Number and diameter of breast-height region branches in a Douglas-fir spacing trial and linkage to log quality

David Briggs
Luciana Ingaramo
Eric Turnblom

Abstract
A Douglas-fir (Pseudotsuga menziesii, Mirb. Franco) spacing trial, planted at 480, 540, 750, 840, 1100, and 1680 trees/ha was studied to investigate the relationship between planting spacing, number and diameter of branches in the breast-height region, and first 5 m log quality. The 540 and 840 tree/ha plantings were in a rectangular design with the distance between rows double that between trees within a row while the others planted in a square design. At age 18, number and diameter of branches ≥8 mm in diameter were measured in a 0.61 m region centered at breast height (BH, 1.3 m). There was no significant effect of planting density on number of BH region branches. The rectangular designs had significantly more branches than the square designs, but this difference was small. The mean diameter of BH region branches was significantly related to both planting density and type of design while the largest diameter of BH region branches and branch index of the BH region were related only to planting density. A subsample of trees was climbed to measure the diameter of the largest branch and branch index corresponding to the 5-m butt log. Highly significant relationships were found between the largest branch diameter and branch index of the butt log and the BH region counterpart measures of trees. Measuring the diameter of the largest branch in the BH region provided superior equations predicting the butt log and is a simple, fast measure to acquire in the field.

Tree branches become knots in logs and wood products and, with the exception of some aesthetic situations such as knotty pine paneling, are undesirable with negative effects on appearance, strength and stiffness of structural products, and yield of remanufactured items. Until recently, relatively little attention was given to managing branches as they develop in timber stands. Trees harvested from old-growth, naturally regenerated second growth, and early plantations contained branches and knots that developed with little or no management influence. Grading rules and sorts assisted in assessing knottiness of logs and products from this unmanaged material by including some combination of number, location, and size of knots among the grade criteria (Bowers 1997, NLRAG 1998, WWPA 2004). Today, managers commonly apply much more intensive management, carefully choosing seedlings that have been genetically improved for high growth potential, planting them at a carefully selected spacing, and subsequently applying a regime that may include weed control, thinning, and fertilization treatments to translate the growth potential into reality. While improved genetics and intensive management have been very successful in producing greater stand volume and larger trees in less time, managers realize that the choice of initial spacing and subsequent treatments also have profound effects on the development of branches and therefore on tree, log, and product quality. Since financial value results from the combination of stand volume, tree size, and quality, there has been an increase in research to understand the connections between silviculture, quality, and value (IUFRO 1992, 1999, 2003).

The authors are, respectively, Professor, College of Forest Resources, Univ. of Washington, Seattle, Washington (dbriggs@u.washington.edu); Researcher, Instituto Nacional de Tecnología Agropecuaria (INTA), Entre Ríos, Argentina (lingaramo@correo.inta.gov.ar), and Associate Professor, College of Forest Resources, Univ. of Washington, Seattle, Washington (ect@u.washington.edu). This research was supported by the Pilchuck Tree Farm, Stanwood, Washington, and the Stand Management Cooperative at the College of Forest Resources, Univ. of Washington, Seattle, Washington. This paper was received for publication in June 2006. Article No.10209.
※Forest Products Society Member.
Forest Prod. J. 57(9):28-34.
Branches can be considered as a population of individuals sharing a common environment subject to competition for resources (Umeki 1995). Particularly, solar radiation is one of the resources that can be hypothesized to be differentially limited at different stocking levels. Branches growing at lower densities capture more light than those growing at higher densities, allowing them not only to reach a greater size but also to provide more carbohydrates for stem growth, which is a relatively low priority sink of photosynthesis allocation (Lanner 1985, Rouvainen and K uuluvaanen 1997, Gartner et al. 2002). While alive, healthy, and able to capture enough light, branches provide resources for stem growth, generating a unique allometric relationship between branch size and stem diameter. However, as branches experience increased competition through higher stand densities, eventually they are unable to provide resources for stem growth and develop a completely different allometric relationship with the stem (Shepherd 1986). It has been suggested that the number of branches present in a tree, as well as the time needed to self-prune are determined primarily by genetic factors with environmental conditions playing a secondary role in these traits (see Johansson 1992). However, trees of a given genetic pedigree on a given site grow at different rates depending on competition associated with different initial planting densities. The most important factor controlling the diameter of branches is the recession of the live crown due to increased competition at higher stocking levels (Ballard and Long 1988, Doruska and Burkhart 1994). Competition leading to crown recession and death of branches is delayed at low densities and branches at a fixed height position in trees growing in those conditions live longer than branches at the same height growing in dense stands. The effect on branch diameter is compounded by the faster growth rates in less dense stands. The main effect of stand density on maximum attainable branch diameter is through the time that branches remain alive and continue to grow in diameter (Moberg 1999). These effects impact tree, log, and product quality characteristics (Ballard and Long 1988).

