. On a forested site, decreasing growth rate as a tree ages is usually a result of stand competition (32). Competition for resources (light, water, soil nutrients) with other organisms and/or environmental fluctuations can impact growth (14). Any of these factors either singly or in combination can affect the tree's growth rate. The principal difficulty in attempting to determine the independent effects of ring width and age is the tendency of the two

factors to naturally confound one another (26). To study the independent effects of age on properties, growth rate influence must be accounted for in some manner.

In eastern cottonwood, a diffuse-porous species, MOR and MOE were found to increase from pith to bark (6). Additionally, MOR and MOE were shown to increase from pith to bark in diffuse-porous quaking aspen (29). However, Quanci's investigation of ring-porous white ash showed no increase in MOR and only a small increase in MOE for this species (26). One potential explanation for the behavior of Quanci's mechanical property results could be the effect of growth rate on annual ring density. It has been shown that SG in ash is affected by growth rate (23). Correlation between SG and the mechanical properties MOE and MOR in both softwoods and hardwoods has been demonstrated for a large number of species (3). It would be reasonable to expect some portion of MOE and MOR variation to be attributed to SG changes.

MATERIALS AND METHODS

The responsibility of choosing the species and sample trees was assigned to the collaborative researchers at Oregon State University. Six red alder trees were selected from an uncultivated site as rep-

resentative specimens. Site information and lean of each selected tree were recorded before felling. The trees were selected from a 40-year-old, even-aged stand of mixed big-leaf maple (*Acer macrophyllum*) and red alder located in the McDonald-Dunn Forest of Oregon State University. Sample trees with similar diameters { $33\pm 3\text{cm}$ ($13\pm 1\text{in.}$)} at breast height, having minimal lean, relatively straight stems, and with relatively few external defects were chosen with the intent of minimizing tree-to-tree variation. After felling, two log sections were taken from each tree, with the first section being taken at breast height (1.5 m) and the second section taken just below the first large branch. The purpose in taking two sections was to allow comparison of height effects. Each log section was then further divided into an upper and a lower piece, each of which was wrapped in plastic, kept cold, and maintained in the green condition. The upper piece was assigned to the Purdue researchers, while the lower piece was retained by Oregon State. In this manner, future comparison of anatomical relations to mechanical properties would retain some basis of commonality. A general schematic picturing the log section orientation with respect to the prepara-

**Bottom of Alder Tree 5,
Opposite Side**

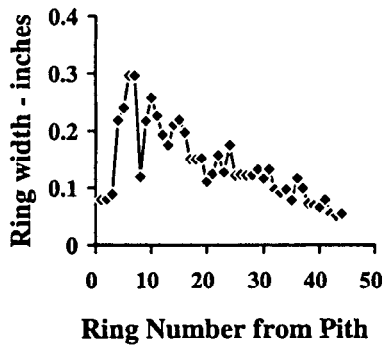


Figure 5. — Ring-width radial profile for the bottom, opposite side of red alder tree section 5.

tion of the Purdue specimen sets is given in **Figure 3**.

The test sections were measured from the pith to the bark in both the opposite and lean directions (no significant difference in lean versus opposite sides was found for any properties), using a microscope-equipped, linear variation measurement table interfaced with an Acurite III digital readout. Growth-ring width measurements were taken to the nearest 0.00254 cm (0.001 in.) along the central radial axis of each test section since the midpoint of each growth ring was the most probable indicator of average growth ring width. The pith was set as the zero reference and measurements were taken continuously from pith to bark in both the lean and opposite directions.

Mechanical testing for all specimens was done on a Riehle Universal Testing Machine using three-point static bending. Individual specimen dimensions were 0.635 cm in width by 0.635 cm in depth by 8.89 cm in length (0.25 by 0.25 by 3.5 in.) giving L/d equal to 14. The modified ASTM (4) three-point bending tests were performed using a 22.72-kg (50-lb.) load cell with a linear variable displacement transducer located at mid-span for recording deflection data. Each specimen was loaded on the radial face to avoid the effect of springwood versus summerwood properties. The load rate was 0.0381 cm/min. (0.015 in/mm). The specimens were randomly chosen for testing in the green condition and later dried for SG measurement. Automated data collection and analysis

**Bottom of Alder Tree 5,
Lean Side**

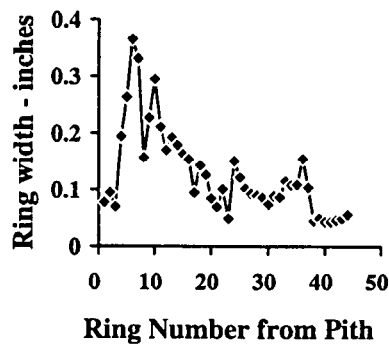


Figure 6.—Ring-width radial profile for the bottom, lean side of red alder tree section 5.

produced MOR, MOE, and total Work data for the 362 specimens.

Specimen number did not indicate the age associated with each property value since specimens usually contained two or more growth rings. Each specimen had to be evaluated to determine the average age to ± 0.01 year. Allowance for known kerf loss was made. Since it was fairly rare for the growth rings to be perfectly straight along a specimen, the criterion for entering the width of each growth ring was based on a visual determination of that growth ring's contribution at the point of maximum moment. Determination of average age for each specimen was based on a weighted percentage of the contributing growth ring widths. Graphs of available properties versus average age were created.

The specimens were divided into 24 groups based on top, bottom, lean, and opposite sides of six trees. Based on those divisions, each independent specimen age had the four dependent properties assigned to it: MOE, MOR, SG, and Work. Therefore, there were 16 working analysis groups for each tree for a total of 96 data sets, each to be analyzed separately.

