AN ABSTRACT OF THE THESIS OF

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Intensive management of young-growth Douglas-fir plantations has emphasized volume growth over wood quality. A better understanding of the variables that affect wood quality is needed so that wood quality and stand yield can be systematically combined into a silviculture program.

This experiment utilized two separate experiments to establish the relationship between wood quality, stand density, and artificial pruning. The influence of initial stand density on branch diameter, wood density, and tracheid length was explored utilizing 56 trees, 19 and 21 years old, at two sites in central western Oregon. Trees were sampled from Nelder plots ranging in density from 309 trees/ha to 18,730 trees/ha. The effects of fixed-height pruning on wood density and tracheid length were investigated using trees 23, 26, and 28 years old, after ten years of growth following pruning.

Mean branch diameter, maximum branch diameter, number of branches/m, longevity of radial branch growth, and longevity of terminal branch growth all increased with decreasing initial tree density. After accounting for initial tree density, 1:2 rectangularity of spacing did not affect indicators of wood quality relative to 1:1 rectangularity of spacing.

When age was held constant, there was no evidence that either wood density or tracheid length at breast height varied with initial tree density or crown characteristics. In contrast, there was evidence that ring density, earlywood density, and percent latewood increased linearly with initial tree density at the 5.27 m sampling height.

There was no significant change in growth rate or wood density at breast height (1.37 m) or 5.27 m as a result of pruning 15% or less of the live crown length. In contrast, pruning to 5.5 m at age 13 resulted in a one-year decrease in earlywood width and an increase in percent latewood at 1.37 m. At the 5.27 m sampling height, there was a temporary increase in earlywood density, percent latewood, and mean ring density. Pruning at age 13 to 3.4 m and 5.5 m resulted in an increase in mean, earlywood, and latewood tracheid length of approximately 6% for three years.

Wide initial spacing, combined with pruning appears to be the best choice for improving wood quality of Douglas-fir. Even though juvenile wood volume will be greater due to wide spacing, the increase in log diameter and clear wood volume will enhance log grade, especially if pruning occurs early in the rotation and is combined with commercial thinning to promote diameter growth.

INFLUENCE OF SPACING AND CROWN RECESSION ON WOOD QUALITY OF INTENSIVELY-MANAGED YOUNG-GROWTH DOUGLAS-FIR

by

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CONTRIBUTION OF AUTHORS

Dr. Michael Newton and Dr. Barbara Gartner were involved in the design, analysis, and writing of each manuscript of this thesis. Dr. Michael Newton and Elizabeth Cole designed, established, and maintained the Nelder plots at each study site. They also provided years of valuable data measurements.

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CHAPTER 1. INTRODUCTION TO DOUGLAS-FIR WOOD QUALITY IN THE PACIFIC NORTHWEST

Wood quality in the Pacific Northwest has declined with the transition from old-growth to young-growth Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*), primarily because of a decrease in average log size and associated decline in high value clear wood content (Ernst and Fahey, 1986). Intensive management of Douglas-fir has moved toward shorter rotation times and wider initial spacing (Smith and Reukema, 1986). The proportion of juvenile wood being processed has increased, resulting in products with lower strength and lower dimensional stability (Fahey et al., 1991). Consequently, increased attention has focused on end-product quality (Senft et al., 1985a).

The Pacific Northwest has become more reliant on young-growth Douglas-fir because of increased reservation of public forest lands and environmental restrictions (Briggs, 1997). Increased pressure on the remaining forestlands has led to harvesting at younger ages and with yields having a higher percentage of juvenile wood. The forest products industry has been adapting to smaller log sizes with different wood characteristics by engineering new composite wood products and using alternative species. In addition, the forest products industry has engineered more efficient small log processing systems, increased the use of residual wood fiber, and invested in secondary wood processing systems (Briggs, 1997). Despite these adjustments in resource utilization, there are many forest management decisions capable of improving Douglas-fir wood quality.

Wood quality is a value judgement based on characteristics desired in the end product. Mitchell (1960) defined wood quality as "the resultant of physical and chemical characteristics possessed by a tree or part of a tree that enable it to meet the property requirements for different end products." Recently Zhang (1997) defined wood quality as "all the wood characteristics and properties that affect the value recovery chain and the serviceability of end products". Log and lumber grade and recovery is primarily influenced by log size, growth rate, and branch characteristics (NLRAG, 1998; WWPA, 1998). However, other wood properties such as wood density, tracheid length, microfibril angle, grain angle, cellulose and lignin content, and chemical extractives, directly, or indirectly influence wood quality, depending on the end-product. Therefore, wood quality is an intricate part of current and future forest management decision-making, especially under circumstances where culture can improve wood quality, hence value.

Wood quality research has focused on the properties of wood density, tracheid length, and branch characteristics. Considerable research has been conducted on wood density variation in Douglas-fir, including the influence of initial spacing (Smith, 1980), fertilization and thinning (Erickson and Harrison, 1974; Megraw and Munk, 1974; Brix and Mitchell, 1980), climate (Kennedy, 1961; Robertson et al., 1990), genetics (McKimmy, 1966; Vargas-Hernandez and Adams, 1991; Abdel-Gadir et al., 1993), and growth rate (Smith, 1956;

McKimmy, 1959). Several studies have investigated variations in tracheid length depending on fertilization and thinning (Erickson and Harrison, 1974), air pollution (de Kort, 1990), and growth rate (Bannan, 1964). Branch characteristics have also received considerable attention, including mean and maximum branch size (Grah, 1961; Smith, 1961; Whiteside et al., 1977; Bier, 1986; Carter et al., 1986; Maguire et al., 1991) and missing annual branch rings (Reukema, 1959; Kershaw et al., 1990). However, there are still gaps in our knowledge concerning the influence of silviculture on wood density, tracheid length, and branch characteristics.

The first objective of this research, addressed in Chapter 2, is to quantify the relationship between branch characteristics and initial tree density in young intensively-managed Douglas-fir trees. Primary interest was in the mean and maximum diameter of branches and number of branches/m in relation to initial plantation spacing and rectangularity. The longevity of branch growth, represented by radial and terminal branch growth was investigated in relation to initial plantation spacing and rectangularity. In addition, the number of years without radial or terminal branch growth was determined as it relates to branch development and its potential contribution to tree growth. This study was unique because it utilized a wide range of initial plantation spacing.

The second objective of this study, addressed in Chapter 3, is to test the hypothesis that wood density and tracheid length change systematically as a function of crown dimensions or distance below the crown. While wood density and tracheid length are increasing with age at a given location, changes are also occurring in the crown. As crown recession occurs, an increase in wood density and tracheid length are expected on the lower bole as the influence of the active live crown diminishes (Larson, 1969b).

The first two objectives were tested using intensively-managed young-growth Douglas-fir planted at initial densities ranging from 309 trees/ha to 18,730 trees/ha in variable density Nelder plots (Nelder, 1962). The Nelder plots have created significant variation in crown structure due to intraspecific competition.

The third objective of this study, addressed in Chapter 4, is to test the hypothesis that radial variation in wood density and tracheid length differs between pruned and unpruned Douglas-fir. This part of the study provided new information on the effects of pruning on tracheid length variation in young intensively-managed Douglas-fir pruned at different stages of crown recession. The study used substantially larger sample sizes than previous experiments (Polge et al., 1973; Jozsa and Sawadsky, 1989).

This thesis explores the influence of silviculture on the quality of Douglas-fir wood. The results are applicable regardless of end-product requirements. A combination of initial tree density and pruning can produce wood with different properties, and consequently satisfy the requirements for an assortment of end-uses. Forest managers can use these data to incorporate yield and wood quality systematically into a silviculture program designed to grow raw material for products with an array of quality characteristics and high value.

CHAPTER 2. BRANCH SIZE AND LONGEVITY IN RELATION TO INITIAL PLANTATION SPACING AND RECTANGULARITY IN YOUNG DOUGLAS-FIR

Abstract

The relationship between branch growth characteristics and initial plantation spacing were investigated for the basal 5 m log of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*). Mean and maximum branch sizes were measured inside bark, as were duration of radial and terminal growth of branches. Data were derived using 3,920 branches on 56 trees, 19 and 21 years old, at two sites in central western Oregon. Trees were sampled from Nelder plots ranging in initial density from 309 trees/ha to 18,730 trees/ha and planted in either 1:2 or 1:1 rectangular spacing geometry. Mean and maximum branch diameter increased with decreasing initial tree density, falling within the range of values documented in previous studies. Within operational planting densities, 469 trees/ha (4.6m x 4.6m) to 1682 trees/ha (2.4 m x 2.4 m), mean branch diameter inside bark ranged from 16 mm to 26 mm and maximum branch diameter inside bark ranged from 22 mm to 36 mm. After accounting for initial tree density, rectangularity had no effect on branch size. The number of branches/m as well as duration of radial and terminal growth increased with decreasing initial tree density, resulting in additional large and persistent branches at wide spacing. The number of years lower branches remained alive without radial branch growth ranged from 0 to 8 years, depending on site, and averaged approximately 1 year, significantly less than reported in studies of older second-growth Douglas-fir. The maximum percentage of branch life spent

without radial growth averaged 22.5% or 30%, depending on site. Using discriminant analysis, several variables were able to categorize over 70% of missing-ring branches correctly. Pruning, combined with wide spacing is recommended to improve the wood quality of intensively-managed young-growth Douglas-fir.

Introduction

Traditionally, volume production and internal rate of economic return have determined the management of Douglas-fir with secondary consideration given to wood quality. Intensive management of Douglas-fir has moved toward shorter rotation times and wider initial spacing (Smith and Reukema, 1986). Wood quality in the Pacific Northwest has declined with the transition from old-growth to young-growth Douglas-fir, primarily because of a decline in average log size and associated decline in high value clear wood content (Ernst and Fahey, 1986). The proportion of juvenile wood in logs being processed has increased, resulting in products with lower strength and dimensional stability than is typical of mature wood from either second- or old-growth (Fahey et al., 1991). Consequently, increased attention has focused on the adverse effects of shorter rotation times and intensive management on end-product quality (Senft et al., 1985a).

Crown formation and structure has been studied extensively in recent years. Crown structure has important implications for forest stand dynamics as well as for individual stem characteristics. Crown structure encompasses branching patterns (Carter et al., 1986; Mäkinen, 1996) and directly influences growth patterns (Duff and Nolan, 1953; Fayle, 1985), stem form (Larson, 1963), and juvenile wood volume (Larson, 1969b; Maguire et al., 1991), all of which influence wood quality and product value (Briggs, 1996).

Branches in a tree's crown are in different stages of vigor depending on their relative position in the tree crown and the position of the tree relative to its neighbors (Mäkinen, 1996). As a branch ages, it becomes increasingly shaded by younger branches in upper whorls, as well as by neighboring tree crowns. This process creates a gradient in branch vigor with relative depth into a tree's crown (Labyak and Schumacher, 1954). Upper crown branches have numerous large buds that act as strong carbon sinks, importing stored carbon for elongation and growth (Sprugel et al., 1991). In contrast, lower shaded branches may fail to form annual growth rings at their base (Andrews and Gill, 1939; Reukema, 1959; Kershaw et al., 1990; Roberts, 1994) and contribute very little carbon to the rest of the tree (Labyak and Schumacher, 1954; Underwood, 1967; Kozlowski and Pallardy, 1997). These lower branches are autonomous for carbon, having insufficient sink strength to draw on carbon reserves from the rest of the tree and fixing just enough carbon to meet their own needs (Sprugel et al., 1991). Eventually, the negative cumulative carbon budget of a lower branch leads to mortality (Witowski, 1996). Review of Douglas-fir pruning studies concluded that pruning does not significantly reduce tree growth if one-third or less of the lower live crown length is removed (O'Hara, 1991; Maguire and Petruncio, 1995). These findings support the theory that the functional crown is composed of approximately the upper two-thirds of the live crown (Underwood, 1967; van Laar, 1969; Assmann, 1970; Maguire and Petruncio, 1995).

The presence, location, angle, frequency, and size of branches are important wood quality considerations (Zobel and van Buijtenen, 1989), especially because Douglas-fir has persistent branches. Branches directly impact log grade (NLRAG, 1998) and lumber grade (WWPA, 1998). In naturally regenerated young-growth stands, a review of the literature shows a minimum of 77 years is required for natural pruning of the basal 4.9 m log (Cahill et al., 1986). This suggests that very little clear high-grade veneer or lumber can be expected from intensively-managed (Fahey et al., 1991) or naturally regenerated young-growth stands (Ernst and Fahey, 1986) without artificial pruning. Mean and maximum knot sizes are commonly used to determine log value and evaluate end-product performance. The average diameter of the largest live limb in each log quadrant has commonly been used to evaluate lumber and veneer recovery (Fahey et al., 1991), predict strength and stiffness of structural lumber (Bier, 1986), and model wood quality under different silvicultural regimes (Maguire et al., 1991).

Juvenile wood has a high proportion of branch wood because of rapid branch diameter growth near the pith (Brown, 1962). The combination of branch wood, grain distortion, increase in compression wood, and poor juvenile wood properties severely impacts end-product quality. Branch size and wood density have the most impact on lumber strength and stiffness (Whiteside et al., 1977; Bier, 1986). Lumber produced from juvenile wood has lower strength and stiffness than mature wood (Barret and Kellogg, 1991). Problems with juvenile wood have even been found in laminated veneer lumber and oriented strand board (Briggs, 1995). More juvenile wood is required to satisfy minimum design requirements because of poor dimensional stability and low strength (Kretschmann et al., 1993). In addition, pulp yields decline and pulp quality changes with an increase in the proportion of juvenile wood (Hatton and Cook, 1992).

Since knots constitute a reduction in product recovery and grade in a majority of end-products, it is important to understand the factors that influence knot development, size, persistence and distribution in juvenile wood. This study investigated the relationship between branch growth characteristics and initial tree density (ITD) in young intensively-managed Douglas-fir. Initial tree density (ITD) ranged from 309 trees/ha to 18,730 trees/ha in either 1:1 or 1:2 rectangular spacing geometry. Primary interest was in the mean and maximum diameter of branches depending on ITD and rectangularity for the basal 5 m log. The number of branches/m, a measure of branch density, was also investigated in relation to ITD and rectangularity for the basal 5 m log. The longevity of branch growth, represented by radial and terminal branch growth was also determined, as well as the number of years a branch remained alive without radial or terminal branch growth.

Methods

Site descriptions

The study was undertaken at two sites in central western Oregon, both of which were converted pasturelands. The Alsea site is 5 km east of Alsea, Oregon, at 125 m, 44°23' N, 123° 33' W. The Valley site is 10 km south of Philomath, Oregon, at 130 m, 44° 26' N, 123° 21' W. The Valley site is representative of the warm, dry summer climate of the Willamette Valley and the Alsea site is typical of the warm summer climate of the Coast Range valleys, exhibiting lower moisture deficit than the Valley site (Cole and Newton, 1986). Available nitrogen is comparable between sites, even though total soil nitrogen is higher at the Valley site (Cole and Newton, 1986). At the Alsea site mean annual precipitation is about 175 cm with a mean annual temperature of 11°C and a frost free season of 200 to 210 days (Zedaker, 1981). At the Valley site mean annual precipitation is about 100 cm, with a mean annual temperature of 13°C and average frost free season of 165 to 200 days (Zedaker, 1981). Estimated site index at 50 years (SI_{50}) is 38 m and 32 m at Alsea and the Valley sites, respectively, based on soil characteristics.

The sites were planted with 2-0, nursery run, bare-root Douglas-fir seedlings from a low elevation, mid-Coast Range source in 1978 and 1980, at the Valley and Alsea sites, respectively. Understory weed control was sustained for 5 years (Cole and Newton, 1986). After 19 total years of growth, dominant trees were approximately 18 m tall at the Valley site and 19 m tall at the Alsea site. In the fall of 1998, the average breast height age of the trees was 15 and 17 years old, at the Alsea and Valley sites, respectively.

Experimental design and tree selection

At each site, trees were planted in variable density Nelder plots (Nelder, 1962), which consist of a series of concentric circles that represent systematic changes in density at a constant proportional rate (Figure 2.1). Space between trees increases 30% from the inside towards the outside of the plot. There are four complete Nelder plots at the Alsea site and two at the Valley site. Originally, each plot consisted of 48 spokes and 17 arcs, creating a total of 816 trees per plot. However, after 6 years of growth, alternate spokes were removed on portions of each plot creating fairly rectangular geometry of 1:2 (Figure 2.1). The remainder of the trees had roughly square geometry at about 1:1. Edge effect was avoided by sampling from arcs 3 through 16 only. Initial

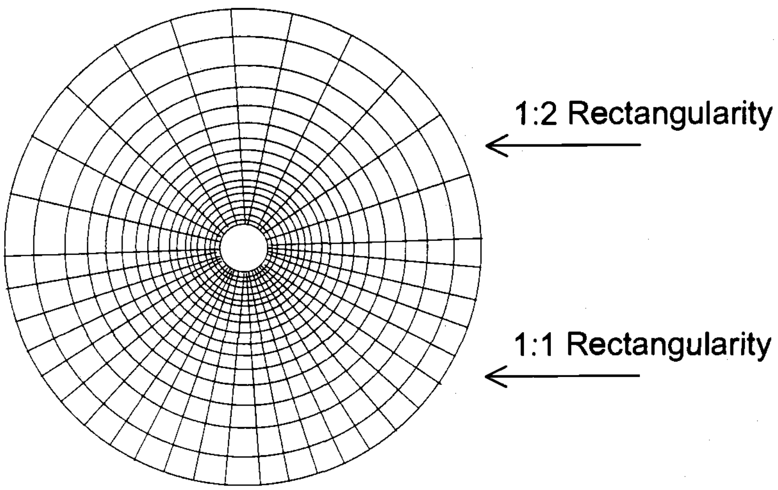


Figure 2.1. Nelder plot layout showing 1:2 and 1:1 rectangularity.

tree density (ITD) ranged from 309 to 9,365 trees per hectare in the rectangular spacing and from 618 to 18,730 trees per hectare in the square spacing.

The objective of the research was to study tree branch development in trees along a density gradient, while keeping sample size manageable. Several factors made subsampling the Nelder plots necessary, rather than using whole Nelder plots as the experimental units. Several hours of field time were required to sample each tree and the work could only be accomplished in the fall, after the cessation of growth, and before inclement weather.