Many studies have modeled branch diameter of trees but they differ greatly in the branch diameter they use and the location in the tree where branch diameter is measured. Some examined the mean diameter of all branches (Grah 1961, Carter et al. 1986, Doruska and Burkhart 1994), others examined the diameter of the largest branch (Uusvaara 1990, Collin and Houllier 1991, 1992, Moberg 1999, Pape 1999, B aldwin et al. 2000, Gerrand and Neilsen 2000), and others examined the average diameter of some subset of largest branches (Whiteside 1982, Inglis and Cleland 1982, Bier 1985, T ombleson et al. 1990, Fahey et al. 1991, M aguire et al. 1991, B razier and Mobb s 1993, DeBell et al. 1994). Similarly, studies differ greatly regarding the location along the stem where branch diameters are measured. Some considered the entire stem (DeBell et al. 1994, Zhang et al. 2002), others considered one or more log positions (Ballard and Long 1988, DeBell et al. 1994, N iemisto 1995, Neilsen and Gerrand 1999), and others considered just the breast height region (Johansson 1992, Pape 1999). Other researchers have focused on crown profile models to predict the number, position, diameter, and length of branches within individual trees (Collin and Houllier 1991, 1992, Doruska and Burkhart 1994, Roeh and M aguire 1997, M aguire et al. 1991, 1999, V estol et al. 1999). Several concluded that although stand and site measures alone can be used successfully to predict branch profiles, appropriate individual tree variables work just as well. In contrast, others (J ohansson 1992, Salminen and V armola 1993, V estol et al. 1999) found that combining stand and site variables such as stocking with individual tree variables produced improved models.

In the Pacific Northwest, the system of log grades and sorts commonly used has 13 mm (1/2 inch) knot diameter intervals, as well as restrictions on the number of knots in each log quadrant (B owers 1997, N LRAG 1998). Therefore, knot size and their frequency and distribution around the log are principal factors in the determination of tree, log, and lumber grades (B owers 1997, B razier and M obbs 1993, N LRAG 1998). The number, size, and type of knot are also important characteristics in grading veneer (APA 1986), appearance grade lumber, and factory/shop lumber to be remanufactured into clear components (WWPA 2004). These product grades also use discrete, step-function knot diameter intervals. In contrast, product recovery studies have found that the relationship between product recovery and log knottness is best described by a continuous function of some type of log branch diameter measurement (ex. Fahey et al. 1991, B eauregard et al. 2002). Fahey et al. (1991) found that Douglas-fir lumber and veneer grade recovery is a continuous function of the largest limb average diameter (LL AD) of a log. LL AD, also known as branch index (B IX), is the average of the largest diameter knot found in each of the 4 faces of the log (Whiteside 1982) and has been widely used in product recovery studies. Fahey’s explanation of the usefulness of LL AD is that it captures the effect that large limbs can be present in just one or multiple faces and a single rough face does not have the same impact on product quality as multiple rough faces do.

Initial planting spacing design provides the first opportunity to regulate the growing space that each tree will have in the future stand. A specified stocking level can be achieved by various combinations of within- and between-row tree distances. Both square and rectangular spacings are used with the choice often dictated by the desire to perform, and requirements of, mechanized silvicultural operations. It has been suggested that when within-row distances are less than between-row distances, competition between adjacent trees will occur earlier in the direction where the distance between trees is least; and that rectangular planting designs produce lower yields and form larger diameter branches toward the greater space between rows (see Salminen and V armola 1993). Although there is agreement between researchers about the effect of rectangular vs. square spacing on tree growth, the literature is scarce and not consistent regarding the effects of planting designs on the size and number of branches (Salminen and V armola 1993, Gerrand and Neilsen 2000).