Determination of a juvenile wood zone relies on the existence of a particular profile. Direct curvilinear relationship between the chosen wood characteristic and age described in the introduction and literature review is the profile most conducive to determination of a juvenile wood zone (**Fig. 4**). Throughout the following discussions, this pattern of rapid property increase in the early years of

growth followed by a plateau in the properties of the mature tree is referred to as the "classic" or "expected" profile (**Fig. 4**).

In any biological material, especially wood, variability is anticipated and provides departure from this classic profile. A non-linear regression data analysis approach was used to attempt to more clearly identify data trends and similarities between data sets and also to identify and bracket juvenile-wood/mature-wood transition ages. The model used for statistical analysis emulates the classic profile by representing the rapid property changes typically found in juvenile wood over time with a curvilinear equation, while the relative stability of property behavior found in mature wood is shown by a plateau. Theoretically, the point at which the derivatives of the two lines are equal, known as the "join point," would indicate the boundary between juvenile and mature wood, dependent on the degree of property variation. Further data analysis was used to statistically group data sets for the various properties to obtain a likely range of juvenile-wood/mature-wood transition ages for MOR, MOE, SG, and Work. In addition, statistical criteria for pooling the profiles within and between trees for each property were examined.

RESULTS AND DISCUSSION

Each property of MOE, MOR, SG, and Work was plotted against the average age of the corresponding specimen. Each tree was divided into four sections for plotting; top, bottom, opposite, and lean. For example, a bottom tree section consisted of two profiles, one taken radially from pith to bark on the lean side, and the other from the side opposite the lean. Top sections were divided in a like manner.

The ring-width profiles were constructed using the width of each ring from pith to bark plotted against the corresponding ring number (RN). Radial profiles of ring width provide the opportunity of observing growth of the tree over time. Typical ring-width profiles are illustrated by the opposite and lean side bottom section of tree 5 in **Figures 5** and **6**, respectively. In all sections, a short period of increasing growth was followed by a decrease in growth-ring width as the tree aged. In general, the age range of 4 to 7 years appeared to be the period of fastest growth and was fol-

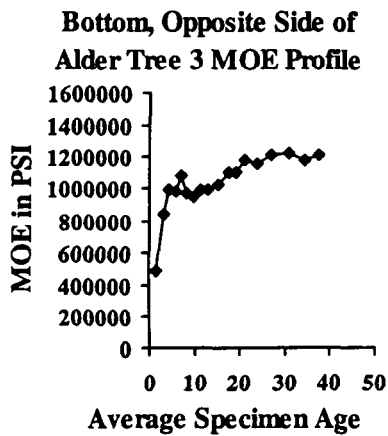


Figure 7. — Graph of MOE for the opposite side of the bottom section of tree 3.

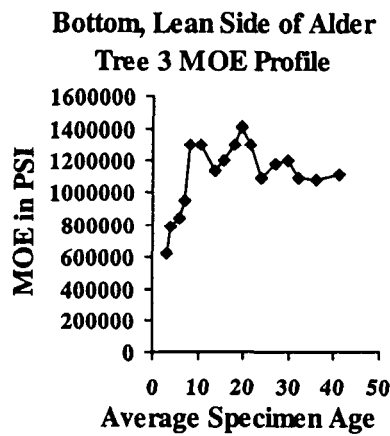


Figure 8. — Graph of MOE for the lean side of the bottom section of tree 3.

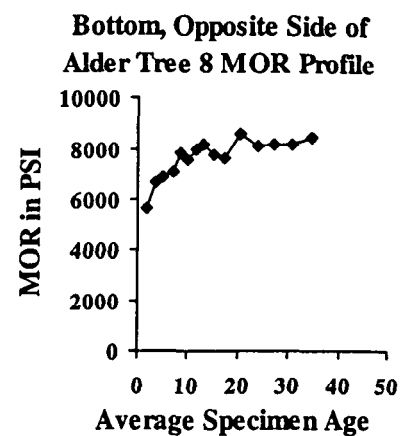


Figure 9. — Graph of MOR for the opposite side of the bottom section of tree 8.

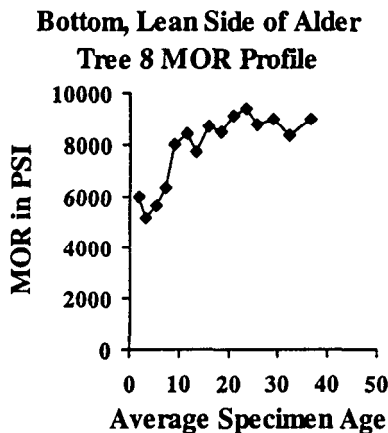


Figure 10. — Graph of MOR for the lean side of the bottom section of tree 8

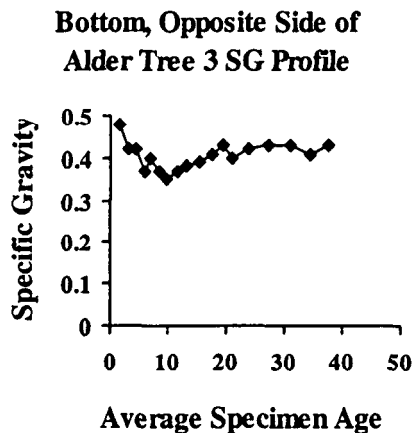


Figure 11. — Graph of SG versus age for the opposite side of the bottom section of tree 3.

lowed by either a decrease or short plateau. Without a detailed management history, direct silvicultural and/or competitive stand effects on growth rate cannot be determined. However, the sample trees had a relatively normal growth pattern for pioneer species in an unmanaged clear-cut.