One tree was sampled from each ITD, within each rectangularity per site. This resulted in a total of 28 trees per site, with half of the trees coming from each spacing geometry. This sample size seemed logistically feasible for provision of adequate precision by regression analysis. Dominant and codominant trees were evaluated for sampling. Trees with forked tops, multiple stems, or irregular branch formation were rejected. The numbers of missing and dead neighbors, out of a total of 8 potential neighbors (Figure 2.2), were tallied for each tree. Neighbor trees numbered 1,3,5, and 7 have the most influence on crown development because of their proximity to the sample tree (Figure 2.2). Therefore, it was a priority that these trees be present whenever possible. Trees were selected in order to choose trees with the fewest missing neighbors due to initial planting loss or early mortality.

Tree and branch measurement

Trees were measured for total height and height to the base of the live crown (BLC) periodically since establishment (Newton and Cole, 1999). Height was measured at each annual node to the nearest centimeter using a height pole. BLC was defined as the height to lowest average live branch. BLC was measured to the nearest meter using a height pole and calibrated ocular estimation.

All main whorl branches were cut off away from the bole at the edge of the branch collar. Trees were pruned to remove all dead branches and at least the lower one-third of live crown length to a minimum of 5.27 m, with maximum sampling height per tree varying according to crown recession. Internodal branches were not sampled or counted. Ramicorn branches were also disregarded because they were uncommon and would create outliers in the data. Branches were labeled according to whorl number, stem height, and log quadrant. Log quadrant was based on the orientation of each tree along its spoke and direction to plot center (Figure 2.2). Branches were recorded as living if they had any green foliage.

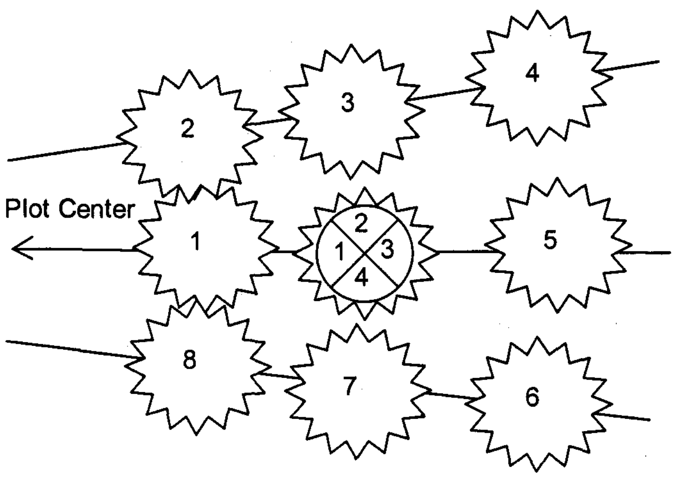


Figure 2.2. The relationship between a sample tree and its eight neighbor trees, as well as log quadrant orientation.

A separate subsample of branches was made. Two dominant, unbroken branches per whorl, 90° apart, were selected from random adjacent quadrants. If unbroken branches were not found, then the most complete branches were sampled. The following measurements were made on-site as the branches were cut off: shoot length, terminal bud length, terminal bud type and the number of internodes present. Bud measurements were only completed on living branches. Bud length was measured with digital calipers to the nearest millimeter. Buds were distinguished and classified as blunt or pointed (Wilson, 1989).

For all branches, the ends of each branch were cut off and stored in a laboratory at approximately 21°C. After two months, all branch basal diameters were measured inside bark to the nearest millimeter with digital calipers. No correction was made for shrinkage of green branches. The end of each branch was re-cut with a bandsaw and then sliced with a razor blade in order to create a smooth surface. The number of annual growth rings at the branch base were counted with a 16 x hand lens. A microscope was used to count the numbers of annual growth rings on a subsample of 100 branches. Rings were counted only if they had both distinct earlywood and latewood.

Data analysis

Mean branch diameter inside bark (MBD), maximum branch diameter inside bark (MXBD), mean number of rings at branch base (RING), and mean number of internodes per branch (NODE), were calculated for all branches between 0.3 m stump height and 5.27 m per tree. This corresponds to the top of the basal 16 ft log, allowing a 1 ft stump and 0.3 ft trim allowance. In addition, average MBD and MXBD per log quadrant were calculated. The number of branch whorls and number of branches/m were also determined between 0.3 m and 5.27 m. A small percentage of branches below 5.27 m were still alive on 12 trees planted between 309 and 1,045 trees/hectare.

Variables were also calculated using the subsample of dominant, unbroken branches sampled from each whorl. The number of years without basal ring production (NORING) and number of years without shoot production (NONODE) were calculated for all live branches in the lower one-third of the live crown length. For each tree, percent of branch life spent with NORING (%NORING) and percent of branch life spent with NONODE (%NONODE) were calculated by dividing NORING and NONODE by total branch age. The branch within the lower one-third of the live crown with maximum %NONODE and %NORING was identified for each tree. Because trees were not felled and sectioned, it was not possible to calculate branch longevity for dead branches as outlined by Maguire and Hann (1987) and used by Kershaw et al. (1990).

Several external branch characteristics were evaluated as predictors in a logistic regression to discriminate missing-ring branches from ring-producing branches. The objective was to determine whether missing-ring branches could be identified by terminal bud presence, bud type, bud size, terminal leader length, and crown position. Models were selected by their R^2 and posterior probability of predicting the correct outcome from the data. The branches used for this analysis were the subsample of unbroken, dominant branches with shoot and bud measurements. Out of a total of 1166 living branches sampled in the lower one-third of the live crown, 676 had complete data necessary for the analysis. Of the 676 possible branches at both sites, 300 ring-producing and 300 missing-ring branches were randomly selected for the analysis.

Multiple regression analysis was used to test whether the response variables were related to ITD, rectangularity, or site, depending on the response variable and hypothesis. Graphical representation illustrated that the data were not linear (Figure 2.3). A transformation using the natural log of the response variable as well as the natural log of ITD was used in most models. Back-transformed values that had been analyzed as natural log values are reported here as median values and compared to actual measured values. Most models were of the following form, as illustrated by the relationship between mean branch diameter (MBD) and initial tree density (ITD) and site: $\ln(MBD) = B_0 + B_1\ln(ITD) + B_2 site + (B_3 Site \times \ln(ITD))$. Reference is made to operational planting densities recently used in the Pacific Northwest, ranging from 469 trees/ha (4.6 m x 4.6 m) to 1682 trees/ha (2.4 m x 2.4 m) (Oliver et al., 1986; Scott et al., 1998; Newton and Cole, 1999).

Results

Base of the live crown (BLC) in relation to initial tree density (ITD)

In the fall of 1998, the base of the live crown (BLC) had receded past 5.27 m for the majority of trees (Figure 2.3). However, 12 of the trees planted between 309 and 1,045 trees/hectare had green branches below 5.27 m. Model predictions may be inaccurate for initial tree densities between 309 to 1045 trees per hectare because estimates used green branches that have the potential for further growth. However, most of the live branches below 5.27 m were heavily shaded and no longer adding radial growth rings. Therefore, it was decided there would be very little difference in model predictions by including green branches in the analysis.

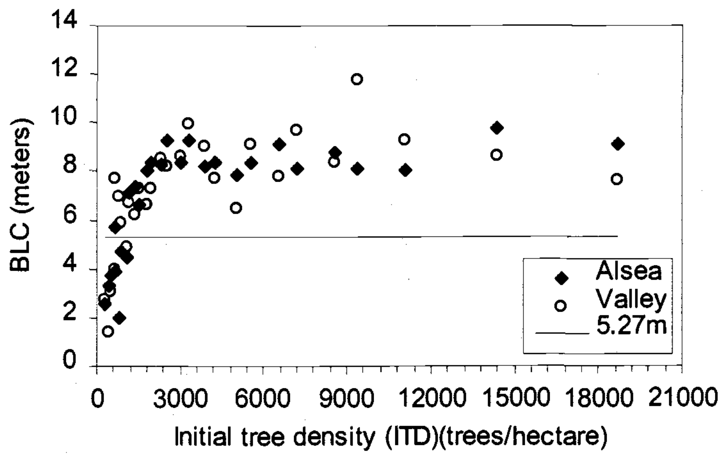


Figure 2.3. Base of the live crown (BLC) and top of the basal log (5.27 m) in relation to initial tree density (ITD) and site.

Mean branch diameter (MBD) in relation to initial tree density (ITD)

Mean branch diameter (MBD) for the basal 5 m log was highly dependent on initial tree density (ITD) at both sites (Figure 2.4). There was a strong linear relationship and significant overlap between sites. After accounting for ITD, there was no evidence the slopes differ between sites (P-value = 0.4447) and the difference in MBD between sites was not significant (P-value = 0.0881), so both sites were analyzed together.

There was no evidence that MBD varied by rectangularity, after adjusting for ITD (P-value = 0.4969). A linear regression of ln(MBD) on ln(ITD) was the most appropriate model for both sites, based on the coefficient of determination, residual fit, and simplicity (Table 2.1). The predicted median MBD ranged from approximately 9 mm at 18,730 tree/ha to 28 mm at 309 trees/ha. Within operational planting densities, 469 trees/ha (4.6 m x 4.6 m) to 1682 trees/ha (2.4 m x 2.4 m), actual measured MBD ranged from 16 mm to 26 mm.

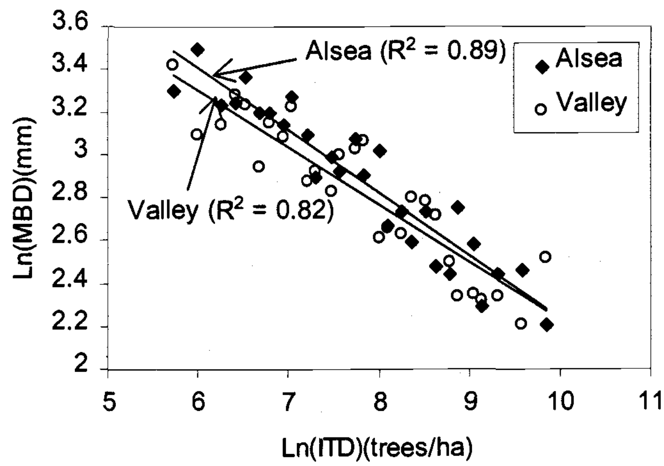


Figure 2.4. Relationship between mean branch diameter (MBD) and initial tree density (ITD) for the basal 5 m log by site.

Table 2.1. Coefficients and standard errors (SE), calculated to describe the relationship between MBD and ITD for the basal 5 m log, both sites combined (n=56) ($\ln(MBD) = B_0 + B_1 \ln(ITD)$).

	B_0	B_1	R^2
Coefficient	4.9755	-0.2887	0.8498
SE	0.1299	0.0165	

Maximum branch diameter (MXBD) in relation to initial tree density (ITD)

Maximum branch diameter (MXBD) for the basal 5 m log was highly dependent on initial tree density (ITD) at both sites (Figure 2.5). There was a strong linear relationship at both sites with significant overlap in the data. After accounting for ITD, there was no evidence that slopes differ between sites (P-value = 0.7889) and the difference in MXBD by site was not significant (P-value = 0.1066), so both sites were analyzed together.

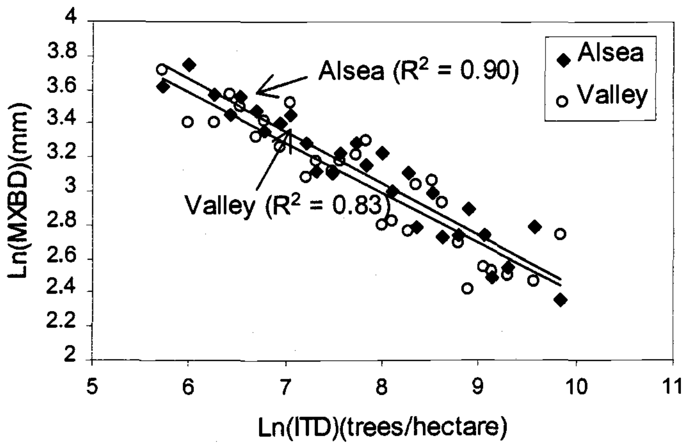


Figure 2.5. Relationship between maximum branch diameter (MXBD) and initial tree density (ITD) for the basal 5 m log by site.

For approximately 68% of the trees in the 1:2 rectangularity, the largest branch occurred in either the 2nd or 4th log quadrant. In contrast, for 54% of the trees in the 1:1 rectangularity, the largest branch occurred in either the 2nd or 4th log quadrant. Although larger branches were found more often in the 2nd or 4th quadrants in the 1:2 rectangularity, these branches did not cause the 1:2 rectangularity to have a higher MXBD (Figure 2.6). Consequently, there was no evidence that MXBD varied by rectangularity, after accounting for ITD (P-value = 0.4143). The predicted median MXBD ranged from approximately 10 mm at 18,730 trees/ha to 37 mm at 309 trees/ha. Within operational planting densities, 469 trees/ha (4.6m x 4.6m) to 1682 trees/ha (2.4 m x 2.4 m), actual measured MXBD ranged from 22 mm to 36 mm and was 17% to 46% higher than measured MBD (mean = 28.5%, SE = 1.8). The largest branch measured in the whole experiment was 47 mm (1.85 in) outside bark.

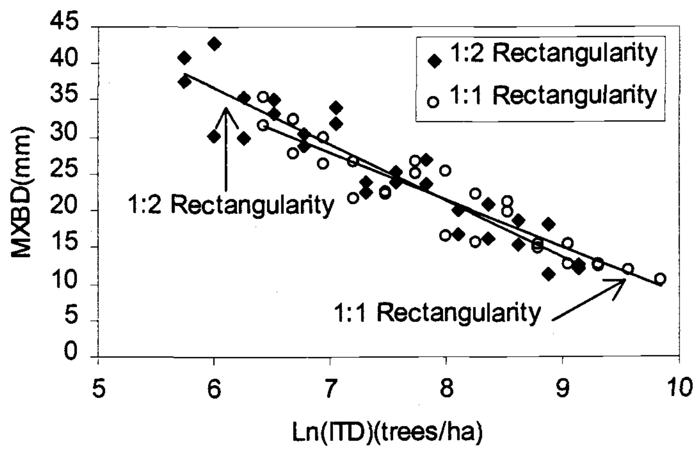


Figure 2.6. Relationship between maximum branch diameter (MXBD) and rectangularity for the basal 5 m log, both sites combined.

Table 2.2. Coefficients and standard errors (SE), calculated to describe the relationship between MXBD and ITD for the basal 5 m log, both sites combined (n=56) ($\ln(MXBD) = B_0 + B_1 \ln(ITD)$)

	B_0	B_1	R^2
Coefficient	5.3940	-0.3121	0.8588
SE	0.1354	0.0172	

<u>Number of branches/m in relation to initial tree density (ITD)</u>

The number of branches per log was converted to branch density or the number of branches/m. There was no difference in the number of branch whorls in the basal 5 m log by site (P-value = 0.5969) or by ITD (P-value = 0.5677, R^2 = 0.0040). This shows that height growth was relatively equal for the first 5.27 m of height growth for the specific stand component that was sampled. The average number of whorls for the first 5 m log was approximately 6.8 and 7, for the Valley site and Alsea site, respectively. However, there was a negative relationship between the number of branches/m and ITD (Figure 2.7). There was no evidence that the number of branches/m varied by site, after accounting for ITD (P-value = 0.5456). There is considerable variation in the number of branches/m, resulting in only 43% of the variation being accounted for by ITD (Table 2.3).

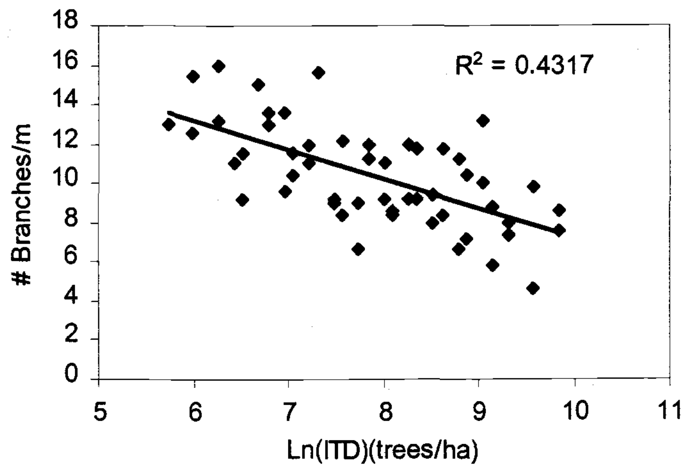


Figure 2.7. Number of branches/m on the basal 5 m log in relation to initial tree density (ITD), both sites combined (n=56).

Table 2.3. Coefficients and standard errors (SE), calculated to describe the relationship between the number of branches/m and ITD for the basal 5 m log, both sites combined (n=56) (Branches/m = B_0 + B_1 ln(ITD)).

	B_0	B_1	R^2
Coefficient	22.1966	-1.4970	0.4317
SE	1.9051	0.2405	

Longevity of radial branch growth (RING) in relation to initial tree density (ITD)

There was a strong negative relationship between the mean number of rings at branch base (RING) in the basal 5 m log and initial tree density (ITD) at both sites (Figure 2.8). There was no evidence for a difference in slope between sites (P-value = 0.4746) and only suggestive evidence for a difference in RING between sites (P-value = 0.0588). Separate analysis by site resulted in near identical results, so the data were analyzed together.

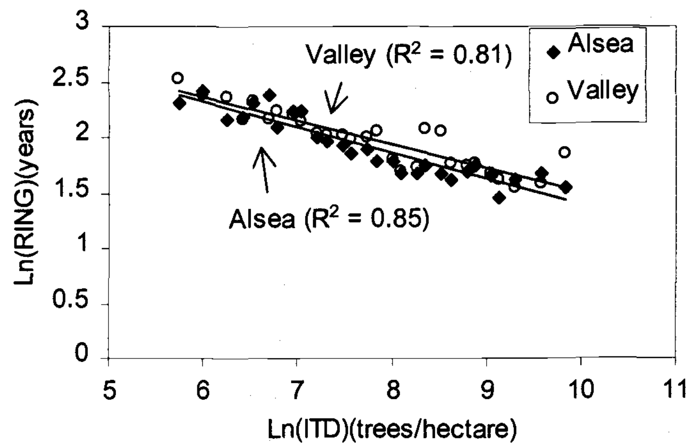


Figure 2.8. Relationship between the mean number of rings at branch base (RING) and initial tree density (ITD) for the basal 5 m log by site.