Objectives

Our study involved measuring an 18-year old Douglas-fir spacing trial with six densities, each replicated six times, located on a single site in the state of Washington. The study involved measuring tree and stand characteristics for growth and yield analysis reported elsewhere (Ingaramo 2003) and measurements of number and diameter of branches in the breast-height region (BH, 1.3 m ± 0.304 m) to assess stem quality. A subsample of trees was climbed to measure the largest branch and LL AD of the 5-m butt log position. Objectives of this paper are 1) to examine the effect of initial planting density and planting design on number and diameter of
branches in this BH region, and 2) to develop relationships between diameter of branches in the BH region and 5-m butt log.

**Methods**

**Study site and experimental design**

A Douglas-fir spacing trial located on the Pilchuck Tree Farm near Stanwood, Snohomish County, Washington, was used for this study. In May of 1983, 2.5 ha on the study site were divided into 50 equal area plots and planted with 2-year-old Douglas-fir seedlings over a range of densities from 480 to 1680 trees per hectare (Table 1). Each of the 50 plots was 22 by 22 m, representing an area of 0.05 ha. Two of the densities were planted with a rectangular design with the distance between rows double the distance between trees within a row, and the other four densities were square spacings. In each plot the outermost row of trees was excluded from the measurement sample to avoid edge effects from contiguous plots. For this study, when a density had more than six plots, six plots were randomly chosen; hence the experiment became a completely randomized design with six replications of six density treatments.

**Stand, site and climatic variables**

The genetic source of seedlings was from unimproved local origin. Few seedlings succumbed to mortality, and those that died were replaced in 1984 and 1985. Site Index is medium to high: 43 m at 50 years (King 1966) or 30 m at 30 years (Flewelling et al. 2001). The site elevation is approximately 330 m above sea level, with a southwestern exposure and a slope of 0 to 10%. According to the Western Regional Climate Center for nearby Sedro Woolley, Washington, mean annual precipitation since 1931 has been approximately 1171 mm, most of which falls from October to April, and mean annual temperature has averaged 10.4 °C. Soils are deep, well-drained, formed in glacial drift with volcanic ash, sandstone and siltstone, with a pH of 5.4. The soil series is Cathcart, classified as Typic Haplloxerands by the USDA classification system. Prior to planting, the site had been used as cattle pasture. The uniform microclimate, soil type, slope, and aspect at the site minimize the potential confounding effects of these variables with differences in growth, yield, and branch characteristics associated with planting density.

**Data collection**

The chosen study plots were measured in the winter of 2001–2002, when the stand age was 18 (20 years from seed). The stand had been previously tagged and measured for DBH in 1990 and 1998. For this study, 12 trees on each plot were chosen based on the 1998 DBH measurement. These included the smallest and the largest plus 10 others selected at random. DBH was measured on all sample trees to the nearest 0.254 cm. A randomly selected sample of 4 trees per plot was selected for measuring total and crown heights. Each of the 12 trees was divided into 4 quadrants or faces (N, S, E and W). In each quadrant, the diameter of all branches greater than or equal to 8 mm, located within 0.305 m above and below breast height was measured with a caliper to the nearest millimeter. Branch diameter was measured perpendicular to the branch axis, in the direction of stem circumference, just beyond the branch collar. Restricting branch measurement to those that were at least 8 mm in diameter excluded many small ‘whiskers’ that tend to self-prune very rapidly and have little, if any, effect on grading. With the exception of a single branch on the southern face of one tree at the lowest density, all measured branches in the BH region of the sample trees were dead. Sample size per spacing was 12 trees per plot in each of 6 plots; hence, 72 trees per density. In the case of the lowest density, one plot had been pruned and was not usable for branch measurements; the total sample across all 6 densities was 35 plots, 420 trees from which 4213 branches in the BH region were measured. As an extension to the study, the sample plots were revisited in May 2003. A subsample of 4 of the original trees that had been chosen for height measurement was climbed with a ladder to measure the largest diameter branch in each face of the 5 m butt log. It was assumed that the stump was 0.305 m and that the log had 0.15 m of trim allowance. The same N-S-E-W quadrant system was used as for measuring branches in the BH region. The owner had initiated thinning in some plots, and where the desired tree had been removed, we substituted the standing tree most similar in DBH; one heavily thinned plot was inaccessible, and as noted previously, one plot had previously been pruned. A total of 136 trees from 34 plots were measured.