As in all property profiles in studies of this type, data variability was a problem, not only as variation between successive data points, but also in regard to discernible data trends. **Figures 7 and 8** show the MOE data profiles of the opposite and lean sides for the bottom section of red alder tree 3. These are representative of “average” trends, some were better, some were worse. In general, the conformance of the profiles to the expected curvilinear-increase/plateau curve or

“classic” trend were somewhat better for MOE data than for the other properties studied. Profiles for the tops, with fewer data points, were less definitive. Eight out of 12 profiles had reasonable conformance to the expected profile for the bottoms and for the tops as well; however, top and bottom and lean and opposite profiles did not always match. (The top section lean side of tree 9 was discarded due to the presence of irregular slope of grain).

The bottom section profiles for MOR were generally less definite (more scatter in the data points) than those for MOE. There were also fewer “classic” trends observed; a flat pith-to-bark profile was observed in some cases, particularly for the top sections. For several of the top sections, the trend did not appear

to “peak out,” reflecting the smaller

the top sections). **Figures 9 and 10** are typical MOR bottom section profiles.

In softwoods, SG is one of the leading indicators of juvenile wood presence. However, SG has been found to be uniform from pith to bark in red alder by several investigators (11,17,22). Although 6 of the 24 SG profiles exhibit a reasonable “classic” profile, there is considerable variation in the data. **Figure 11** shows a typical SG profile. Visual observation of SG behavior over time suggests that SG is unlikely to be a reliable indicator of presence or extent of juvenile wood.

Work profiles exhibited unreliable, inconsistent profile trends, and highly variable data. Lack of consistency for both the profile trends and data results preclude the use of Work in predicting juvenile wood presence or in correlation with other properties.

Based on the amount of variation evidenced in the property profiles, it was decided to determine if the individual data sets could be statistically combined (pooled). Analysis of variance (ANOVA) was applied using the SAS (30) general linear model to the grouped data for the properties of MOE and MOR to determine whether there were significant differences between and within trees. Should the trees prove similar, it would be possible to make inferences for all six rather than one (or part of one) tree. Enlarging the data analysis set by pooling usually reduces the effect(s) of individual data variation and allows a clearer view of general trends. The data set was

divided into three classes: trees (T), height (H), and lean (L). Class T was divided into six levels corresponding to the six red alder trees. Height was divided into two levels corresponding to either the upper or lower tree sections.

The ANOVA results for MOE are given in **Table 1** and are based on type III sum of squares. In **Table 1**, between-tree variation (T) for MOE is shown to be significant at the 99.95 percent confidence level. Height effect between trees is significant at the 95 percent confidence level. However, within each tree, the opposite and lean sides (but not the heights) can be pooled, as there appears to be no significant difference between them.

Visual examination is an effective tool for determining trends, but it is dependent upon the judgment of the individual. Bendtsen and Senft (6) used subjective analysis to determine a juvenile wood zone in eastern cottonwood. Quanci (26) also used subjective analysis to determine juvenile wood cessation points in Douglas-fir and white ash. In a radial profile, data groupings that defy statistical analysis can often be clarified by observation. However, subjective analysis by its very nature cannot be used consistently, particularly when employed by more than one observer.

Segmented regression is a statistical analysis technique that is often used to analyze response relationships between the dependent and independent variable(s) that are difficult to represent by a straight line (28). The nature of the expected juvenile wood property curve demonstrates the need for such an analysis technique. The underlying assumption for analysis of the expected property curve is that there are two discrete groups of data composing the entire data set, i.e., juvenile and mature wood. In previous research where property response to age was analyzed (1), the two different groups of data were represented in a segmented regression model by two straight lines with different slopes. The place at which those two lines met (join point), indicated the point at which the first group (juvenile wood) ended, and the second group (mature wood) began. However, the point at which any two segments join is based on the meeting of two linear regression lines, and may be divorced from the actual data curve by a sizable amount.

TABLE 1. — Modulus of elasticity ANOVA results for pooled alder data.

Property	Class	Degrees of freedom	Pr > F ^a
MOE	T	5	0.0001**
MOE	H	1	0.02411
MOE	T × H	5	0.7398
MOE	L	1	0.2290
MOE	T × L	5	0.3884
MOE	H × L	1	0.5576
MOE	T × H × L	4	0.3084

^a ** and * indicate significance at the 0.01 and 0.05 confidence levels, respectively.

TABLE 2. — Comparison of visual and NLIN Join point results of combined opposite and lean MOE values for red alder.

Tree section	Top visual join point	Bottom visual join point	Top NLIN join points	Bottom NLIN join points
	----- (yr.) -----			
3	11	18	9.9	11.3
4	12	18	14.2	39.3 ^a
5	13	15	5.5	11.9
8	10	15	10.6	16.6
9	9	16	9.1	18.6
10	12	15	12	20.3
Mean	11.2	16.2	10.2	15.7
Standard error of mean	0.6	0.6	1.2	1.8
Confidence limits (95%)	9.6 to 12.7	14.6 to 17.7	6.9 to 13.2	10.8 to 20.7

^a Value not included in calculation of mean, standard error of mean, and confidence limits.

When this occurs, it casts doubt on the ability of the model to approximate the true relationship. Visual assessment may differ from segmented regression analysis by a significant amount even for specimens that follow a “classic,” well-defined form.

In this study, a non-linear regression SAS procedure (NLIN) was used in an attempt to more accurately determine a join point. This analysis utilizes a non-linear data estimation for the juvenile wood area coupled with linear trend estimation for mature wood areas. The analysis was based on the hypothesis that the property values increased rapidly along a data-determined curve and then reached a plateau level.