After accounting for ITD, there was no evidence that rectangularity affected RING (P-value = 0.3617). The best fitting model included a cubic term for ln(ITD) and accounted for approximately 90% of the variation in RING (Table 2.4). Predicted median RING per tree ranged from approximately 5 years at 18,730 trees/ha to 12 years at 309 trees/ha. Within operational planting densities, 469 trees/ha (4.6 m x 4.6 m) to 1682 trees/ha (2.4 m x 2.4 m), actual measured RING ranged from 7 to 11 years.

Table 2.4. Coefficients and standard errors (SE), calculated to describe the relationship between RING and ITD for the basal 5 m log, both sites combined (n=56) ($\ln(RING) = B_0 + B_1\ln(ITD) + B_2\ln(ITD)^3$)

	B_0	B_1	B_2	R^2
Coefficient	4.8443	-0.4498	0.0012	0.9008
SE	0.4113	0.0805	0.0004	

<u>Longevity of terminal branch growth (NODE) in relation to initial tree density (ITD)</u>

There was a strong negative relationship between the mean number of years of terminal branch growth (NODE) and initial tree density (ITD) for both sites (Figure 2.9). There was no evidence that the slope of the regressions differed by site (P-value = 0.9938), but there was a difference in NODE for a given ITD by site (P-value = 0.0006).

There was no evidence that rectangularity influenced NODE, after adjusting for ITD at Alsea (P-value = 0.7486) or the Valley sites (P-value =

0.7456). Final regression models accounted for 78% to 88% of the variation in NODE (Table 2.5). Predicted median NODE was nearly identical regardless of site, ranging from approximately 5 years at 18,730 trees/ha to 13 years at 309 trees/ha. Within operational planting densities, 469 trees/ha (4.6 m x 4.6 m) to 1682 trees/ha (2.4 m x 2.4 m), actual measured NODE ranged from 8 to 13 years and was on average one year greater than RING.

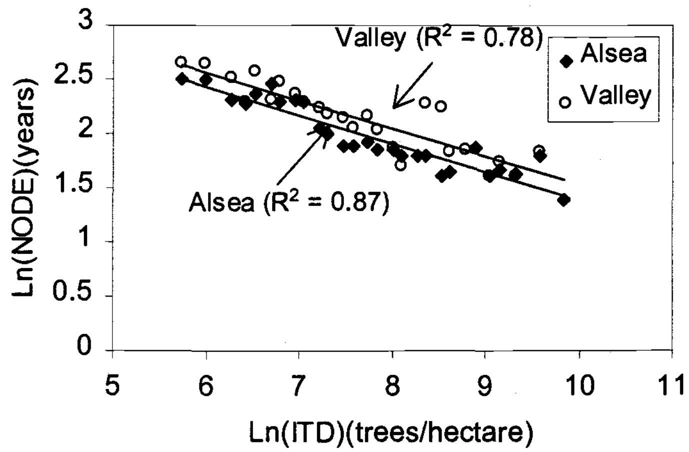


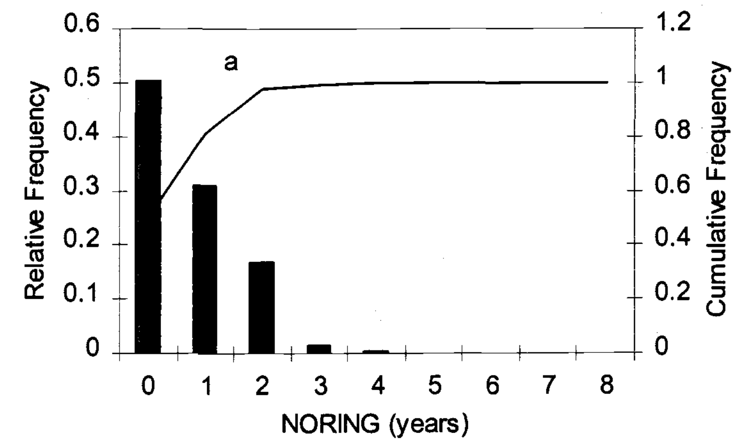
Figure 2.9. Relationship between the mean number of branch internodes (NODE) and initial tree density (ITD) for the basal 5 m log by site.

Table 2.5. Coefficients and standard errors (SE), calculated to describe the relationship between NODE and ITD for the basal 5 m log by site. ($\ln(NODE) = B_0 + B_1\ln(ITD) + B_2\ln(ITD)^3$)

	B_0	B_1	B_2	R^2
Alsea				
Coefficient	5.3885	-0.5360	0.0015	0.8859
SE	0.7000	0.1362	0.0007	
Valley				
Coefficient	4.1202	-0.2591		0.7837
SE	0.2189	0.0284		

Number of missing basal branch rings (NORING) by site

The number of missing basal branch rings (NORING) in the lower one-third of the live crown ranged from 0 to 4 years (mean = 0.71, SE = 0.0341) at the Alsea site (Figure 2.10a) and ranged from 0 to 8 years (mean = 1.4 SE = 0.0691) at the Valley site (Figure 2.10b). A majority of branches at both sites had one or less years of imperceptible growth.



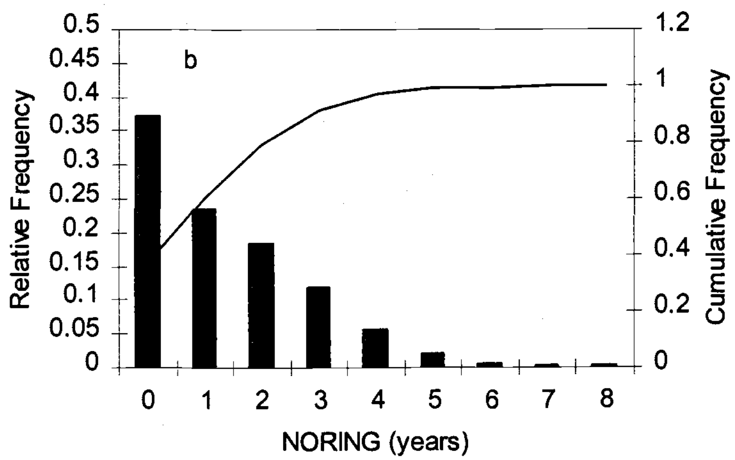


Figure 2.10. Relative (bars) and cumulative (lines) frequency distribution of the number of missing annual basal rings (NORING) in the lower one-third of the live crown for (a) the Alsea site and (b) the Valley site.

The frequency of ring-producing branches increases with increasing height into the live crown because of a decline in branch age and increase in vigor (Figure 2.11). In the lower 10% of live crown length, fewer than 27% of branches are still adding radial increment. Above 30% live crown length, a majority of the branches are still adding annual increment, with radial increment increasing with decreasing branch age.

Maximum NORING increased with decreasing ITD, in a log-log relationship at Alsea (P-value = 0.0001, R^2 = 0.4370) and the Valley site (P-value = 0.0035, R^2 = 0.2767). However, there was no evidence that maximum %NORING varied with ITD at Alsea (P-value = 0.3644) or the Valley site (P-value = 0.6345). The maximum %NORING, in the lower one-third of each tree, ranged from 11% to 33% (mean = 22.5%, SE = 1.12) and from 14% to 47% (mean = 30%, SE = 1.55) at the Alsea and Valley sites, respectively.

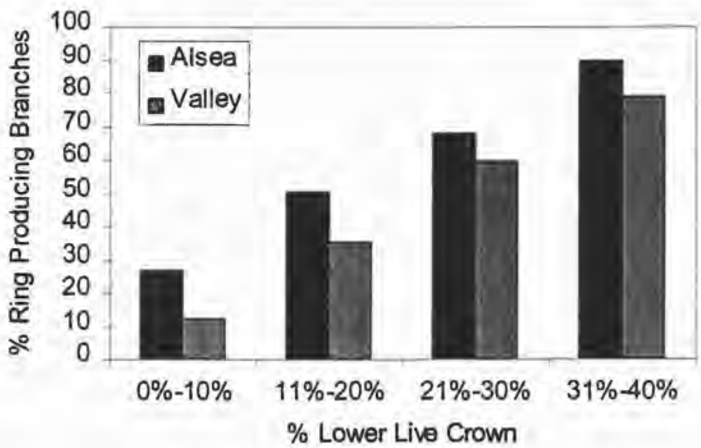
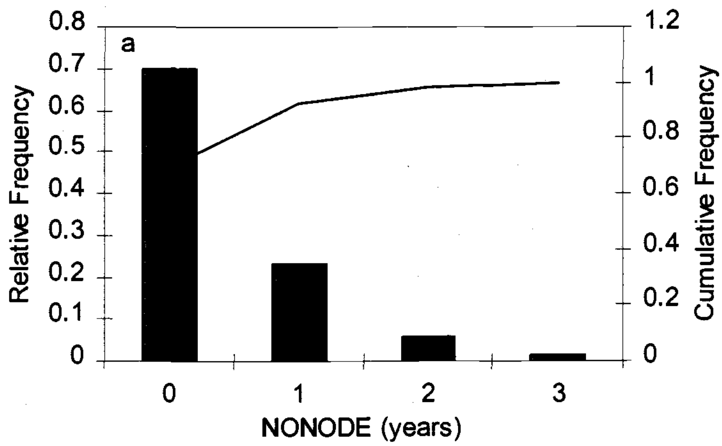


Figure 2.11. Percentage of ring-producing whorl branches by lower crown position and site.

Number of missing branch internodes (NONODE) by site

The number of years branches failed to flush (NONODE), but remained alive in the lower one-third of the live crown was nearly identical regardless of site (Figures 2.12a-b). NONODE ranged from 0 to 3 years (mean = 0.39, SE = 0.0389) at Alsea (Figure 2.12a) and ranged from 0 to 3 years (mean = 0.38 years, SE = 0.0405) at the Valley site (Figure 2.12b). Approximately 70% of all branches had current terminal shoot growth in the lower one-third of the live crown at both sites. The percentage of branches with terminal leader growth



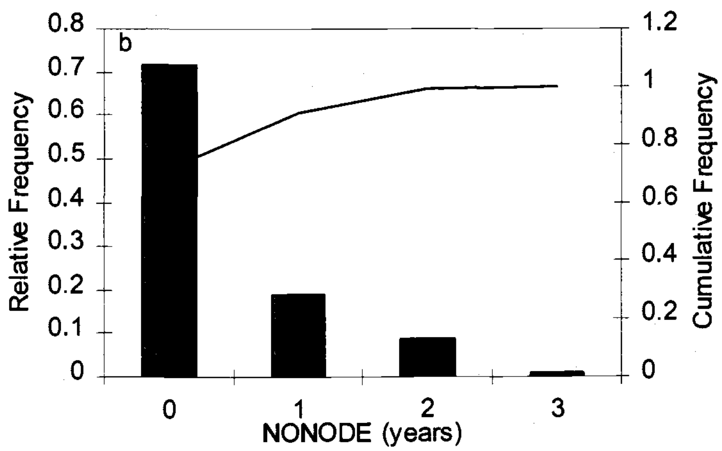


Figure 2.12. Relative (bars) and cumulative (lines) frequency distribution of the number of missing branch internodes (NONODE) in the lower one-third on the live crown for (a) the Alsea site and (b) the Valley site.

increases with increasing height in the live crown (Figure 2.13). However, even in the lower 10% of the crown, a majority of the branches are still elongating.

Maximum NONODE decreased nonlinearly with increasing ITD at Alsea (P-value = 0.0067 and R^2 = 0.2508 after a natural log transformation of NONODE and ITD), but there was no evidence for a similar relationship at the Valley site (P-value = 0.9540). Maximum %NONODE did not vary with ITD at either site (P-value = 0.5944, Alsea; P-value = 0.2414, Valley). Maximum %NONODE, in the lower one-third of the live crown, was nearly identical at both sites, ranging from 0% to 33% (mean = 17%, SE = 1.42) and from 0% to 36% (mean = 16%, SE = 1.87) at the Alsea and Valley sites, respectively.

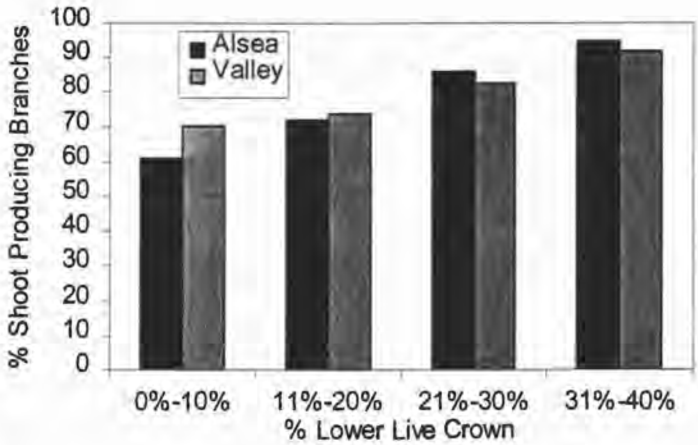


Figure 2.13. Percentage of terminal flushing branches by lower crown position and site.

Indicators of NORING

During fieldwork, missing-ring branches were observed to have short terminal shoots, small blunt terminal buds, and were located in the lower one-third of the live crown. To confirm these field observations, several external branch characteristics were evaluated as predictors in a logistic regression to discriminate missing-ring branches from ring-producing branches. The objective was to determine whether missing-ring branches could be identified by terminal bud presence, terminal bud type (pointed or blunt) (Wilson, 1989), terminal bud size, terminal leader length, and crown position (Table 2.6).

Table 2.6. Percentage of 300 ring-producing and 300 missing-ring branches correctly classified from discriminant analysis as either having, or not having, ring-production in 1998.

	% Correctly classified as:		
Variable	No ring production	Ring production	R^2
Terminal shoot length (mm)	68.4	50.5	0.10
Crown position (%)	74.4	71.7	0.23
Terminal bud type	70.0	81.1	0.24
Terminal bud presence	95.3	51.9	0.27
Terminal bud size (mm)	78.5	70.4	0.31
Bud + bud size + crown position	77.1	82.8	0.41

The single best indicator of missing-ring branches is the absence of a terminal bud (Table 2.6). At both sites, when a branch failed to form a terminal bud, there was a 92% chance that these branches had also stopped forming annual basal rings. Using the logistic regression model, approximately 95.3% of missing-ring branches could be correctly classified (Table 2.6). Every variable provided greater than a 68% correct classification rate, significantly better than random classification, which would have had a 50% success rate. Stepwise regression resulted in the variables terminal bud presence, terminal bud size, and crown position being selected (Table 2.6). This model had the highest R^2 and had the best posterior probability of correctly classifying ring-producing branches.

Practical implications for artificial pruning

A widely accepted rule-of-thumb is that the lower one-third of the live crown could be pruned without serious growth impact (O'Hara, 1991). Within operational planting densities, 469 trees/ha (4.6 m x 4.6 m) to 1682 trees/ha (2.4 m x 2.4 m), it took between 13 and 17 years, and averaged about 15 years, until the lower one-third of the live crown was below 5.27 m, with timing delayed slightly by wider spacing (Figure 2.14).

The first whorl located just below 5.27 m had already lived between 63% and 85% of its potential life (mean =75%). Within approximately 2 years, radial

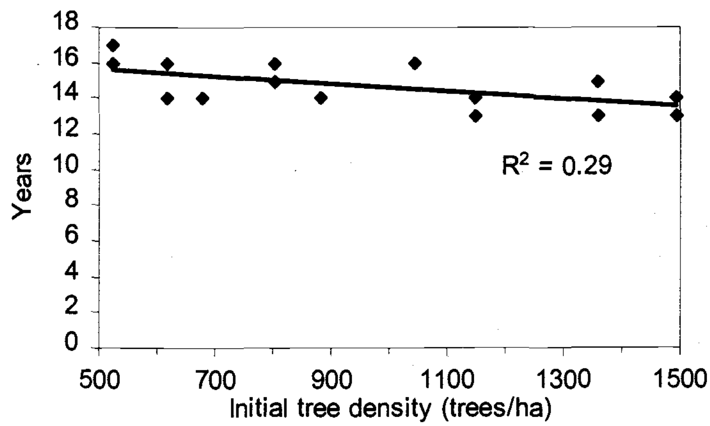


Figure 2.14. Age when the top of the lower one-third of the live crown length is below 5.27 m.

growth would cease on the majority of branches. A subsample of 75 branches indicates that between 76% and 95% (mean = 88.5%) of final branch diameter is reached when a branch has completed 75% of its ring-producing life span. Therefore, by the time a branch falls into the lower one-third of the live crown, it has lived approximately 75% of its ring-producing life and completed approximately 88% of its cumulative radial growth. At this point, radial and terminal growth has been significantly reduced and pruning the branch would be desirable.

Discussion

Initial tree density (ITD) was the primary determinant of mean and maximum branch diameter and accounted for the majority of variation found in the study. For Douglas-fir in the Pacific Northwest, the relationship between stand density and branch diameter has long been recognized (Eversole, 1955; Grah, 1961; Smith, 1961; Carter et al., 1986; Reukema and Smith, 1987). Within operational planting densities, 469 trees/ha (4.6 m x 4.6 m) to 1682 trees/ha (2.4 m x 2.4 m), mean branch diameter (MBD) ranged from 16 mm to 26 mm. This is similar to average diameters reported in other studies (Eversole, 1955; Smith, 1961; Carter et al., 1986; Reukema and Smith, 1987).

When making inference between branch diameter and knot size, it is important to note that branch diameter often does not equal the knot size calculated during log grading. During log grading, knot size is calculated by averaging the narrow and wide measurements and includes only the center or hardened area of the knot, excluding the branch collar (NLRAG, 1994). For naturally regenerated Douglas-fir in northern California, Grah (1961) reported that over 20% of lower 4.9 m logs at 4 m and wider spacing (673 trees/ha) developed knots greater than 63 mm (2.5 in.), disqualifying them for No. 2 Sawmill logs (NLRAG, 1998). When spacing exceeded 5.5 m (332 trees/ha), 100% of the lower 4.9 m logs developed knots greater than 63 mm. It should be noted that Grah (1961) measured branch diameter but made inference to knots without any correction. In contrast, Smith (1961) came to a different conclusion, reporting lower average and maximum branch diameters for 184 of the largest young-growth Douglas-fir in the University of British Columbia forests, where maximum branch diameter did not exceed 63 mm. For plantation Douglas-fir in New Zealand, branch size rarely exceeds 40 mm, except for open grown "wolf" trees, and is most commonly 25 mm or less (Whiteside et al., 1977). Maguire et al. (1991) predicted the mean of the four largest branches (BD_4) per 12.2 m log with the growth model ORGANON under six different stand density regimes and harvest at age 65. Providing that ITD was 498 trees/ha or 1,195 trees/ha, no harvested volume would include logs with BD_4 >63 mm, even with various commercial thinning regimes. However, precommercial thinning to 298 trees/ha at age 9 resulted in about 50% of the total harvested volume in logs with BD_4 > 63 mm. Therefore, very wide, or completely open spacing is required for the development of branches over 63 mm. In this study, the largest branch measured was 47 mm outside bark, where ITD ranged from 309 trees/ha to 18,730 trees/ha.