**Statistical analysis**

Analysis was conducted in two phases. First, means for the number and diameter of branches were calculated from the 12 sample trees per plot. Stepwise linear regression was used to analyze the effect of planting design and initial density on number and diameter of branches in the BH region. The general model had the form:

$$Y = a_0 + a_1 \ln D + a_2 S + a_3 \ln DS + \varepsilon$$  \[1\]

where the dependent variable $Y$ is either the number of branches (NBR BH), branch diameter (M BD BH), largest branch diameter (L BD BH), or largest limb average diameter (L L A DBH) of the BH region of a tree. Dependent variables are InD, the density level from 480 to 1680 trees per hectare; $S$, a dummy variable for rectangular (0) and square (1) spacing design; and InDS, the interaction of density level and spacing design. Coefficients are $a_0$, the overall mean for the dependent variable, $a_1$, $a_2$, and $a_3$ are regression coefficients for the dependent variables, and $\varepsilon$ is the random error. Preliminary analyses revealed that the natural logarithm of initial density ($\ln D$) provided a better fit of the model. Significance of the regression models was tested by analysis of variance and the Tukey test. The level of significance in the tests was $\alpha = 0.05$ if not specified otherwise.

In the second phase of analysis, simple linear regression was used to develop relationships to predict log branch diameter indices from BH region counterparts. Models were produced using the means calculated from the four trees sampled...
on each plot and again for the individual trees. The general model had the form:

\[ Y = b_0 + b_1 X + \varepsilon \]  

where \( Y \), the dependent variable, is either the largest branch diameter (LBD5) or largest limb average diameter (LLADB5) of the 5-m butt log. The dependent variable \( X \) is either the largest branch diameter (LBDBH) or largest limb average diameter (LLADBH) of the BH region of the tree. Coefficients \( b_0 \), the overall mean for the dependent variable, \( b_1 \) is the regression coefficient for the dependent variable, and \( \varepsilon \) is the random error. All statistical analyses were performed using the SAS \(^\text{®} \) package for Windows \(^\text{®} \) V8 (SAS Institute 1999 to 2001).

### Results and discussion

Table 2 summarizes mean stand statistics by planting density at age 18 (Ingaramo 2003). Mean total height shows subtle differences among the densities that were not statistically significant. Quadratic mean diameter, live crown ratio, individual tree volume, and basal area decrease with increasing density, while total basal area and standing volume per hectare increase with increasing density. Table 3 summarizes means for the BH region branch variables considered. The trends of larger branch diameters with lower densities may simply result from allometry; lower densities have larger diameter trees and the relationship between BH branch diameters and DBH of trees may be the result of allometry that is constant across densities. In an attempt to remove the effect of DBH from density, the cross-sectional area of branches in the BH region was divided by the bole surface area of the BH region to determine if the calculated branch area ratio (BAR) variable in Table 3.

### Number of BH region branches

The mean number of BH region branches (NBRBH) 8 mm or larger ranged from 8.9 to 11.1 per tree (Table 3) with the two rectangular designs having the two highest counts. A analysis with Model 1 (Table 4) revealed that density was not a statistically significant \( (p = 0.73) \) predictor of NBR, whereas using square or rectangular spacing was significant \( (p = 0.012) \). The lack of density effect has been reported by others (Ballard & Long 1988, Johansson 1992, Baldwin et al. 2000). Johansson (1992) suggested that number of branches is determined primarily by genetic factors with environmental conditions playing a secondary role in these traits. Since the trees on this study site are from the same seed source, this genetic control effect seems to be confirmed. Since we counted only branches 8 mm and larger, the greater growing space between rows of the rectangular spacings may have allowed more branches to exceed the 8 mm threshold. Therefore, while the total number of branches formed may be constant according to the genetic control hypothesis, the diameter distribution of those branches may have more branches exceeding 8 mm, which would affect our branch count. However, the average difference between the closest square and rectangular densities is only 1 and 2 branches and, while statistically significant, may not be of practical importance in tree, log, or product grading.

### Diameter of BH region branches

The mean diameter of all BH branches 8 mm or larger (MBDBH) ranged from 19.7 to 29.9 mm (Table 3) with a general trend of increasing MBDBH with decreasing density. The square plot designs tend to have slightly larger MBDBH than the rectangular designs that are closest in density. A analysis with Model 1 (Table 5) revealed that both density \( (p < 0.0001) \) and use of square vs. rectangular design \( (p < 0.0001) \) were significant predictors of MBDBH. Similar effects of density have been found for eucalyptus (Gerrand and Nielsen 2000) and Scots pine (Salminen and Varmola 1993). The effect of square vs. rectangular design may be influenced by the increased number of branches 8 mm and larger in the rectangular design; a shift in the diameter distribution of 8 mm and larger branches is likely to affect the mean.