Based on the ANOVA results, MOE values for the opposite and lean sides were combined within each tree. Results for NLIN join point age estimates for the top and bottom sections of each tree are given in **Table 2**. **Figure 12** shows a representative example of the combined tree sections. All data sets except for bottom section 4 (**Fig. 13**) showed good conformation between NLIN join point

estimates and visual observation. In bottom section 4, the general data trend is upward from pith to bark, although visually, MOE appears to plateau around year 16. In **Table 2**, the average age of the bottom sections is 15.7 years by the NLIN analysis, which is significantly greater than the mean value of 10.2 years for the top sections. The average visual estimates (based on two estimators) of 16.2 years for the bottom sections and 11.2 years for the top sections are in close agreement with the average NLIN values, even though individual tree comparative estimates differ significantly.

Based on the evidence presented to this point, MOE appears to be a good indicator of juvenile wood presence. The increase in number of data points obtained by pooling the data appeared effective in reducing specimen-to-specimen variation effects on NLIN estimation of join points. Further information about MOE behavior is presented in **Table 3**, which shows the plateau values associated with the age join points. The plateau values represent the level of MOE

(measured in psi) at which the mature wood zone is assumed to begin.

The *Wood Handbook* (36) lists the average MOE value for green red alder as 1.17×10^6 psi, with a 22 percent average coefficient of variation. Therefore, the upper range extends to about 1.33×10^6 psi. The mean values for red alder given in **Table 3** are higher than those given in the *Wood Handbook*, and trees 9 and 10 are at or above the upper boundary.

However, the overall MOE levels for the trees in this study appear to be in reasonable agreement with established values for the species.

For MOR, there was no statistical justification for pooling the between-tree data, within-height data, or within-lean data. Therefore, NLIN analysis was done on each individual data set. **Table 4** shows the observed and NLIN join points for the alder bottom sections. **Fig-**

ure 14 shows a representative profile combined with an NLIN analysis curve for an MOR bottom section with a well-defined join point. **Figure 15** shows the profile from an atypical data set combined with the NLIN analysis curve. The continually increasing MOR values prevented the NLIN analysis program from defining any plateau. While MOR had a similar property pattern of initial curved increase followed by a plateau as was found in MOE, the degree of specimen-to-specimen variability significantly reduced the ability of NLIN to pick a consistent join point.

NON-STATISTICAL ANALYSIS

Although not defensible in the strictest statistical sense, there are some persuasive arguments for grouping (used to differentiate from the term referred to as "pooled" in the previous statistical sections) the alder data for all six trees (tops versus bottoms). The foremost argument is the reduction of specimen-to-specimen variation effects on NLIN estimation of join points. Ideally, larger sample sets would be procured from individual trees. However, stem size and available testing material limited sample set size. Grouping the data allows a simulation of a larger data set.

There are also some areas of commonality for the trees chosen in this study. The site was chosen as typical of red alder succession. As a pioneer species, red alder commonly appears on recently logged sites. Genetic effects and micro-environment notwithstanding, all six trees could logically be considered "normal" representative members of a red alder stand in the Corvallis, Oreg., region. The trees are all close to the same age and developed under similar environmental conditions (cut in close proximity to each other). If there are general or shared trends, grouping the data for all six trees may make those trends more visible. Grouping the data also reduces the effect of troublesome individual specimen variation. The objective of this entire study was to develop knowledge about property relationships to age for use in predicting when the juvenile wood zone ends. Identification (or further confirmation) of a general trend by subjective means could provide useful information for a study on a larger scale.

MOE and MOR data sets are presented as the grouped tops and bottoms,

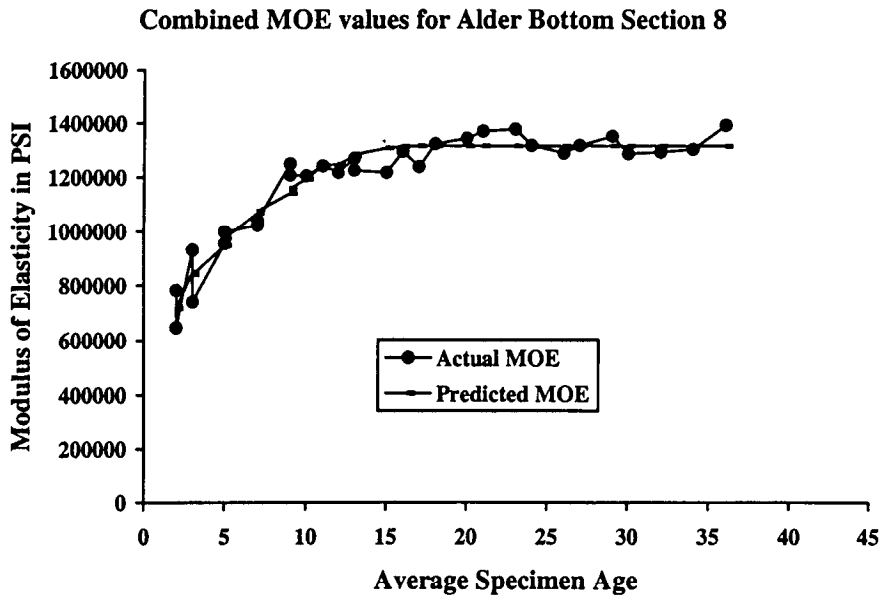


Figure 12. — Pooled MOE alder data for bottom of tree 8, graphed against the NLIN predicted curve.