There was no difference observed in mean or maximum branch diameter due to the 1:2 rectangularity. In natural regeneration, asymmetric crowns may develop due to non-uniform spacing of neighbor trees. However, there was no evidence that the 1:2 rectangularity influenced mean or maximum branch diameter in this study. Rapid diameter growth occurs while a branch is in a favorable upper crown position (Forward and Nolan, 1961; Brown, 1962). As branches become shaded by upper whorl branches and by neighbor trees, diameter growth declines. Branches in less favorable quadrants, due to the 1:2 rectangularity, were observed to grow towards a more favorable light environment in adjacent log quadrants. The largest branches were found more often in the 2nd or 4th quadrants. However, rectangularity had no significant influence on overall branch diameter. This conclusion is subject to the lower 5 m log of intensively-managed Douglas-fir. Reukema and Smith (1987) concluded that 1:2 rectangularity resulted in "efficient production of large trees of high value and adequate quality". They proposed 1:2 rectangularity, 3 m x 6 m spacing, and pruning to 6 m for optimum clear wood production in Douglas-fir.

The number of branches/m increased with decreasing initial tree density (ITD). Carter (1986) concluded that wider spacing in Douglas-fir, such as 4.5 m, resulted in not only larger and more persistent branches, but also an increase in the number per whorl. Mäkinen (1996) found that "the number of new branches was almost completely independent of stand and tree characteristics" in the upper crown of Scots pine. Therefore, differences observed in the number of dead branches in the lower crown may be a result of the early mortality of smaller branches as competition in the mid and lower crown increases. The more favorable light environment in the wider spacings allowed more branches to persist. It is unknown how many branches in the extremely narrow spacings fell off prior to sampling, but due to their small size they would have no effect on log grade. Therefore, the increase in branches/m, as well as increase in mean and maximum branch diameter due to wider spacing will negatively impact wood quality for the standpoint of knot characteristics. However, large vigorous branches are required to grow the larger diameter trees found at wider spacing.

Longevity of terminal and radial branch growth increased with decreasing stand density. There was a significant range in longevity of terminal and radial branch growth. Years of terminal growth generally exceeded years of radial growth by an average of one year. However, it is difficult to estimate how long branches will persist. Several studies have determined the number of years necessary for natural pruning in naturally regenerated young-growth Douglas-fir to a specified log length (Bransford and Munger, 1939; Kachin, 1939; Paul, 1947; Kotok, 1951). However, none of the studies measured differences due to initial stand density, referring only to site index or tree size. It is obvious that the longevity of radial growth increases with decreasing ITD, but more information is needed in order to determine the persistence of branches in relation to ITD, especially in intensively managed, widely-spaced plantations.

The young Douglas-fir in this study had a fairly small range in the number of years without radial branch growth (NORING) compared to other studies. In the lowest live branch of *Abies lasiopcarpa*, NORING ranged from 0 to 28 years with a mean of 12 years (Roberts, 1994). In western Washington, Douglas-fir ranging in age from 35 to 70 years had 9 to 10 years of NORING with a maximum 15 years (Reukema, 1959). In South Dakota, *Pinus ponderosa* ranging in age from 40 to 100 years had between 0 and 34 years of NORING (Andrews and Gill, 1939). Kershaw et al. (1990) studied duration of branch diameter growth and branch longevity for 2,153 branches immediately below the current live crown of 354 Douglas-fir trees in southwestern Oregon. Trees were sampled from a broad range of ages and sizes. NORING ranged from 0 to 49 years with a mean of 8 years. In this study, NORING only ranged from 0 to 4 years at Alsea and from 0 to 8 years at the Valley site. The small range is caused by a combination of fast height growth and self-shading in combination with a high tree survival rate and effective vegetation control. The Nelder design had more uniform spacing than would be found in natural stands. The range of spacing used in the study has provided a more precise estimate of NORING in intensively-managed young-growth Douglas-fir during the critical period of growth when pruning would be a viable option.

Assuming the branches studied were near death, maximum %NORING was very similar to what has been reported in other studies. Maximum percent NORING averaged 22.5% at Alsea and 30% at the Valley site. Kershaw et al. (1990) found that branches averaged 34% of their life without basal ring production. Approximately 44% of the branches in the lower one-third of the live crown have current radial and terminal growth. However, once a branch falls into the lower one-third of the live crown, approximately 88% of expected radial growth has occurred. Within 2 years radial growth will cease, followed within a year by the end of terminal elongation. These lower branches lack a vigorous terminal bud, having insufficient sink strength to draw on carbon reserves from the rest of the tree (Sprugel et al., 1991) and eventually die because of a negative incremental carbon balance (Witowski, 1996). This suggests that they also contribute very little to stem growth.

In this study several variables were able to categorize over 70% of missing-ring branches correctly. In general, missing-ring branches were found in the lower third of the live crown, had small terminal buds, and short terminal shoots. Roberts (1994) found that the ratio of branch dry weight to fresh weight discriminated between ring-producing and missing-ring branches with 85% accuracy. Also, the ratio of foliage weight to total branch weight provided 70% accuracy. In this study, the lack of a terminal bud was the best indicator of branches that have ceased radial growth. However, this is only a conservative measure since buds may remain dormant for several years (Kozlowski and Pallardy, 1997). Wilson (1989) found that blunt buds less than 1 mm failed to elongate in young Douglas-fir. Smaller buds in the lower branches of red pine trees failed to elongate (Kozlowski et al., 1973). These observations suggest that basal ring production could end years before a terminal bud is missing in branches. This is generally consistent with the relative priorities for photosynthate allocation at the tree-level between shoot elongation and diameter growth (Kozlowski, 1992; Sprugel et al., 1991).

This study has several practical conclusions. First, branch diameter in the lower 5 m log is very dependent on initial tree density (ITD), which is easily controlled with forest management. The choice of ITD is one of the most important decisions made by a forest manager. For current operational planting spacings of 4.6 x 4.6 m and closer, knot size is unlikely to exceed 63 mm, providing for at least No. 2 Sawmill logs (NLRAG, 1998). This conclusion is important to woodland owners who are planning to sell logs in the marketplace. Considering a rotation length of 60 years, pruning is necessary to grow logs of grades better than No. 2 Sawmill logs, based on results of natural pruning studies (Bransford and Munger, 1939; Kachin, 1939; Paul, 1947; Kotok, 1951). Without artificial pruning, the production of large logs of high quality would require planting at high densities, pre-commercial thinning after the onset of crown recession, and carefully planned commercial thinning treatments combined with extended rotation lengths greater than 70 years (Newton and Cole, 1987). Multiple entries and extended rotation lengths are difficult to justify economically (Fight et al., 1995), but this regime could provide improved wood quality where short rotations and even-aged management is not an option.

Intensive site preparation, planting, and maintenance are necessary in order to avoid excessively wide plantation spacing. There is evidence that plantation densities below 300 trees/hectare may encourage branch diameters over 63 mm to develop (Grah, 1961; Maguire et al., 1991). This wide spacing will result in additional large and persistent knots and prevent the formation of clear wood. There is also evidence that wide spacing, combined with intensive management may exacerbate swelling at branch nodes, the number of double whorls, and stem sinuosity (Carter et al., 1986).

A second important conclusion is that 1:2 rectangularity of spacing did not impact mean branch diameter, maximum branch diameter, or longevity of branch growth in the lower 5 m log. The 1:2 rectangularity of spacing would be advantageous if spacing were wider between rows than within rows, allowing easier access for plantation maintenance and harvesting at the first thinning. However, it would be difficult to apply 1:2 rectangularity on steep terrain. This approach would be more appropriate on a flat plantation. Within the range of plantation densities studied, silvicultural operations should focus on providing uniform spacing when possible. Further research is necessary to determine whether a rectangularity more extreme than 1:2 would result in anomalous branch diameter growth.

The cumulative evidence indicates that pruning the lower one-third of the live crown is a reasonable compromise between wood quality and volume growth loss. Higher value logs would compensate for any minor decrease in growth. Within operational planting densities, the lower one-third of the live crown could be pruned when trees are between 13 and 17 years old, producing a clear basal 5 m log. Branches should be pruned as soon as possible, which shortens healing time and initiates clear wood formation sooner. Maintaining trees in a healthy vigorous state through careful density management will provide for faster pruned stub occlusion and a larger volume of clear wood.

Wide initial spacing, combined with pruning appears to be the best choice for improving wood quality of Douglas-fir. Pruning is cost effective when applied early in the rotation and combined with wide spacing (Fight et al., 1995). Another advantage of lower initial plantation density is the reduced cost of stand establishment and the elimination of precommercial thinning costs. Narrow spacing cannot adequately control branch diameter to grow clear wood on shorter rotations without pruning.

CHAPTER 3. WOOD DENSITY AND TRACHEID LENGTH VARIATION IN RELATION TO INITIAL TREE DENSITY AND CROWN CHARACTERISTICS IN YOUNG DOUGLAS-FIR

Abstract

Data were collected from Nelder plots to test the hypothesis that wood density and tracheid length increase with more rapid crown recession under greater initial tree density in Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) plantations. Fifty-six trees were sampled from 19- and 21-year-old intensively managed sites in central western Oregon. Initial density ranged from 309 trees/ha to 18,730 trees/ha in a Nelder design. Ring density, earlywood density, latewood density, and percent latewood were calculated for three radial wood zones from pith to bark at breast height (1.37 m) and one outer-wood zone at 5.27 m. In addition, outer-wood tracheid length was calculated at 1.37 m. When age was held constant, there was no evidence that wood density or percent latewood varied with initial tree density (ITD) or crown characteristics at breast height. There was evidence that trees under severe competition had lower latewood density (LD) at breast height, especially as ring width decreases below 1.0 mm. There was evidence that ring density, earlywood density, and percent latewood increased linearly with ITD at 5.27 m. Ring density, earlywood density, and percent latewood at 5.27 m were positively correlated with increasing height to diameter ratio and height to the base of the live crown. However, regression analysis revealed that neither initial tree density nor crown characteristics could explain a majority of the variation in wood properties. Wide initial spacing and

artificial pruning are recommended in order to improve the quality of intensively-managed young-growth Douglas-fir.

Introduction

Wood density

Wood density is the "single most important indicator of clear wood quality" and has been shown to strongly influence wood strength and the yield of pulp (Jozsa et al. 1989). Numerous studies with Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) in the Pacific Northwest (Barret and Kellogg, 1991) as well as in New Zealand (Whiteside et al., 1977; Bier, 1986) show that low juvenile wood density results in lumber products with reduced strength and stiffness. Problems associated with lower density juvenile wood have also been reported with laminated veneer lumber and oriented strand board (Briggs, 1995). Larger dimensional products are required to satisfy minimum design requirements because of poor dimensional stability and lower strength (Kretschmann et al., 1993). In addition, pulp yields decline and pulp quality changes with wood density (Hatton and Cook, 1992).

Wood density is a function of tracheid cell wall thickness and radial lumen diameter. Radial cell wall thickness and cell diameter have been shown to be independent of each other by studies in which photoperiod, light intensity, and water stress are manipulated (Zimmerman and Brown, 1974). The timing of cambial activity, rate of cell division, and radial cell diameter are influenced by growth-regulating hormones produced in terminal shoots and other portions of the crown (Larson, 1994). Cell wall thickness is influenced by the supply of carbohydrates from the crown (Larson, 1969b) and is a compromise under competition for carbohydrates with other growth areas (Kozlowski, 1992).

Tracheid length

Tracheid length is the second most important determinant of wood and pulp quality. Tracheid length influences hand sheet properties of unbleached kraft pulp (Hatton and Hunt, 1989) as well as mechanical pulps (Hatton and Johal, 1989). A minimum tracheid length of 2.5 to 3.0 mm is required for high quality pulp production from conifers, but increasing tracheid length beyond 3.5 mm has a minimal effect (Zobel, 1989). Unbleached kraft pulp from juvenile wood had greater interbonding than kraft pulp from mature wood, resulting in higher burst and tensile strength, but reduced tear strength (Hatton and Hunt, 1989). This difference in properties was attributed to an increase in fiber coarseness as fiber length increases from pith to bark.

Tracheid length in Douglas-fir increases rapidly from the pith to approximately age 15 to 20, then levels out after age 30 to 40 (Duffield, 1964; Erickson and Harrison, 1974; Hatton and Hunt, 1989). This trend is consistent regardless of height, although tracheid length was found to be slightly shorter at the base (0.6 m) of young-growth Douglas-fir in Washington (Megraw, 1986a).

Tracheid length is dependent on the length of its parent cambial initial. In gymnosperms, tracheids elongate 5% to 10% more than their cambial initial (Bailey, 1920). The length of the cambial initial depends on the rate of cambium anticlinal division. Wide growth rings with a high percent of earlywood require a larger number of anticlinal divisions, reducing the average fusiform initial length (Bannan, 1964; Larson, 1994). In contrast, low rates of anticlinal division are associated with above average tracheid length (Bannan, 1967). Tracheids produced in the earlywood are shorter than tracheids produced in the latewood, depending on species (Dinwoodie, 1961). In addition, pseudotransverse division occurs more frequently in younger trees, forming shorter fusiform cambial initials, and therefore, shorter tracheids (Bannan, 1967; Kozlowski and Pallardy, 1997).

There is conflicting evidence concerning the relationship between tracheid length and growth rate (Dinwoodie, 1961; Zobel and van Buijtenen, 1989). The general assumption is that as growth rate increases, tracheid length decreases (Bannan, 1967). However, in Douglas-fir there is evidence that in rings less than 0.5 mm, tracheid length may decline (Bannan, 1964; de Kort, 1990). Bannan (1964) found that maximum tracheid length in Douglas-fir was associated with a ring width of approximately 1.0 mm.

Crown development and vigor

The active live crown has been implicated as the driving force in wood formation (Larson, 1969b; Briggs, 1996). There is a "high degree of correlation between developmental events occurring in the crown and the formation of wood along the bole beneath" (Brown, 1970). External factors such as temperature, nutrients, moisture and light exert their influence directly on the growth of the crown and only indirectly on wood formation (Larson, 1962; Briggs and Smith, 1986).

Wood formed in close proximity to the active live crown and near the pith is referred to as "juvenile wood". Juvenile wood has been identified as a growing concern, especially in the quality of young-growth plantations (Larson, 1969b; Senft et al., 1985a). The chemical and physical properties of juvenile wood are highly variable. Wood density and tracheid length increase and microfibril angle decreases from pith to bark. In most softwoods, juvenile wood has lower wood density, larger microfibril angle, lower percentage latewood, lower cellulose content, and shorter tracheids than mature wood (Bendtsen, 1978).

The literature suggests that two factors are primarily responsible for the formation of juvenile wood. These two factors are crown structure and the age of the cambium (Zobel and Sprague, 1998). There is suggestive evidence that the juvenile wood period lasts longer in widely spaced or open-grown trees due to the influence of the large crown (Larson, 1969a; Briggs and Smith, 1986; Di Lucca, 1989). Zobel and Sprague (1998) found that open-grown southern pine produced mature wood and concluded that the age of the cambium is of primary importance in the formation of juvenile wood. In contrast, DiLucca (1989) concluded that for open-grown Douglas-fir, the transition from juvenile to mature wood is not abrupt, based on the wood density. DiLucca (1989) determined that the transition from juvenile to mature wood occurs approximately 3.8 m below the "functional" live crown in stand-grown trees, corresponding to the base of the live crown (Maguire and Petruncio, 1995).

The purpose of this study was to test the hypothesis that wood density and tracheid length are influenced by variation in crown development imposed by different initial spacings during the juvenile period of wood formation. While wood density and tracheid length are increasing with age at a given height, the distance to the base of the live crown increases and the length and width of the crown change. As crown recession progresses, an increase in wood density and tracheid length are expected on the lower bole as the influence of the live crown diminishes with increasing distance from the site of wood formation. This hypothesis was tested using intensively-managed young-growth Douglas-fir, 19 and 21 years old, planted at initial densities ranging from 309 trees/ha to 18,730 trees/ha in variable density Nelder plots (Nelder, 1962). Significant variation in crown structure has developed over the past 19 to 21 years due to intraspecific competition.

Specific questions include:

1. Is there an increase in wood density or tracheid length with increasing initial tree density?
2. Is there an increase in wood density at a given age with increasing distance below the live crown?
3. If wood density is correlated with initial tree density or crown characteristics, can the correlation be attributed to earlywood density, latewood density, or percent latewood?
4. Is more variation in wood density and tracheid length accounted for by initial tree density or individual tree variables, such as diameter at breast height, height to the base of the live crown, or height to diameter ratio?

Methods

Site descriptions

The study was undertaken at two sites in central western Oregon, both of which were converted pasturelands. The Alsea site is 5 km east of Alsea, Oregon, at 125 m, 44°23' N, 123° 33' W. The Valley site is 10 km south of Philomath, Oregon, at 130 m, 44° 26' N, 123° 21' W. The Valley site is representative of the warm, dry summer climate of the Willamette Valley and the Alsea site is typical of the warm summer climate of the Coast Range valleys, exhibiting lower moisture deficit than the Valley site (Cole and Newton, 1986). Available nitrogen is comparable between sites, even though total soil nitrogen is higher at the Valley site (Cole and Newton, 1986). At the Alsea site mean annual precipitation is about 175 cm with a mean annual temperature of 11°C and a frost free season of 200 to 210 days (Zedaker, 1981). At the Valley site mean annual precipitation is about 100 cm, with a mean annual temperature of 13°C and average frost free season of 165 to 200 days (Zedaker, 1981). Estimated site index at 50 years (SI_{50}) is 38 m and 32 m at Alsea and the Valley sites, respectively, based on soil characteristics.