Because large-diameter branches result in large knots with greater impact on product value and since grading rules specify the maximum knot diameter allowed in a grade, the largest BH region branch diameter (LBDBH) is likely to be of greater interest than the mean branch diameter. Mean values of LBDBH range from 25.6 mm to 39.3 mm with a trend of increasing LBDBH with decreasing density (Table 3). A analysis with Model 1 (Table 5) revealed that only density was a significant predictor of LBDBH \( (p < 0.0001) \). Since largest limb average diameter (LLADB) has been successfully used in predicting product recovery from logs, we calculated LLADB from the branches in the BH region to determine if LLADB can be predicted from density and planting design. Mean values of LLADB increased from 21.3 mm to 32.7 mm with decreasing density (Table 3). A analysis with Model 1 (Table 5) revealed that only density was a significant predictor of LLADB \( (p < 0.0001) \). Although the results for predicting LBDBH and LLADB are similar, measuring LLADB would require more field measurement than measuring LBDBH; hence, we expect the former would be preferred in field practice.

We also used Model 1 to investigate branch area ratio (BAR) where we attempted to isolate the effect of allometry
between branch and tree diameter from density. Analysis with Model 1 revealed a highly significant \((p < 0.0001)\) effect of density on BAR and no effect of square vs. rectangular planting design. This result agrees with Shepherd (1986), who indicated that as branches experience increased competition at higher densities the allometric relation between branches and the stem changes, but disagrees with several crown profile modeling studies mentioned earlier that concluded that tree variables alone work as well as stand variables in predicting crown profiles and branch diameters. Future research will be needed to further investigate this issue.

Relation to log quality

Table 6 presents a combined summary of knot diameter classes commonly found in lumber and log grades and sorts (Bowers 1997, WWPA 2004). Figure 1 shows the frequency distribution of mean branch diameter (MBDBH) for 18-year-old Douglas-fir trees planted at different stocking levels.

Table 3.—Means and SDs of number and diameter of BH region branches ≥8-mm diameter in the Pilchuck tree farm spacing trial at age 18.

<table>
<thead>
<tr>
<th>Density level, trees/ha (D)</th>
<th>480</th>
<th>540</th>
<th>750</th>
<th>840</th>
<th>1080</th>
<th>1680</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacing, m</td>
<td>4.5 by 4.5</td>
<td>6 by 3</td>
<td>3.5 by 3.5</td>
<td>5 by 2.5</td>
<td>3 by 3</td>
<td>2.5 by 2.5</td>
</tr>
<tr>
<td>Number of branches (NBRBH)</td>
<td>10.1 (0.93)a</td>
<td>10.8 (1.71)</td>
<td>8.9 (1.74)</td>
<td>11.1 (1.97)</td>
<td>10.1 (1.29)</td>
<td>9.2 (1.08)</td>
</tr>
<tr>
<td>Mean branch diameter (MBDBH), mm</td>
<td>29.9 (1.56)</td>
<td>26.6 (2.01)</td>
<td>24.8 (2.51)</td>
<td>22.4 (0.83)</td>
<td>22.9 (0.90)</td>
<td>19.7 (1.41)</td>
</tr>
<tr>
<td>Largest branch diameter (LBDDBH), mm</td>
<td>39.2 (6.583)</td>
<td>35.8 (5.782)</td>
<td>31.8 (5.753)</td>
<td>31.5 (5.428)</td>
<td>30.7 (7.025)</td>
<td>25.6 (5.645)</td>
</tr>
<tr>
<td>Largest limb average diameter (LLADDBH), mm</td>
<td>32.7 (3.34)</td>
<td>29.7 (1.56)</td>
<td>26.2 (2.60)</td>
<td>25.9 (1.17)</td>
<td>25.7 (1.58)</td>
<td>21.3 (1.43)</td>
</tr>
<tr>
<td>Branch area ratio (BAR)</td>
<td>1.45 (0.16)</td>
<td>1.25 (0.10)</td>
<td>0.98 (0.23)</td>
<td>1.05 (0.20)</td>
<td>1.09 (0.09)</td>
<td>0.85 (0.10)</td>
</tr>
</tbody>
</table>

a Values in parentheses are SDs.