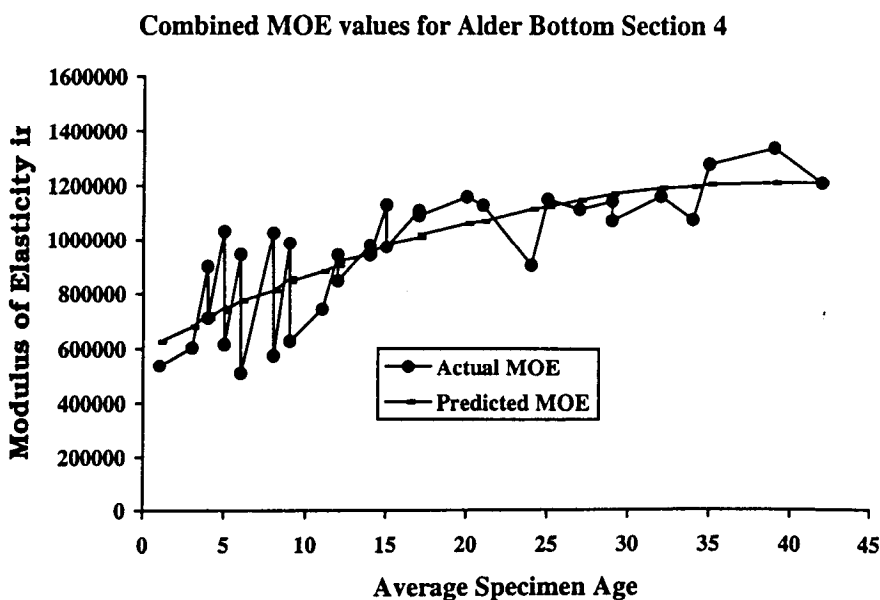


Figure 13.— Pooled MOE alder data for bottom of tree 4, graphed against the NLIN predicted curve.

respectively. **Figures 16 and 17** show the MOE values for the top and bottom of the alder tree sections. The joint points are given in **Table 5**, along with the plateau values. The joint points are all within the confidence limits presented earlier in **Table 2**. The plateau values are also within the confidence limits given in **Table 3**. The form of the grouped data for both sets was typical of the expected “up and over” shape for juvenile wood transition to maturity. The MOR trend for the bottom section in **Figure 19** also showed the expected profile. However, the top portion of the grouped data for MOR shown in **Figure 18** was less clear. This tendency was in agreement with the trend demonstrated earlier in that MOR shows indications of juvenile wood influence, but with less consistency than MOE. SG showed no significant indication of juvenile wood influence, in accordance with the results presented previously.

It should also be noted that for **Figures 16 through 19**, what seems to be multiple identical predictions in the quadratic portion of the curve is actually an artifact created by the graphing software. Many of the actual data points used in the calculation are very close together and it was beyond the capabilities of the graphing program to resolve the

TABLE 3. —Non-linear regression plateau results of combined opposite and lean MOE values for red alder top and bottom sections

Tree section	Top MOE values	Bottom MOE values
	----- (psi) -----	
3	1.27×10^6	1.16×10^6
4	1.21×10^6	1.21×10^6
5	1.27×10^6	1.28×10^6
8	1.29×10^6	1.35×10^6
9	1.35×10^6	1.32×10^6
10	1.36×10^6	1.35×10^6
Mean	1.29×10^6	1.28×10^6
Standard error of mean	22,590	30,144
Confidence limits (95%)	1.23×10^6 to 1.35×10^6	1.19×10^6 to 1.36×10^6

TABLE 4. —Red alder bottom tree section NLIN joint point results versus subjective visual determination of the juvenile wood cessation point for MOR.

Tree section	Sample size	NLIN joint point	Visual joint point
Bottom, opposite section of tree 3	18	2	15
Bottom, lean section of tree 3	17	12	12
Bottom, opposite section of tree 4	16	3	15
Bottom, lean section of tree 4	17	160	14
Bottom, opposite section of tree 5	18	18	13
Bottom, lean section of tree 5	16	9	9
Bottom, opposite section of tree 8	15	15	12
Bottom, lean section of tree 8	15	23	16
Bottom, opposite section of tree 9	17	31	12
Bottom, lean section of tree 9	20	25	15
Bottom, opposite section of tree 10	17	20	15
Bottom, lean section of tree 10	15	26	14

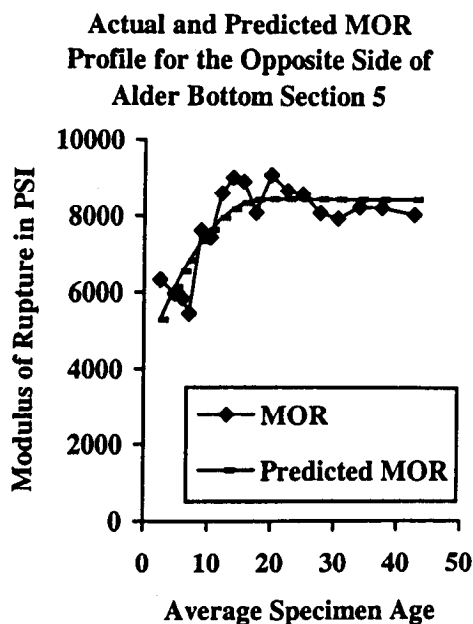


Figure 14. —Typical NLIN curve results for MOR and average age in the opposite side of alder bottom section 5.