The sites were planted with 2-0, nursery run, bare-root Douglas-fir seedlings from a low elevation, mid-Coast Range source in 1978 and 1980, at the Valley and Alsea sites, respectively . Understory weed control was sustained for 5 years (Cole and Newton, 1986). After 19 total years of growth, dominant trees were approximately 18 m tall at the Valley site and 19 m tall at the Alsea site. In the fall of 1998, the average breast height age of the trees was 15 and 17 years old, at the Alsea and Valley sites, respectively.

Experimental design and tree selection

The trees were planted in variable density Nelder plots (Nelder, 1962), which consist of a series of concentric circles that represent systematic changes in density at a constant proportional rate (Figure 3.1). Space between trees increases 30% from the inside towards the outside of the plot. There are four complete Nelder plots at the Alsea site and two at the Valley site. Originally, each plot consisted of 48 spokes and 17 arcs, creating a total of 816 trees per plot. However, after 6 years of growth, alternate spokes were removed on portions of each plot creating a fairly rectangular geometry of 1:2 (Figure 3.1). The remainder of the trees had roughly square geometry at about 1:1. Edge effect was avoided by sampling from arcs 3 through 16 only. Initial tree density (ITD) ranged from 309 to 9,365 trees per hectare in the rectangular spacing and from 618 to 18,730 trees per hectare in the square spacing.

The objective of the research was to study trees along a density gradient, while keeping sample size manageable. Several factors made subsampling the Nelder plots necessary, rather than using Nelder plots as the experimental units. Several hours of field time were required to sample each tree and the work could only be accomplished in the fall, after the cessation of growth, and before inclement weather. One tree was sampled from each ITD, within each rectangularity per site. This resulted in a total of 28 trees per site with half of the trees coming from each spacing geometry. This sample size seemed logistically feasible for regression analysis of the data.

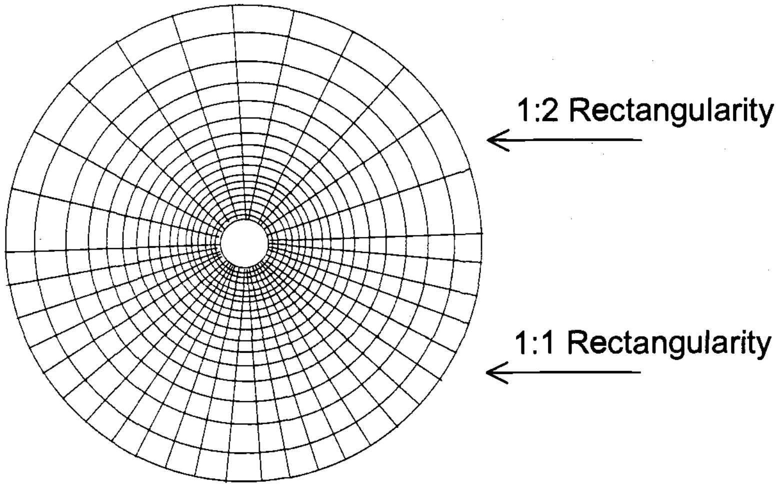


Figure 3.1. Nelder plot layout showing 1:2 and 1:1 rectangularity.

Dominant and codominant trees were evaluated for sampling. Trees with forked tops, multiple stems, or irregular branch formation were rejected. The numbers of missing and dead neighbors, out of a total of 8 potential neighbors were tallied for each tree (Figure 3.2). Neighbor trees numbered 1,3,5, and 7 have the most influence on crown development because of their proximity to the sample tree (Figure 3.2). Therefore, it was a priority that these trees be present whenever possible. Trees were selected in order to choose trees with the fewest missing neighbors due to initial planting loss or early mortality. Because of mortality, 8 live neighbors did not surround all trees, especially as ITD increased over 3,278 trees per hectare.

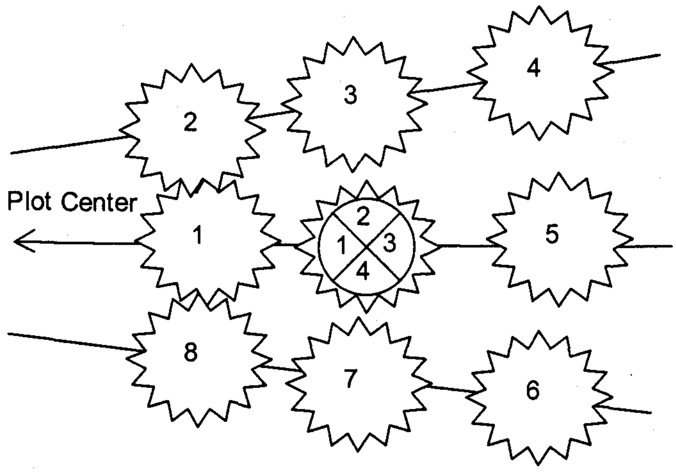


Figure 3.2. The relationship between a sample tree and its eight neighbor trees, as well as log quadrant orientation.

Tree measurement

Trees were measured for diameter at breast height (DBH), total height (HT), and height to the base of the live crown (BLC) periodically since establishment. DBH was measured with a diameter tape to the nearest millimeter at 1.37 m. Height was measured to the nearest centimeter using a height pole. BLC was defined as the height to lowest average live branch. BLC was measured to the nearest meter using a height pole and ocular estimation. Measurements of DBH, HT, and BLC used in the current analysis included the years 1990, 1993, 1996, and 1998. The diameter at 5.27 m (D16) was measured with a diameter tape to the nearest mm in 1998. Live crown length was calculated as the difference between HT and BLC. PLC was determined by dividing the live crown length by HT. HD was calculated by taking the ratio between HT (cm) and DBH (cm).

Two dominant, unbroken branches per whorl, 90° apart, were selected from random adjacent quadrants. If unbroken branches were not found, then the most complete branches were sampled. Annual cumulative growth in branch length was reconstructed for each sample branch. Branches were assumed to be living if they were above BLC for that year. Crown width (CW) was calculated by taking the quadratic average and multiplying it by 2. The whorl with maximum CW above BLC was recorded as CW for each year.

Increment Core Collection

Two 5-mm increment cores were extracted per tree at breast height (1.37 m) for wood density and growth ring analysis. In addition, one 8-mm increment core was extracted at breast height for tracheid length measurement. The 5-mm increment cores were taken 90° from each other and at an angle of 90° to the bole of the tree. One 5-mm core was also extracted at 5.27 m above the ground for wood density and growth ring analysis. This height (5.27 m) corresponds to the top of the basal 16 ft log, allowing a 1 ft stump and 0.3 ft trim allowance.

Wood Density Data Collection

The 5-mm increment cores were air-dried and then cut to approximately 1.5 mm thick longitudinal dimension using a Hubert Pneumatic Instruments precision sample saw. The cut samples were treated to remove resin and extractives that may alter the attenuation of X-rays, so that accurate measurements from the direct reading X-ray densitometer were possible.

Samples were treated by submerging them in a near boiling 2:1 mixture of 95% ethyl alcohol and toluene for eight hours. The ethyl alcohol and toluene mixture was changed every two hours. Cores were allowed to equilibrate to the moisture content of the X-ray room at approximately 12% moisture content.

The cores were scanned using a direct-reading X-ray densitometer. Data were collected every 0.1 mm along the length of each increment core. The density values were imported into DendroScan 4.5 (Varem-Sanders and Campbell, 1996). DendroScan 4.5 determined the boundaries between growth rings and between earlywood and latewood. The boundary between earlywood and latewood is where the density is equal to the average of the minimum earlywood and maximum latewood densities. "This result is a good analog of the biological earlywood/latewood boundary that is consistent for most rings (Varem-Sanders and Campbell, 1996)." All units of wood density are expressed as basic relative density using dry weight and green volume (Jozsa and Middleton, 1994). The following tree-ring variables were generated: ring width (RW), earlywood width (EWW), latewood width (LWW), average ring density (RD), earlywood density (EWD), and latewood density (LWD). Percent latewood (PL) was calculated by dividing LWW by RW.

Wood density was sampled from four wood zones according to the number of rings from the pith and sample height (Table 3.1 and Figure 3.3). Each wood zone contained three growth rings centered on a field measurement year. For example, growth rings from 1995, 1996, and 1997 were averaged to get RD, EWD, LWD, and PL for the Valley site when the trees were 19 years old.

The only exception is in the outer- and upper-wood zones for Alsea, where only 1997 and 1998 were averaged. It was not possible to sample in 1999 in order to have three growth rings centered on the 1998 field season.

Table 3.1. Wood zones as categorized by total average tree age and average ring age from pith, by site and sampling height.

Site	Wood zone	Sample height (m)	Average tree age	Average ring number from the pith
Valley	Inner	1.37	13	9
	Mid	1.37	16	12
	Outer	1.37	19	15
	Upper	5.27	19	10
Alsea	Inner	1.37	14	10
	Mid	1.37	17	13
	Outer	1.37	19	15
	Upper	5.27	19	10

Tracheid Length Data Collection

The growth rings corresponding with the 14th and 15th ring from the pith were combined from each 8-mm increment core. This coincided with 1995 and 1996 at the Valley site, and 1997 and 1998 at Alsea. This sample position was chosen in order to examine the oldest wood possible that would permit comparisons between sites. Samples were macerated by heating at 85°C in a 10% solution of 1:1 nitric acid and hydrogen peroxide in water. Samples were rinsed with water and then stained with aqueous safranin. The macerated fibers were mounted on slides with glycerin as the mounting medium. Three separate random selections from each sample were mounted on three separate slides, resulting in 9 random bunches of cells per sample.

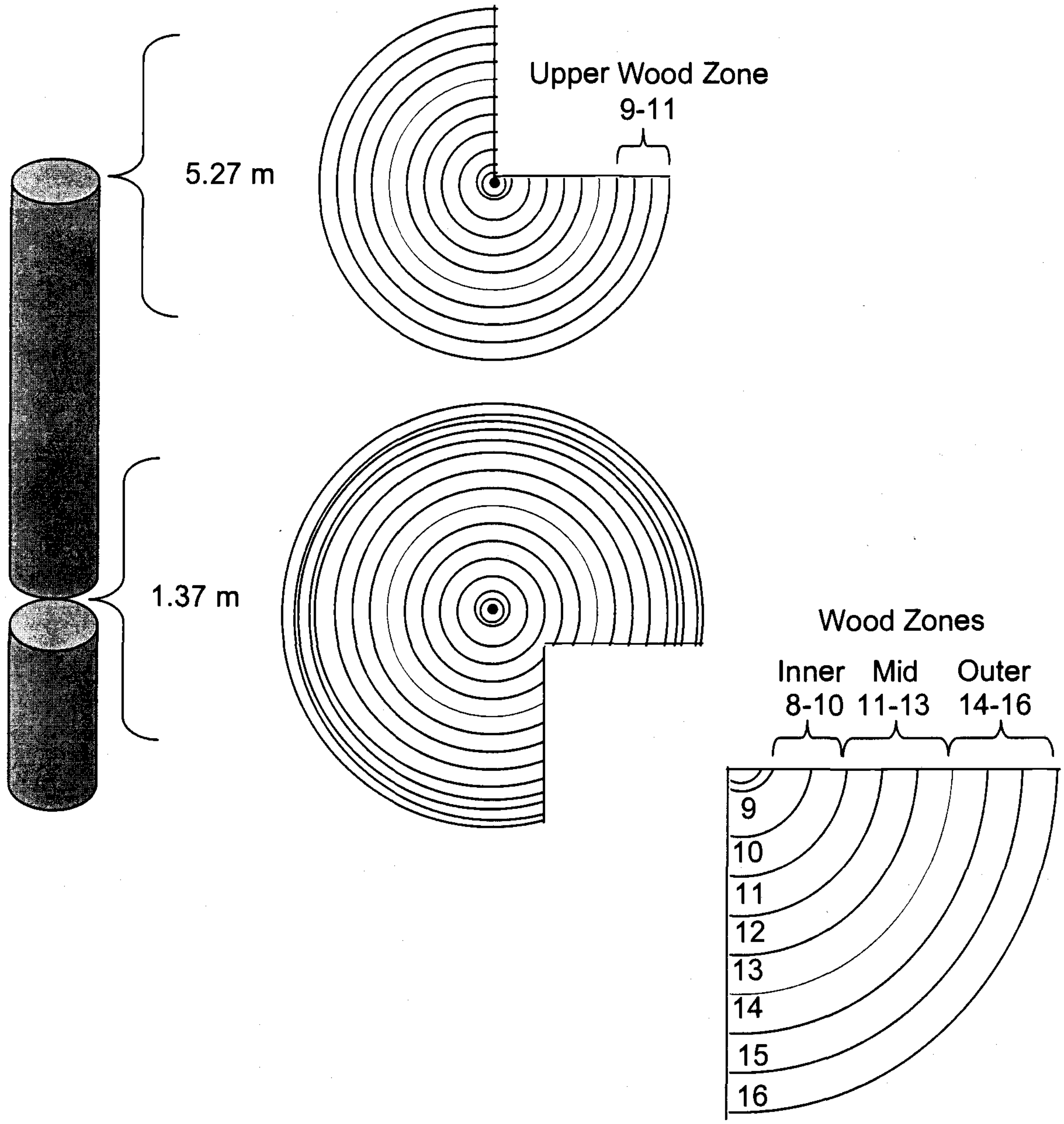


Figure 3.3. Location of increment core extraction (1.37 m and 5.27 m) and corresponding wood zones used for wood anatomy sampling (Valley site).

A total of 100 unbroken tracheids per sample were measured using an image-analysis system. The images of the slides were captured through a CCD video camera attached to a stereo-microscope. Tracheid length was captured and analyzed using the public-domain software program NIH *Image*, version 1.9 for Macintosh (Rasband, 1992). Calculating the average of 100 tracheids gave 95% confidence interval widths between 0.05 mm and 0.10 mm.

Data analysis

The objective of the analysis was to determine whether tracheid length, ring density (RD), earlywood density (EWD), latewood density (LWD), or percent latewood (PL) were correlated with initial tree density (ITD) using simple linear regression. Graphical representation illustrated that the data were not linear. A transformation using the natural log of the response variable as well as the natural log of ITD were used to create linear relationships. Most models were of the following form, as illustrated by the relationship between ring density (RD) and initial tree density (ITD): $\ln(RD) = B_0 + B_1\ln(ITD)$. Multiple regression was used to determine whether tracheid length, RD, EWD, LWD, or PL could be predicted with DBH, D16, HD, PLC, CW, or BLC. Stepwise selection was used in order to screen the best explanatory variables and reduce the chance of multicolinearity. The main purpose of the separate analyses was to determine if individual tree variables or ITD was a better predictor of wood density and tracheid length, while holding age constant.

Results

Wood density in relation to initial tree density (ITD) and individual tree variables

Graphical examination of the data found that the four smallest trees at each site had unusually low latewood density (LWD) (Figure 3.4). This was

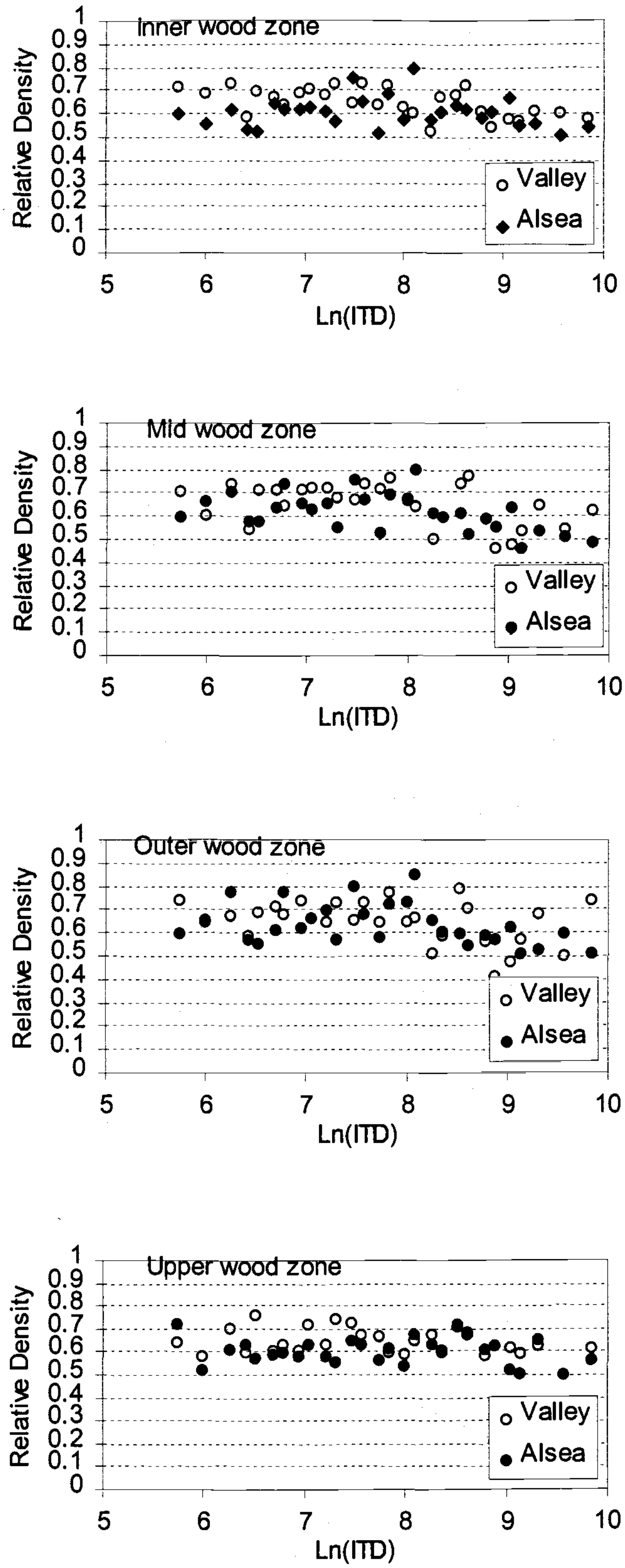


Figure 3.4. Relationship between latewood density (LWD) and initial tree density (ITD) by wood zone and site.

especially apparent in the mid- and outer-wood zones. These trees were planted at initial densities of 7203.5, 8524, 9365, and 14404 trees/ha at the Valley site and at 5541, 9365, 11082, and 18730 trees/ha at the Alsea site. These trees had consistently the lowest DBH and highest HD at each site. They did not differ in percent latewood (PL) or earlywood density (EWD) from the other trees. However, these trees had lower latewood density (LWD) than the other trees (Figure 3.4). Consequently, ring density (RD) was also lower for these trees. The lower LWD may be a measurement error due to the difficulty in measuring LWD in growth rings less than 1 mm. All analyses included the four smallest trees at each site. However, statistically significant regressions were reanalyzed excluding the four smallest trees for comparison.