Table 4.—Regression relationships between number of BH region branches ≥8-mm diameter and initial planting density and square vs rectangular planting design.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Equation</th>
<th>(R^2_{adj})</th>
<th>(SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBRBH 35</td>
<td>(= 10.96 + 1.42S)</td>
<td>0.012</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Table 5.—Regression relationships between diameter of BH region branches ≥8-mm diameter and initial planting density and square vs rectangular planting design.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Equation</th>
<th>(R^2_{adj})</th>
<th>(SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBDBH 35 = 76.44 to 7.98 lnD + 2.14 S</td>
<td>&lt;0.0001</td>
<td>0.78</td>
<td>1.67</td>
</tr>
<tr>
<td>LBDBH 35 = 97.82 to 9.76 lnD</td>
<td>&lt;0.0001</td>
<td>0.78</td>
<td>2.22</td>
</tr>
<tr>
<td>LLADDBH 35 = 80.24 to 7.96 lnD</td>
<td>&lt;0.0001</td>
<td>0.71</td>
<td>2.17</td>
</tr>
<tr>
<td>BAR 35 = 3.69 to 0.38 lnD</td>
<td>&lt;0.0001</td>
<td>0.47</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Table 6.—Knot diameter classes commonly used in log and product grading rules (Bowers 1997, WWPA 2004120)

<table>
<thead>
<tr>
<th>Class</th>
<th>Imperial units (in)</th>
<th>Metric units (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin</td>
<td>&lt;1/2</td>
<td>&lt;13</td>
</tr>
<tr>
<td>Small</td>
<td>1/2 to 1</td>
<td>13 to 25</td>
</tr>
<tr>
<td>Medium</td>
<td>1 to 1/2</td>
<td>26 to 38</td>
</tr>
<tr>
<td>Large</td>
<td>1 1/2 to 2</td>
<td>39 to 51</td>
</tr>
<tr>
<td>Very large</td>
<td>&gt;2</td>
<td>&gt;51</td>
</tr>
</tbody>
</table>

Figure 1.—Frequency distribution of mean branch diameter (MBDBH) for 18-year-old Douglas-fir trees planted at different stocking levels.
sample of 4 trees per plot and 5 to 6 plots per density, preliminary analysis revealed no systematic patterns with density, and as a result the data for all densities were pooled. Future research with a larger sample should be undertaken to explore the possibility of a density effect. Results show that either LBDBH or LLADBH can be used to predict LBDS or LLAD5 for plot means (Table 7) and for individual trees (Table 8). However, LBDBH generally produced better models than LLADBH and would be more convenient to measure in the field. We believe that the reason why LLADBH produced inferior results is that it is possible to have clear faces in the BH region contributing zeros to the LLADBH calculation while along the log all faces contribute a measurable branch. This increased the variability of LLADBH and weakened its predictive value. Extending the length of the BH region may reduce this effect but may add to inconvenience in the field.

Forest managers and silviculturists can estimate the LB or LLAD of the 5-m butt log simply by measuring the LBDBH. Since the largest diameter knot often is part of log grading criteria (Bowers 1997, NLRA G 1998) and LLAD provides a link to product recovery (Fahey et al. 1991), this simple field procedure and the equations allow managers to predict the potential effect of branch diameter on grades of butt logs, lumber, or veneer that individual trees or a stand may yield. Such tree-to-log-to-product linkages may prove useful for assessing potential marketability of stands.

Conclusions

With respect to branches in the BH region that were at least 8 mm in diameter, this study found that 1) square vs. rectangular spacing designs had a significant effect on number of branches and mean diameter of branches but not on the largest branch or branch index; and 2) initial planting density had a significant effect on mean diameter of branches, diameter of the largest branch, branch index, and branch area ratio but had no effect on number of branches.

With respect to linking a branch diameter measurement in the BH region of trees to logs, this study found that either the largest diameter branch or branch index of the BH region could be used to predict counterparts for the 5-m butt log. However, the largest diameter branch of the BH region produced superior equations and would be simpler to measure in the field. The simple measure of the diameter of the largest branch in the BH region would allow managers to develop tree-to-log-to-product linkages that would be useful for assessing value for marketing purposes or to assess the effects of silvicultural treatments along the tree to product chain.

### Literature cited