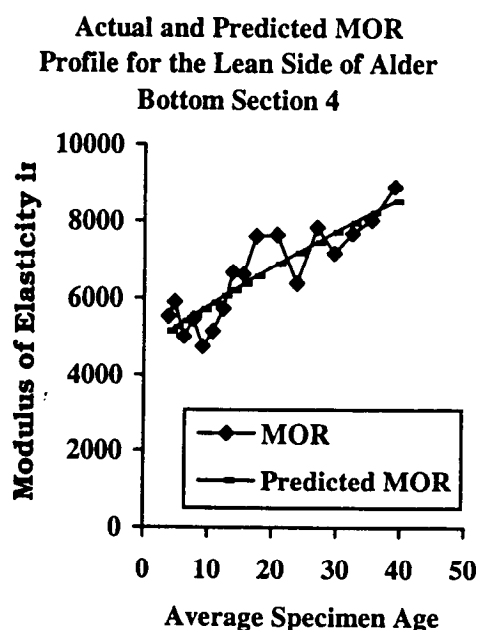


Figure 15. —Atypical NLIN curve results for MOR and average age in the lean side of alder bottom section 4.

Combined MOE Values for Alder Top Sections

gradations. Each predicted value is in fact discrete from all others.

CONCLUSIONS

MOE is a good indicator of juvenile wood presence in red alder. Radial profiles of all alder sections exhibited a rapid increase in MOE during the early years of growth, and 16 of 24 profiles exhibited the expected juvenile wood pattern of increase through the juvenile years followed by a plateau as the tree matured. Statistical analysis with non-linear regression on individual and pooled data sets provided an average join point (end of the juvenile wood transition zone of influence) of 10 ± 3 years for the top sections of alder. This was significantly (at the 95% confidence level) different than the average join point age of 16 ± 4 years for the bottom sections. The average plateau (mature wood) values of MOE for the top and bottom were 1.29×10^6 psi and 1.28×10^6 psi, respectively.

MOR showed evidence of juvenile wood influence in both the radial profiles and the non-linear regression results. However, specimen-to-specimen variation and a lack of consistency precludes the use of MOR as a reliable juvenile wood indicator in red alder. SG and apparent Work did not provide any evidence of juvenile wood influence in red alder.

Observational analysis of MOE patterns for the grouped top and bottom profiles showed a definite conformance to the expected juvenile wood curve. The join points for MOE of 11.6 years (for the grouped tops) and 18.3 years (for the grouped bottoms) are similar to the average join point age results given in **Table 2**. Also, as was seen in the statistical analysis, a clear difference was observed between the join points for the top and bottom MOE data sets. MOR showed evidence of juvenile wood influence, particularly in the grouped bottoms. However, the lack of a consistently clear behavior trend precludes the use of MOR as a reliable juvenile wood presence indicator. No significant evidence of juvenile wood effect on SG was observed.

RECOMMENDATIONS

To insure correlation between anatomical and physical/mechanical data, anatomical data should be gathered from the mechanical test specimens after testing. To minimize the potential loss of

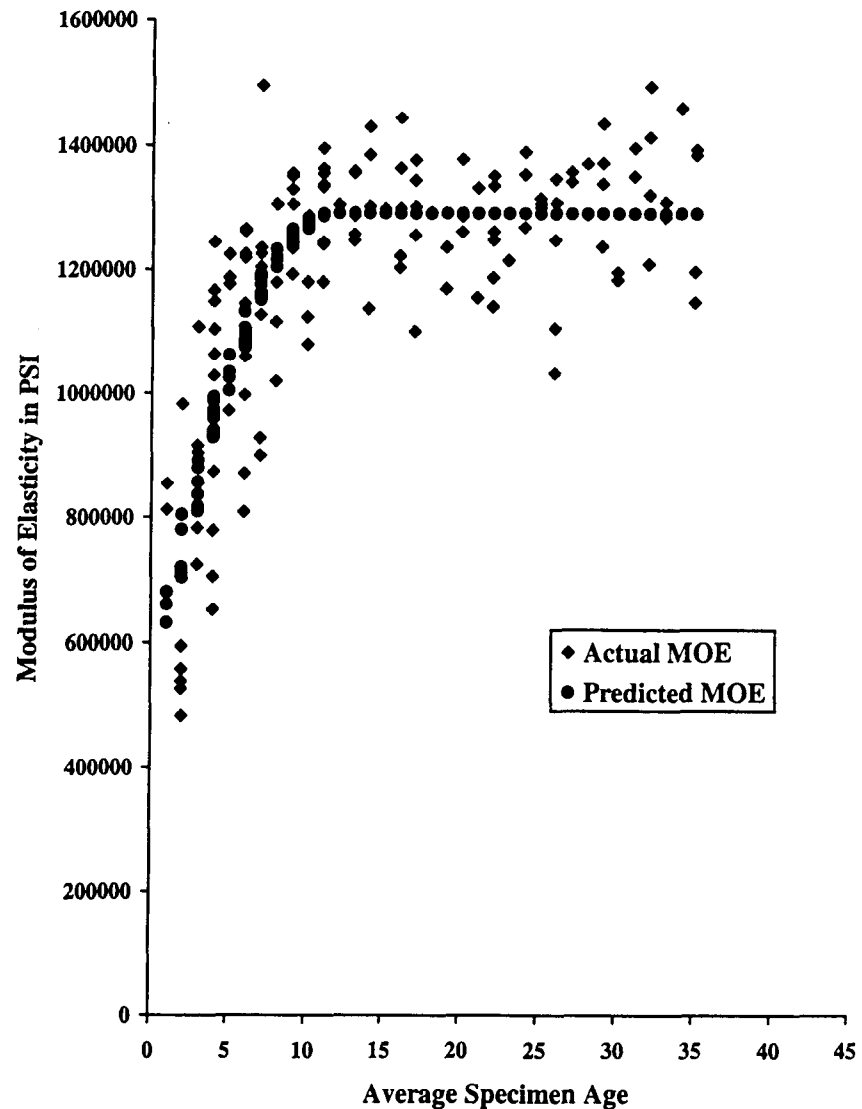


Figure 16. — Graph of the grouped alder MOE top data against the predicted NLIN curve.