Mean ring density (RD) increased from the inner towards the outer-wood zones (Figure 3.5). There were no apparent differences in RD between sites except for in the upper-wood zone. The inner and upper-wood zones are shown next to each other for comparison since both are approximately 10 rings from the pith, differing only by sample height (Figure 3.5).

For the inner-wood zone, there is no apparent difference in mean ring density (RD) by site (Figures 3.5 and 3.6). RD averaged 0.41 and 0.39 at the Valley and Alsea sites, respectively. However, the relationship between RD and initial tree density (ITD) differ by site (Table 3.2). There appears to be a negative relationship between RD and initial tree density (ITD) at the Valley site, but no significant relationship at the Alsea site. At the valley site, 14% of the variation in RD is explained by ITD. The relationship between RD and ITD became non-significant when the four smallest trees were removed from the analysis (P-value = 0.2197). A similar conclusion was made for the relationship between earlywood density (EWD) and ITD. The removal of the four smallest trees led to a non-significant relationship (P-value = 0.1483). Approximately 33% of the variation in latewood density (LWD) was explained by ITD. Removing the four smallest trees only reduced the significance of the relationship (R^2 = 0.1964, P-value = 0.0301). The best predictor of LWD at the Valley site was the height to diameter ratio (HD) (Table 3.3), explaining approximately 54% of the variation, significantly more than using ITD alone (Table 3.2).

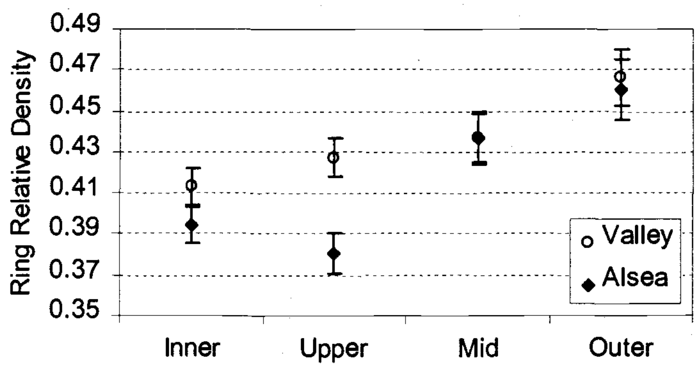


Figure 3.5. Mean ring density (RD) and standard errors calculated for each wood zone by site.

For the mid-wood zone, latewood density (LWD) decreased with an increase in initial tree density (ITD) at both sites (Table 3.2). Approximately 19% and 23% of the variation in LWD was explained by ITD at the Valley and Alsea, respectively. Similar to results in the inner-wood zone, four small trees were strongly influencing the regression model. The regression was not significant

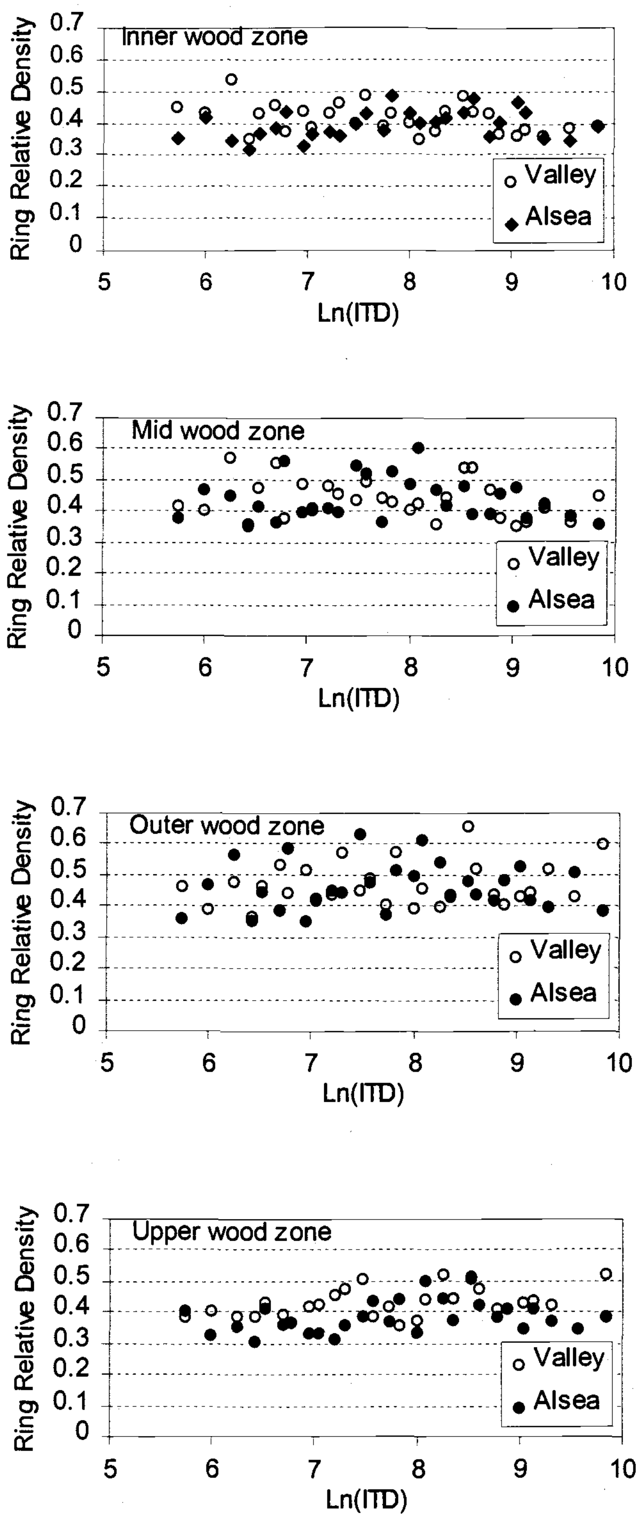


Figure 3.6. Relationship between ring density (RD) and initial tree density (ITD) by wood zone and site.

Table 3.2. Coefficients, R^2, and P-value for the simple linear regression of RD, EWD, LWD, and PL on ln(ITD). These results include all sample trees. Significant relationships (P-value < 0.05) are shown in bold.

Site	Wood Zone	Variable	Intercept	Ln(ITD)	R^2	P-value
Valley	Inner	**RD**	**0.537**	**-0.0159**	**0.1420**	**0.0440**
		EWD	**0.3324**	**-0.0006**	**0.2141**	**0.0132**
		LWD	**0.8927**	**-0.0313**	**0.3280**	**0.0014**
		PL	0.3118	0.0059	0.0097	0.6187
Alsea	Inner	RD	0.3089	0.013	0.0400	0.3075
		EWD	0.223	0.007	0.0557	0.2268
		LWD	0.6314	-0.0032	0.0031	0.7798
		PL	0.1802	0.0286	0.0840	0.1345
Valley	Mid	RD	0.5361	-0.0127	0.0533	0.2372
		EWD	0.2815	0.0036	0.0077	0.6574
		LWD	**0.9155**	**-0.0346**	**0.1918**	**0.0197**
		PL	0.4318	0.0066	0.0082	0.6458
Alsea	Mid	RD	0.4549	-0.0024	0.0016	0.8395
		EWD	0.2304	0.0102	0.0585	0.2150
		LWD	**0.881**	**-0.0346**	**0.2260**	**0.0106**
		PL	0.2508	0.0224	0.0998	0.1014
Valley	Outer	RD	0.3743	0.0118	0.0359	0.3345
		EWD	**0.1533**	**0.0252**	**0.2794**	**0.0038**
		LWD	**0.886**	**-0.0308**	**0.1421**	**0.0480**
		PL	0.2028	0.0247	0.1077	0.0888
Alsea	Outer	RD	0.4247	0.0046	0.0045	0.7334
		EWD	0.2061	0.0164	0.0849	0.1324
		LWD	0.8542	-0.0286	0.1297	0.0598
		PL	0.2408	0.0241	0.0706	0.1717
Valley	Upper	**RD**	**0.2641**	**0.0213**	**0.2348**	**0.0121**
		EWD	**0.1059**	**0.0249**	**0.3576**	**0.0013**
		LWD	0.7146	-0.0091	0.0337	0.3696
		PL	**0.1648**	**0.0271**	**0.1697**	**0.0365**
Alsea	Upper	RD	0.2725	0.0139	0.0901	0.1206
		EWD	**0.1445**	**0.0157**	**0.1640**	**0.0325**
		LWD	0.6749	0.0097	0.0363	0.3316
		PL	0.2168	0.0168	0.0486	0.2595

with the four smallest trees removed at the Valley (P-value = 0.2273) or at the Alsea site (P-value = 0.1658). The best predictor of LWD was the height to diameter ratio (HD), explaining approximately 20% and 48% of the variation at the Alsea and Valley sites, respectively (Table 3.3).

For the outer-wood zone, latewood density (LWD) appears to be related to initial tree density (ITD) at both sites (Table 3.2). However, when the four smallest trees were removed from the regression, LWD was no longer related to ITD (Valley P-value = 0.8169, Alsea P-value = 0.6221). At the Valley site three out of four of the trees failed to produce a growth ring in 1998 and two failed to grow in 1997. None of the trees at Alsea failed to form annual growth rings at breast height by 1998. The best predictor of LWD was the height to diameter ratio (HD), explaining approximately 13% and 44% of the variation at the Alsea and Valley sites, respectively (Table 3.3). At the Valley site, approximately 28% of the variation in earlywood density (EWD) was explained by ITD (Table 3.2). Stepwise selection resulted in approximately 24% of the variation in EWD being explained by percent live crown (PLC) at the Valley site (Table 3.3).

The results from the upper-wood zone differ from results found at breast height. At both sites, earlywood density (EWD) appears to be positively affected by initial tree density (ITD) (Table 3.2). In addition, 30% and 37% of the variation in EWD is accounted for using individual tree variables at the Alsea and Valley sites, respectively (Table 3.3). At the Valley site ring density (RD), earlywood density (EWD), and percent latewood (PL) increase with increasing ITD.

Table 3.3. Coefficients, R^2, and P-value for the best multiple regression of RD, EWD, LWD, and PL on sets of tree variables. Missing information indicates none of the variables met the 0.15 significance level.

Site	Wood Zone	Variable	Model	R^2	P-value
Valley	Inner	RD	0.4927 - 0.0010(HD)	0.2277	0.0102
		ED	0.3154 - 0.0001(BLC)	0.2316	0.0095
		LD	0.8099 - 0.0020(HD)	0.5374	0.0001
		PL			
Alsea	Inner	RD			
		ED			
		LD			
		PL	0.3125 + 0.0003(BLC)	0.1314	0.0580
Valley	Mid	RD	0.5194 - 0.0009(HD)	0.1869	0.0216
		ED			
		LD	0.8364 - 0.0021(HD)	0.4861	0.0001
		PL			
Alsea	Mid	RD			
		ED			
		LD	0.7288 - 0.0012(HD)	0.1997	0.0171
		PL			
Valley	Outer	RD			
		ED	0.4290 - 0.1658(PLC)	0.2390	0.0083
		LD	0.8358 - 0.0021(HD)	0.4439	0.0001
		PL			
Alsea	Outer	RD			
		ED			
		LD	0.7270 - 0.0009(HD)	0.1347	0.0547
		PL			
Valley	Upper	RD	0.6328 - 0.0729 ln(DBH)	0.2456	0.0100
		ED	0.3696 - 0.0005(D16)	0.3677	0.0010
		LD			
		PL	0.4782 - 0.0060(DBH)	0.2246	0.0145
Alsea	Upper	RD	0.1221 + 0.0015(HD) + 0.0002(CW)	0.3719	0.0030
		ED	0.1984 + 0.0007(HD)	0.2959	0.0028
		LD			
		PL	-0.2741 + 0.0029(HD) +0.00057(CW)	0.4795	0.0003

The upper-wood zone is the only wood zone where RD is positively correlated with ITD. Results from the stepwise selection indicate that diameter at breast height (DBH) and diameter at 5.27 m (D16) are the best prediction variables for the Valley site (Table 3.3). At the Alsea site, height to diameter ratio (HD) and crown width (CW) were the best prediction variables (Table 3.3). At both sites more of the variation in wood density was accounted for using the individual tree variables rather than using ITD alone.

Tracheid length and initial tree density

There was no apparent pattern in mean tracheid length with changes in initial tree density (ITD) at either the Valley site (P-value = 0.2808) or Alsea (P-value = 0.1042) (Figure 3.7). Tracheid length ranged from 2.59 mm to 3.54 mm, with a mean of 3.11 mm (SE = 0.048), at the Valley site. For Alsea, tracheid length ranged from 2.86 mm to 3.41 mm, with a mean of 3.29 (SE = 0.039).

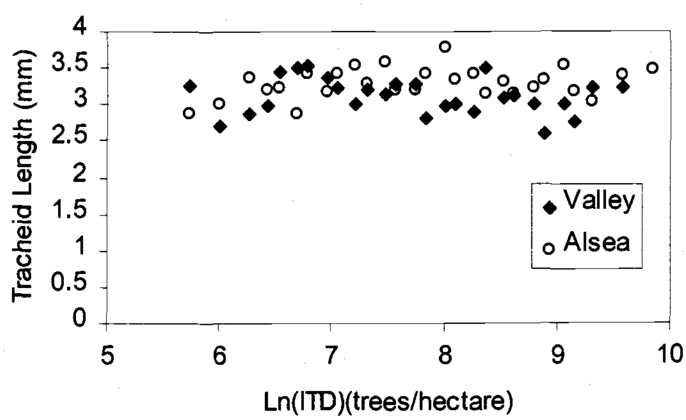


Figure 3.7. Relationship between tracheid length and initial tree density (ITD) by site.

There is strong evidence that a quadratic relationship exists between tracheid length and ring width at Alsea (P-value = 0.0019), with the model accounting for about 40% of the variation (Figure 3.8). Tracheid length increases from 0.5 to 2 mm and then begins to decrease. In contrast, the relationship is not significant at the Valley site (P-value = 0.1467, model R^2 = 0.1478).

Tracheid length and individual tree variables

Linear relationships were found between tracheid length and certain explanatory variables. However, explanatory variables were differed by site. Multiple regression, using stepwise selection, indicated that tracheid length was negatively related to height to diameter ratio (HD) at the Valley site (P-value = 0.0215). Only 20% of the variation in tracheid length was accounted for by HD. Graphical analysis of the regression indicated that two of the smallest trees with short tracheids were affecting the relationship. The trees were two of the four trees mentioned earlier in the wood density planted at 7203.5 and 9365

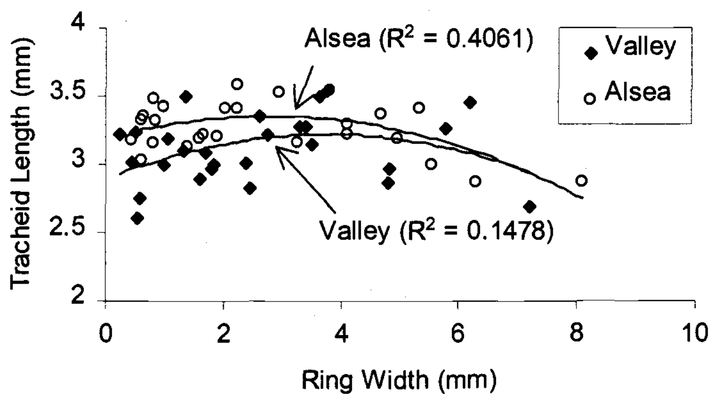


Figure 3.8. Quadratic relationship between tracheid length and ring width by site. (Tracheid length = $B_0 + B_1 \ln(ITD) + B_2 \ln(ITD)^2$)

trees/hectare. Since these small trees had high HD's and short tracheids, they were influencing the slope and significance of the regression. When they were removed from the analysis, the relationship was no longer significant between tracheid length and HD (P-value = 0.4524).

At Alsea, multiple regression, using stepwise selection, indicated that tracheid length was linearly related to height to the base of the live crown (BLC) (R^2 = 0.2917). BLC ranged from 2 m to 10 m, but the distribution was skewed making a linear relationship difficult to justify, even with various transformations. A majority of the trees had experienced crown recession above 7 m. Eight of the sample trees had BLC less than 6 m, averaging 3.8 m (SE = 0.42). Trees with lower BLC also had a shorter mean tracheid length of 3.14 mm (SE = 0.07), in contrast to 3.35 mm (SE = 0.04) for the trees with higher BLC. This is a difference of 0.213 mm between groups (95% CI = 0.05 mm to 0.37 mm, P-value = 0.01).

Discussion

There was not convincing evidence to conclude that initial tree density (ITD) affected ring density (RD), earlywood density (ED), or percent latewood (PL) at breast height, while holding age constant. The one exception was the significant relationship between ED and ITD for the outer-wood zone at the Valley site. Briggs and Smith (1986) concluded that initial spacing has no influence on wood density, tracheid size, or microfibril angle, while holding age constant. Although initial spacing directly influences crown structure (Eversole, 1955; Curtis and Reukema, 1970; Reukema and Smith, 1987), young trees are “sufficiently vigorous and healthy regardless of spacing”, with little difference in wood properties until later in life (Briggs and Smith, 1986). Minor effects of initial spacing found in this study were primarily due to the extremes of spacing used in the Nelder design. Under operational conditions, it is unlikely that significant differences would be observed at breast height.

Individual tree variables did offer better predictive power for modeling wood density at breast height. For example, for the inner-wood zone at the Valley site, about 33% of the variation in latewood density (LWD) was explained by ITD, compared to almost 54% of the variation in LWD being explained by the height to diameter ratio (HD).

Numerous studies have found for a given age and site, ring width, or growth rate, has no significant effect on wood density (Smith, 1956; Kennedy, 1961; McKimmy, 1966; Megraw, 1986a ; Jozsa et al., 1989). After a comprehensive literature review, Zobel and van Buijtenen (1989) concluded that increased growth rate does not lower wood density in Douglas-fir, hard pines, or larch. Smith (1956) found that ring width alone accounted for only 22% of variation in mean wood density of three growth zones measured from pith to bark. Kennedy (1961) determined that percentage latewood, and not growth rate, had the greatest degree of correlation with wood density. McKimmy (1966) also found that growth rate alone did not significantly affect wood density. Finally, Megraw (1986a) concluded that “specific gravity and growth rate are virtually independent traits in Douglas-fir”.