TABLE 5. —Join points and plateau values for MOE and MOR properties in grouped red alder

Property	Age	Plateau value
	67.1	(psi)
MOE - top	11.6	1.29×10^6
MOE - bottom	18.3	1.26×10^6
MOR - top	16.1	8,156
MOR - bottom	24.5	8,122

data, potential test trees should have the growth rate and pattern checked by increment core prior to being felled for testing. Alternatively, downed timber could be used by checking the sawn faces prior to choosing test samples. In

either case, the goal would be to select trees with approximately the same growth rate.

The natural variability of wood is well known. These suggestions offer some methods of dealing with problems en-

Combined MOE Values for Alder Bottom Sections

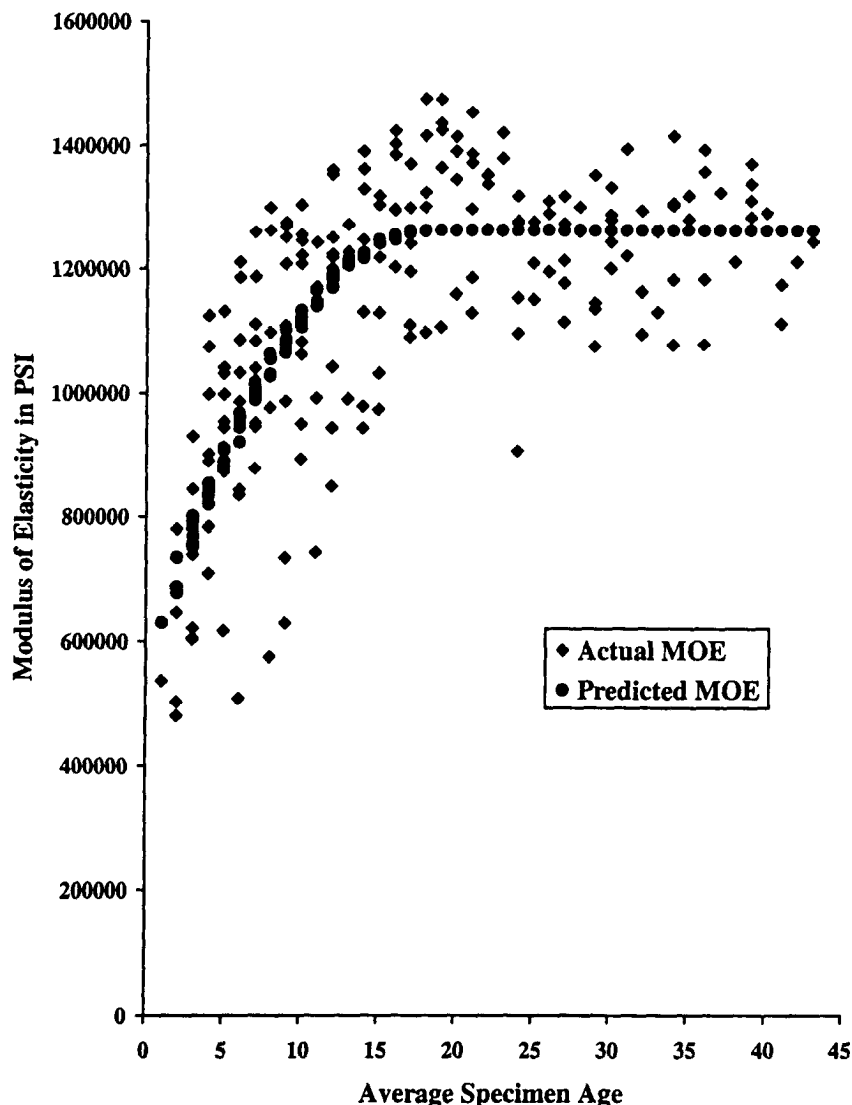


Figure 17. — Graph of the grouped alder MOE bottom data against the predicted NCIN curve.

countered in this study. Not only should a greater number of trees be tested, but the number of specimens from within the tree should be increased, i.e., tree sections of greater diameter should be chosen. The effectiveness of the non-linear regression technique described in this study is greatly enhanced by the clear establishment of a plateau area in the mature wood zone. In non-linear regression analysis, small data sets are inherently vulnerable to individual specimen variation effects.

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Combined MOR Values for Alder Top Sections