There are situations where stand density may affect wood density. For example, thinning studies have shown both positive and negative changes in wood density (Zobel and van Buijtenen, 1989). However, variation in wood density is usually 5% or less in magnitude, lasting for only a short period following thinning (Briggs and Smith, 1986; Megraw, 1986a). On sites where trees have insufficient summer moisture, thinning may increase percent latewood by prolonging the formation of latewood (Megraw, 1986b). In contrast, Brix (1972) found that summer irrigation of young Douglas-fir prolonged the formation of earlywood and decreased percentage latewood as compared to untreated trees.

Trees in this study were 15 and 17 years old at breast height. Their young age prevented the determination of the juvenile to mature wood transition. Abdel-Gadir and Krahmer (1993) concluded that at least 45 growth rings from the pith were necessary in order to determine the age of demarcation between juvenile and mature wood in Douglas-fir, since some trees were found to produce juvenile wood for 36 years. Zobel and van Buijtenen (1989) emphasize that the juvenile to mature wood transition may differ depending on what wood property is being employed. The transition may occur in wood density before the transition in tracheid length. Di Lucca (1989) found the juvenile to mature wood transition ranged between 15 to 34 years and averaged 22 years based on wood density for stand-grown Douglas-fir trees. Abdel-Gadir and Krahmer (1993) determined that the transition from juvenile to mature wood occurred at approximately age 26, based on wood density, and at approximately age 30 or 24, based on earlywood width or latewood width, respectively. Senft et al. (1985b) determined that the transition to mature wood occurred at approximately age 15 based on wood density, modulus of rupture, and modulus of elasticity in Douglas-fir.

Considering the previous studies, all of the wood in the current study would be classified as juvenile wood based on age. This is because the outer-wood zone averaged 15 rings from the pith, less than the juvenile to mature wood transition determined in other studies for Douglas-fir. Average juvenile wood density has been found to be 0.409 (Abdel-Gadir et al., 1993), 0.39 (Bendtsen, 1978), and 0.38 (Senft et al., 1985b). Average mature wood density has been reported to be 0.45 (Bendtsen, 1978), 0.5 (Senft et al., 1985b), and 0.467 (Abdel-Gadir et al., 1993). In this study, wood density ranged from 0.31 to 0.53, and averaged 0.40, for the inner-wood zone. For the outer-wood zone, wood density ranged from 0.35 to 0.65, and averaged 0.46. Therefore, average wood density was in transition from juvenile wood to mature wood from the inner- towards the outer-wood zone, nearly reaching mature wood densities by the 15th ring from the pith. Despite the fact that certain trees had reached mature level wood density, there was no evidence that trees with greater crown recession had higher density wood at breast height. Wood density increased from pith to bark in most trees, even trees planted at the widest spacing, contradicting the conclusions of Di Lucca (1989).

Most studies have only evaluated wood quality at breast height. There was evidence that certain wood properties may be related to initial tree density (ITD) or individual tree characteristics at 5.27 m. Ring density (RD), earlywood density (EWD), and percent latewood (PL) were positively correlated with increasing HD and BLC and were negatively correlated with DBH, PLC, and CW. However, regression analysis revealed that neither initial tree density (ITD) nor individual tree variables could explain a majority of the variation in wood properties.

There was evidence that trees under severe competition have lower latewood density (LWD) at breast height. A study on the effects of air pollution on crown vitality and wood quality in the Netherlands found that LWD declined in non-vital Douglas-fir (de Kort et al., 1991). Non-vital trees suffered from greater than 50% needle loss. Non-vital trees had severely reduced ring width (RW) and a reduction in ring density (RD). This trend was especially evident in growth rings less than 0.5 mm wide. In this study, the smallest four trees at each site had significantly lower LWD and a significant reduction in RW. LWD declined as RW declined to 1 mm or less. At the Valley site, some of the trees eventually failed to form annual growth rings at very high ITD's. Intensive forest management would prevent the extreme competition observed in this study, preventing a decline in LWD.

There was no evidence that tracheid length varied with initial tree density (ITD) at breast height. A study on Douglas-fir in the Netherlands found that in non-vital trees a dramatic decline in ring width created a shortening of earlywood and latewood tracheids (de Kort, 1990). Non-vital trees in this study also suffered from over 50% needle loss. In the lower bole of senescent trees, rings less that 0.5 mm showed decreases in tracheid length (Bannan, 1967). In this study, the four smallest trees at each site had an average ring width of 0.45 mm and 1.25 mm at the Valley and Alsea sites, respectively. Of these eight trees, only two trees from the Valley site had noticeably shorter tracheids.

At Alsea a quadratic relationship was significant between tracheid length and ring width. Tracheid length appeared to peak near 2 mm, declining slightly in narrower or wider growth rings. Similarly, maximum tracheid length was associated with a ring width of 1 mm in *Pinus strobus* (Bannan, 1967) and Douglas-fir (Bannan, 1964). An increase or decrease in ring width resulted in shorter tracheids.

Results from this study lead to the conclusion that growing trees at the wider spacings, 309 to 1,682 trees/hectare, would not significantly reduce wood density or tracheid length in the wood zones studied. In modern forest management, the large range in initial tree density (ITD) used in this study would rarely be observed because initial planting density and precommercial thinning normally prevent this extreme competition. Under operational conditions very little difference in wood density or tracheid length would be observed due to ITD as compared to inherent tree-to-tree variability (Zobel and van Buijtenen, 1989).

Initial plantation spacing is one of the most important decisions a forest manager can make. Wide initial spacing, combined with pruning appears to be the best choice for improving wood quality of Douglas-fir. Lower initial plantation densities reduce cost of stand establishment and eliminate precommercial thinning costs. The primary disadvantage of wider initial spacing is an increase in juvenile wood volume during formative years (Maguire et al., 1991). At this time, a higher premium is paid for large diameter logs because of an increase in volume recovery which more than offsets for a reduction in grade (Fight et al., 1995), making wide initial spacing an even more attractive option.

CHAPTER 4. WOOD DENSITY AND TRACHEID LENGTH VARIATION FOLLOWING PRUNING IN YOUNG DOUGLAS-FIR

Abstract

The effects of fixed height pruning on wood density and tracheid length were investigated in intensively-managed young-growth Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) at one site in central western Oregon. Trees were pruned to a fixed height at ages 13,16, and 18 years old in 1988 and then had ten years of subsequent growth. Fixed height pruning to 5.5 m at age 16 and 18 resulted in 15% and 10% crown reduction, respectively. There was no significant change in growth rate or wood density at breast height (1.37 m) or 5.27 m as a result of these light pruning treatments. In contrast, fixed height pruning to 5.5 m at age 13 resulted in a 50% live crown length reduction. There was a one year decrease in earlywood width and an increase in percent latewood and wood density at 1.37 m. At 5.27 m, there was a temporary increase in earlywood density, percent latewood, and mean ring density. Fixed height pruning to 3.4 m at age 13, followed by pruning to 5.5 m at age 15 resulted in no apparent change in growth rate or wood density. However, pruning at age 13 to 3.4 m and 5.5 m resulted in an increase in mean, earlywood, and latewood tracheid length of approximately 6% for a three year period. Pruning early in the rotation would benefit wood quality by shortening branch healing time, initiating clear wood formation sooner, and providing for a longer period of clear wood production. Pruning should be combined with wide initial spacing and a commercial thinning regime to promote clear wood formation.

Introduction

Pruning has been identified as a possible approach for improving wood quality attributes of second-growth Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) (O'Hara, 1991; Fight et al., 1995). In New Zealand, where Douglas-fir has been introduced, the wood quality of extremely fast-grown trees has been improved by intensive pruning treatments or careful spacing treatments (Reutebuch, 1995). Traditionally, pruning studies have concentrated on the growth and yield of trees following pruning treatments (O'Hara, 1991). However, research is lacking on changes in wood properties as a result of pruning (Maguire and Petruncio, 1995).

Review of Douglas-fir pruning studies in the Pacific Northwest indicates that pruning the lower one-third of the live crown will not impact diameter or height growth significantly (O'Hara, 1991). In addition, pruning has been shown to be economically feasible, especially when performed early in the rotation (Fight et al., 1995). Therefore, pruning offers a viable option for improving Douglas-fir wood quality. However, further research needs to be conducted on the effects of pruning on wood characteristics to determine the optimal combined pruning and stand density regime for a given situation.

The presence, location, angle, frequency, and size of branches are important wood quality considerations (Zobel and van Buijtenen, 1989), especially since Douglas-fir has persistent branches. Branches directly impact log grade (NLRAG, 1998) and lumber grade (WWPA, 1998). In natural young-growth stands, a minimum of 77 years is required for natural pruning of the basal

4.9 m log (Bransford and Munger, 1939; Kachin, 1939; Kotok, 1951; Paul, 1947). In addition, very little clear high grade veneer or lumber can be expected from intensively-managed (Fahey et al., 1991) or naturally regenerated young-growth stands (Ernst and Fahey, 1986) without artificial pruning. This is particularly crucial since the current trend is moving towards wider spacing, 469 trees/ha to 741 trees/ha (Oliver et al., 1986; Reukema and Smith, 1987; Scott et al., 1998; Newton and Cole, 1999), resulting in relatively large and persistent knots compared to dense natural stands.

It is often assumed that pruning will accelerate the transition from juvenile to mature wood, but few studies have investigated the effects of pruning on wood properties. Live branch pruning may cause an immediate increase in wood density and has been shown to decrease stem taper (O'Hara, 1991). However, some researchers argue that a permanent shift to mature wood does not occur simply because wood density changes after pruning. Briggs (1995) asserts that pruning can only be proven to cause a true transition to mature wood if "length, microfibril angle, chemistry, and other characteristics of tracheids suddenly shifted to mature wood norms".

The purpose of this study is to determine changes in anatomical properties of Douglas-fir that have been pruned to different fixed heights. The study is intended to mimic management that would occur in intensively managed plantations. A combination of fixed height pruning treatments and commercial thinning were implemented. The main objective is to compare radial variation in wood density and tracheid length in pruned versus unpruned Douglas-fir.

Changes in wood density and tracheid length are compared immediately before pruning and in the ten years following pruning. Specific questions are as follows:

1. Does ring density increase immediately after pruning at 1.37 m or 5.27 m?
2. If density increases immediately after pruning, is it a result of an increase in earlywood density, latewood density, percent latewood, or a combination of components?
3. Does mean tracheid length increase immediately after pruning at breast height?
4. If mean tracheid length increases immediately after pruning, is it a result of an increase in earlywood tracheid length, latewood tracheid length, percent latewood, or a combination of components?

Methods

Site description

The study site is located approximately 5 km south of Philomath, Oregon at 125 m, 44° 29' N, 123° 22' W. Mean annual precipitation is about 120 cm, with a mean annual temperature of 13°C and average frost free season of 165 to 200 days (Zedaker, 1981). Estimated site index at 50 years (SI_{50}) is 38 m.

The study location was most likely a *Quercus garryana* woodland prior to settlement in the mid- to late-1800's (Franklin and Dyrness, 1988). The property was farmed from the mid-1860's until the early 1960's when it was converted to Christmas tree plantations of Douglas-fir. At age 3, 750 trees/ha were identified as timber trees. Timber trees were allowed to grow to their current size at a density of 741 trees/ha. The stand is now a closed canopy *Pseudotsuga menziesii* forest in the stem exclusion stage (Oliver and Larson, 1996).

Experimental design and treatments

The study has a completely randomized design. There are three age classes of trees. In the fall of 1998 when the study was undertaken, the trees were 23, 26, and 28 years old and 19, 22, and 24 years old at breast height. These age classes are referenced as age classes 1, 2, and 3, respectively. There are nine 405 m^2 plots in age class 1 and six each in age classes 2 and 3. All plots started with an initial tree density of 741 trees/ha and were commercially thinned to 494 trees/ha, 20 years after planting for age classes 1 and 2, and 22 years after planting for age class 3. The commercial thinning removed small saw logs with a low thinning and removal of defective trees.

For each plot, 10 healthy dominant or codominant trees were selected in the winter of 1987-1988 for pruning. Plots were randomly assigned a pruning treatment at that time. There were three treatments in age class 1 and two treatments in age classes 2 and 3. In age class 1, three plots were pruned to 5.5 m, three plots were pruned to 3.4 m, and three plots were left untreated. The pruning treatments resulted in crown reductions of approximately 50% and 30% for the 5.5 m and 3.4 m treatments, respectively (Figure 4.1). In the fall of 1990, trees pruned to 3.4 m received a second lift to 5.5 m, resulting in 18% crown reduction (Figure 4.1). For age classes 2 and 3, three plots were pruned to 5.5 m and three plots were left untreated. These treatments resulted in approximately 15% and 10% crown reduction in age classes 2 and 3, respectively (Figure 4.1). The treatments were designated by age class and by treatment as follows: control, one-lift, and two-lift. All trees were pruned in the winter of 1988 prior to the 1989 growing season. Pruning was accomplished manually with a pole-type branch pruning saw.

For each age class, trees were stratified by diameter at breast height and divided into four size classes. From each plot, four trees were randomly selected for sampling. In addition, from each age class, three trees were randomly selected from each treatment and size class to ensure that the treatment and control groups were comparable and covered a range of diameters. This provided a total of 12 trees from each treatment group, creating of total of 36 trees in age class 1, 24 in age class 2, and 24 in age class 3.

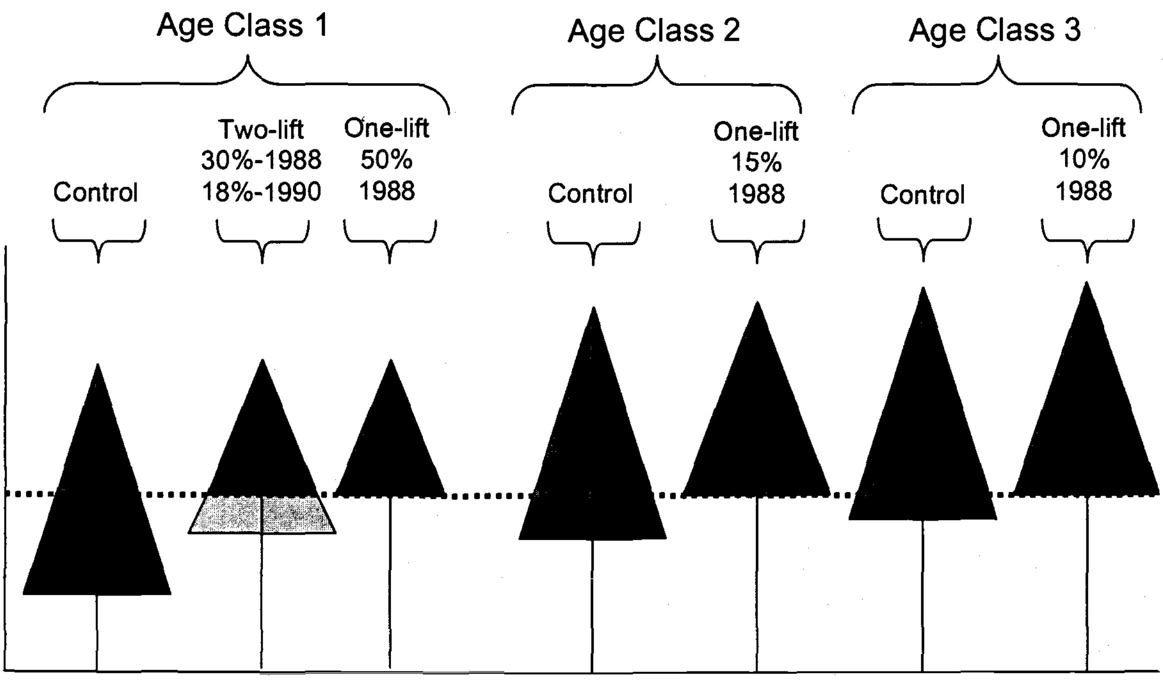


Figure 4.1. Percent crown removed by age class, treatment, and year of pruning (Dashed line represents 5.5 m).

Increment Core Collection

One 5-mm increment core was extracted, per tree at breast height (1.37 m) and at 5.27 m for wood density and growth ring analysis. The 5.27 m core corresponds to the top of the basal 16 ft log, allowing a 1 ft stump and 0.3 ft trim allowance. In addition, in age class 1, four randomly chosen trees from each pruning treatment were cored with an 8 mm increment core at breast height for tracheid length measurement.

Wood Density Data Collection

The 5-mm increment cores were air-dried and then cut to approximately 1.5-mm thick longitudinal dimension using a Hubert Pneumatic Instruments precision sample saw. The cut samples were treated to remove resin and extractives that may alter the attenuation of X-rays, so that accurate measurements from the direct reading X-ray densitometer were possible. Samples were treated by submerging them in a near boiling 2:1 mixture of 95% ethyl alcohol and toluene for eight hours. The ethyl alcohol and toluene mixture was changed every two hours. Cores were allowed to equilibrate to the moisture content of the X-ray room at approximately 12% moisture content.

The cores were scanned using a computerized, direct reading X-ray densitometer. Data were collected every 0.1 mm along the length of each increment core. The density values were imported into DendroScan 4.5 for ring width and ring density analysis and output (Varem-Sanders and Campbell, 1996). DendroScan 4.5 was used to calculate the boundaries between growth rings and between earlywood and latewood. The boundary between earlywood and latewood is where the density is equal to the average of the minimum earlywood and maximum latewood densities. "This result is a good analog of the biological earlywood/latewood boundary that is consistent for most rings (Varem-Sanders and Campbell, 1996)." All units of wood density are expressed as basic relative density using dry weight and green volume (Jozsa and Middleton, 1994). The following tree-ring variables were generated: ring width, earlywood width, latewood width, average ring density, earlywood density, and latewood density. Percent latewood was calculated by dividing latewood width by ring width.

Tracheid Length Data Collection

From each 8-mm increment core, every growth ring from 1986 to 1998 was divided into earlywood and latewood. Samples were macerated by heating at 85°C in a 10% solution of 1:1 nitric acid and hydrogen peroxide in water. Samples were rinsed and then stained with aqueous safranin. The macerated fibers were mounted on slides with glycerin as the mounting medium. Three separate random selections from each sample were mounted on three separate slides. Fifty unbroken earlywood and latewood tracheids per ring were measured using an image-analysis system. The images of the slides were captured through a CCD video camera attached to a stereo-microscope. Tracheid length was captured and analyzed using the public-domain software program NIH *Image*, version 1.9 for Macintosh (Rasband, 1992). Calculating the average of 50 earlywood tracheids gave 95% confidence interval widths between 0.05 mm and 0.16 mm. Calculating the average of 50 latewood tracheids 95% confidence interval widths between 0.04 mm and 0.11 mm. Mean tracheid length was calculated by applying a weighted average of earlywood and latewood.