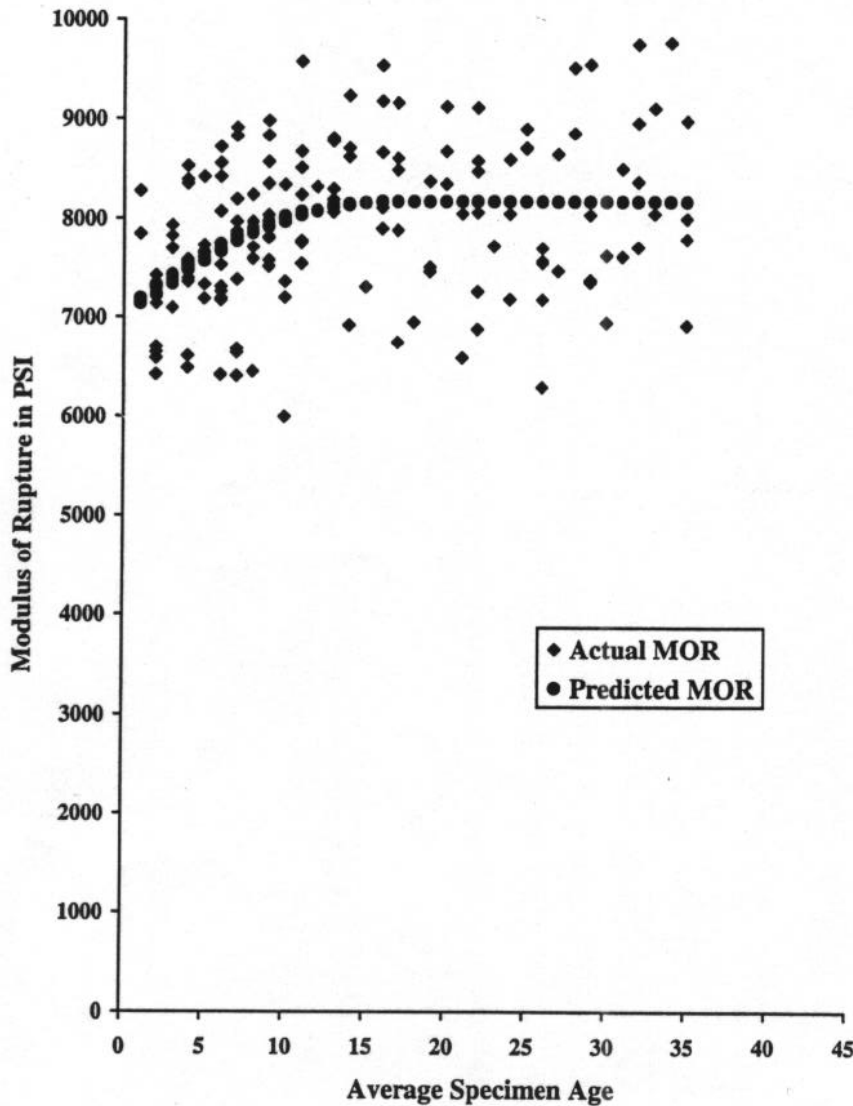


Figure 18. — Graph of the grouped alder MOR top data against the predicted NLIN curve.

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Combined MOR Values for Alder Bottom Sections

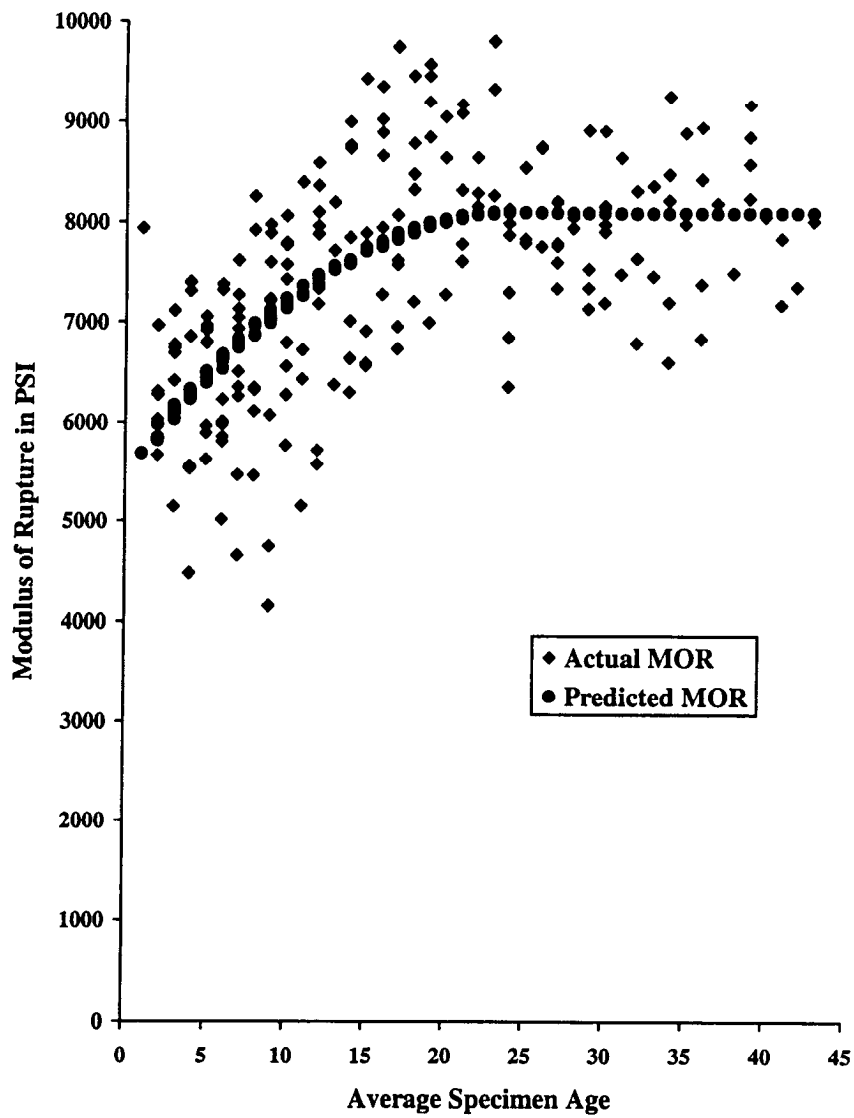


Figure 19.—Graph of grouped alder MOR bottom data against the predicted NLIN curve