Data Analysis

There were several assumption made prior to analysis. Because individual trees and not plots were pruned, individual trees were treated as randomly chosen experimental units. It was assumed that changes due to climate would affect all the treatment groups alike. Therefore, there would not be a treatment and climate interaction.

The response variables were graphically analyzed in order to determine whether any treatment differences could be detected. Variables with visual treatment differences were further investigated using treatment means and confidence intervals. Statistically important differences were evaluated with analysis of variance or t-tests where appropriate.

Results

Relative density at breast height

Age class 1 shows changes over the observed period regardless of treatment but there was little difference between treatment groups (Figure 4.2). In 1989, relative density increased significantly in all treatments following pruning, even in the unpruned control group. From 1988 to 1989, earlywood width decreased causing an increase in percent latewood and ring density in all treatments. Earlywood width decreased by 41% for control, 140% for one-lift, and 37% for two-lift (Figure 4.3). The dramatic decline in earlywood width for the

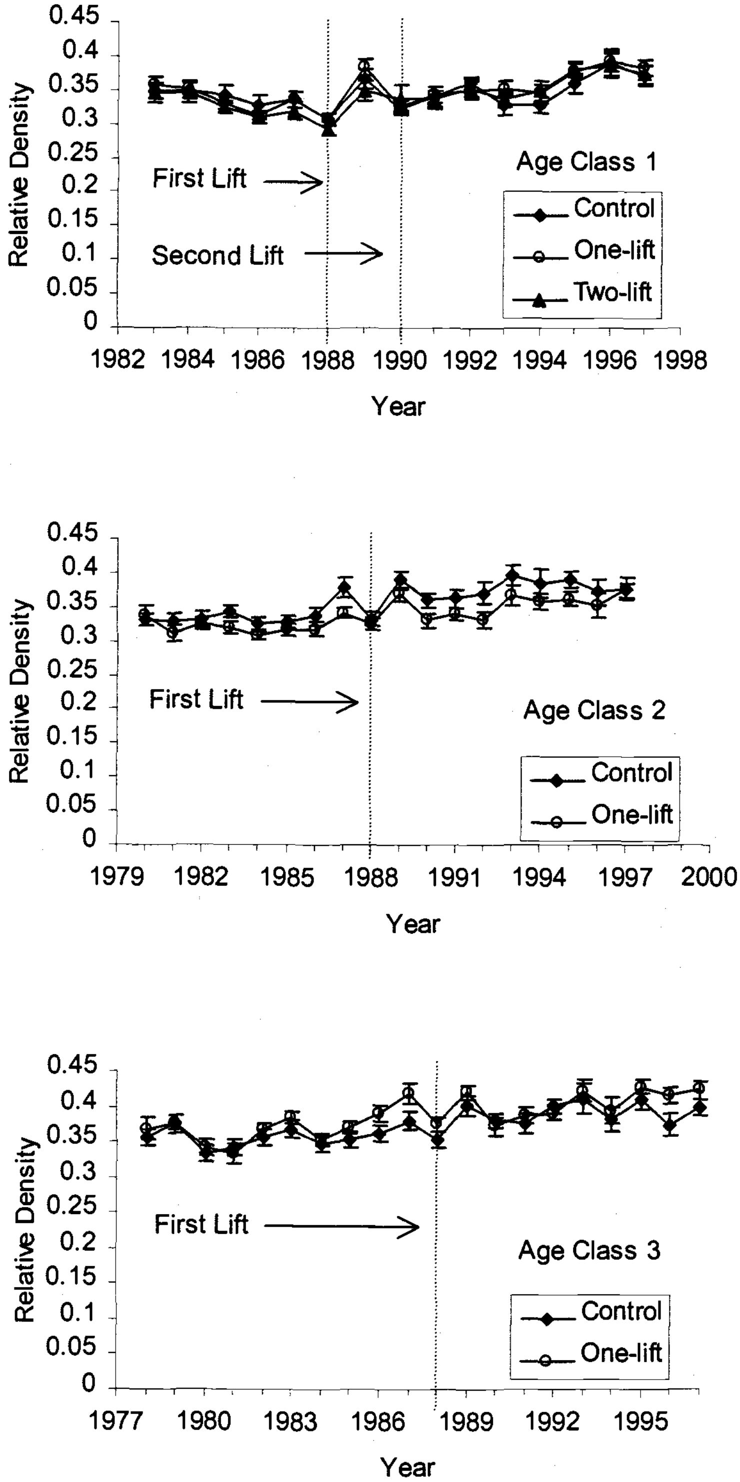


Figure 4.2. Mean relative density and standard errors calculated for each age class and pruning treatment at 1.37 m.

one-lift treatment lasted one year. By 1990, there was little difference between treatment groups. Mean relative density for the one-lift treatment was 0.0168 higher than control in 1989. Relative density increased by 20.0% for control, 25.0% for one-lift, and 19.2% for two-lift for the one year. Despite the larger increase in relative density for the one-lift treatment, there was no statistical difference between it and the control treatment (One-sided p-value = 0.1992, t-test).

In age class 2, there were also strong yearly changes in relative density (Figure 4.2). It was apparent that the control group has higher relative density before and after pruning. In 1989, relative density increased significantly in both treatments following pruning.

In age class 3, there were strong yearly changes due to climate (Figure 4.2). The pruned group had higher relative density prior to 1990 and after 1993. However, between 1990 and 1993 there was relatively little difference between groups. Relative density for both treatments increased from 1988 to 1989.

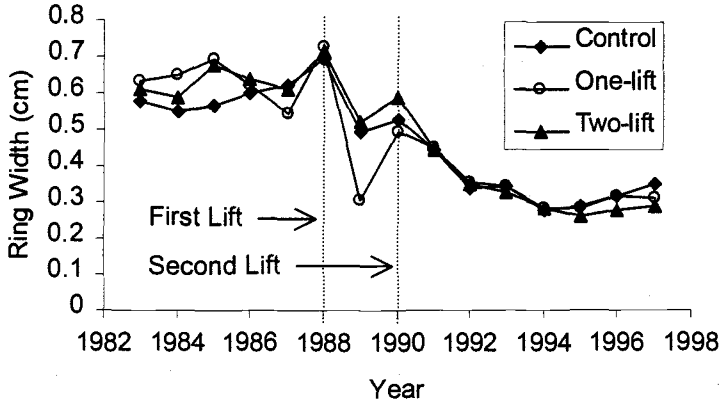


Figure 4.3. Mean earlywood width at 1.37 m in age class 1 by treatment.

Relative density at 5.27 meters

Relative density at 5.27 m follows the same general pattern that was found at breast height (Figure 4.4). There were strong yearly changes in relative density, which were similar regardless of age class. Relative density increased from 1988 to 1989 regardless of age class or treatment.

In age class 1, there were treatment differences immediately following pruning in 1989 (Figure 4.4). In 1988 there was no difference in relative density between treatments (P-value = 0.5029). However, in 1989 relative density in the one-lift treatment was greater than control (One-sided p-value = 0.0044, t-test). From 1988 to 1989 relative density increased by 9.0% for control, 17.7% for one-lift, and 6.3% for two-lift. The increase in the one-lift treatment was due to a larger increase in percent latewood and a slight increase in earlywood density.

In age class 2, there was strong annual variation in relative density (Figure 4.4). However, there were no apparent differences due to pruning. The only exception is in 1995 when the one-lift treatment increased in relative density over treatment 1. However, it is unlikely that this was related to the pruning treatment from 1988.

In age class 3, there was also strong year-to-year variation in relative density (Figure 4.4). As with age class 2, the pruning treatment was not severe enough to increase relative density at 5.27 m. Relative density is nearly equal from year to year. Beginning in 1993 relative density in the one-lift treatment appears to be slightly higher than control. It is unlikely that this is related to the pruning treatment from 1988.

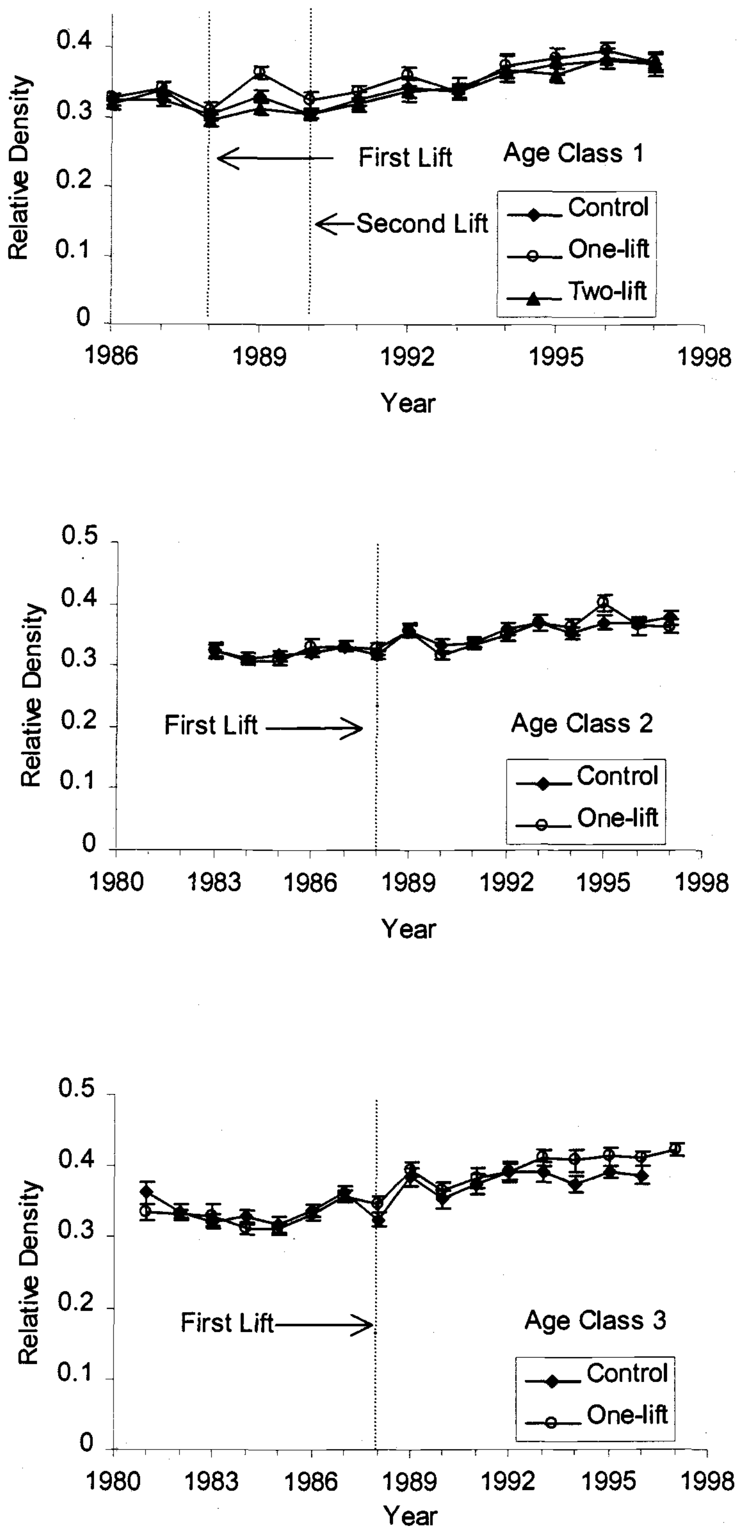


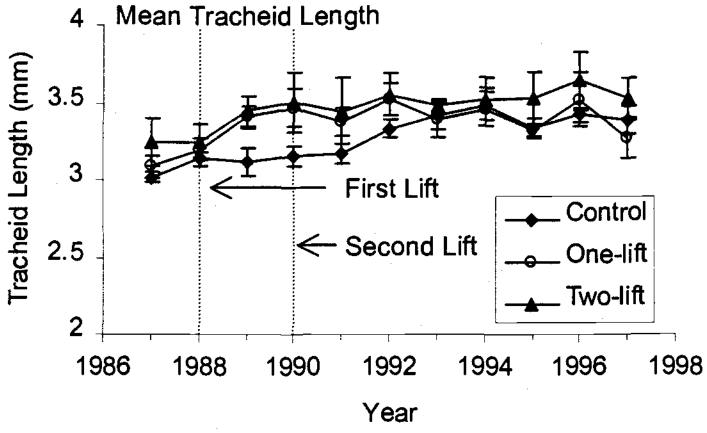
Figure 4.4. Mean relative density and standard errors calculated by age class and pruning treatment at 5.27 m.

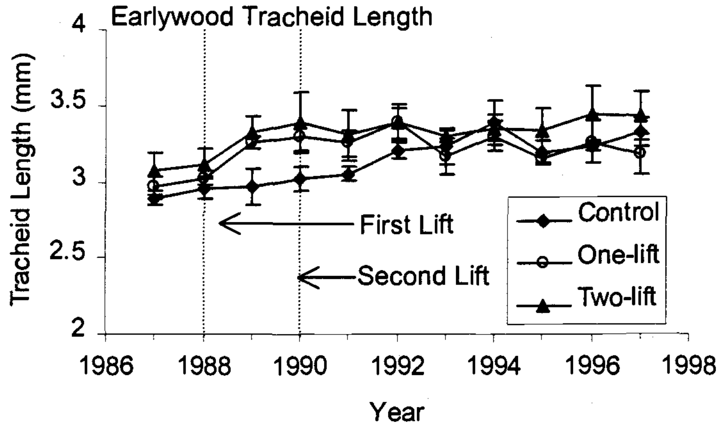
Tracheid length variation for age class 1 at breast height

For the control group, mean tracheid length ranged from approximately 3.0 mm to 3.4 mm between 1987 and 1997, the 8th and 18th growth ring from the pith. These values are similar to results published for approximately the same range in age (Erickson and Harrison, 1974; Megraw, 1986a). Mean tracheid length increased in the pruned treatments over control following pruning (Figure 4.5). From 1988 to 1989, mean tracheid length remained unchanged in control, increased by 6.6% in the one-lift treatment, and increased by 6.3% in the two-lift treatment. By 1992 there is relatively little difference between treatments, which had the same crown length then.

The temporary increase in mean tracheid length resulted from an increase in both earlywood and latewood tracheid length (Figure 4.5). For the control group, earlywood tracheid length ranged from approximately 2.8 mm to 3.3 mm between 1987 and 1997, the 8th and 18th growth ring from the pith. In 1989, earlywood tracheid length increased by 7.7% for the one-lift treatment and 6.6% for the two-lift treatment. By 1992 there was relatively little difference between treatments.

As with earlywood tracheid length, there is an increase in latewood tracheid length following pruning (Figure 4.5). For the control group, latewood tracheid length ranged from approximately 3.3 mm to 3.7 mm between 1987 and 1997, the 8th and 18th growth ring from the pith. Latewood tracheid length increased by 6.9% for the one-lift treatment and 6.3% for the two-lift treatment in 1989. At the same time control only increased by 1% from 1988 to 1989.





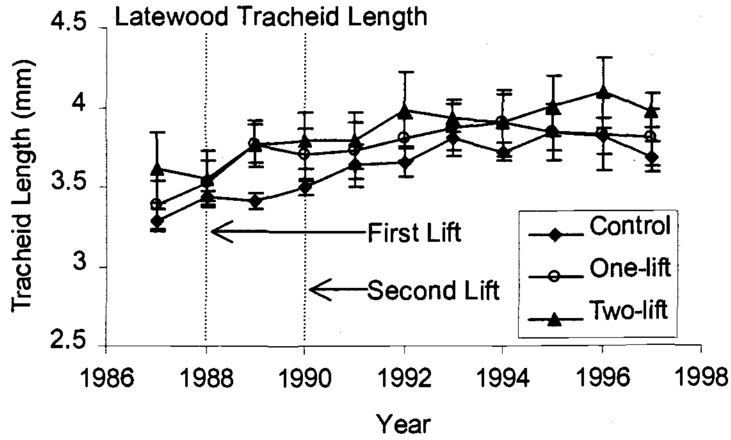


Figure 4.5. Mean tracheid length, earlywood tracheid length, and latewood tracheid length at 1.37 m for age class 1, showing mean and standard error by treatment (n=4).

Discussion

There is significant annual variation in wood density due to changes in the climate (Fritts, 1976; Robertson et al., 1990). Trends due to climate were observed uniformly across pruning treatments and commercial thinnings. Between 1988 and 1989, relative density increased significantly. This relationship was observed in all age classes, treatments, and sampling heights. The main reason for this increase was an increase in percent latewood. Percent latewood increased primarily when a dry spring led to a decrease in earlywood width. January through June precipitation in 1987 was 67% of normal in Corvallis, Oregon (NOAA, 1989). Earlywood growth is dependent on current photosynthate production (Kozlowski, 1992). Variation in ring width of Douglas-fir has been reported to be correlated with autumn and spring precipitation (Fritts, 1976). Water deficit in the spring could have reduced both cambial growth rate and the availability of photosynthate for earlywood production.

There was not sufficient evidence to conclude that pruning changed relative density at breast height in this study, even with 50% live crown reduction in age class 1. In age class 1, the trees were pruned when they were 9 years old at breast height. At his point the live crown base was below 1.37 m. Pruning to 5.5 m did not cause an immediate transition to mature wood, based on relative density. Percent latewood at breast height was very sensitive to annual variation. If 1989 had been an average year, the effects of pruning in the one-lift treatment may have been more pronounced. Regardless of annual variation, any increase in relative density was only temporary and did not lead to an earlier transition to mature wood characteristics.

Mean ring density increased at 5.27 m for age class 1 for the one-lift treatment. Mean ring density increased because of an increase in percent latewood and slight increase in earlywood density. However, the increase in ring density was only temporary, lasting one year. Therefore, there was no indication that the one-lift treatment resulted in an earlier transition to mature wood at either point in the tree. The pruning intensity for the two-lift treatment , age class 1, was not severe enough to produce a response at 5.27 m. In addition, the pruning treatments in age classes 2 and 3, of 15% and 10%, respectively, were not severe enough to increase ring density at 5.27 m.

Few studies focus on changes in wood density following pruning in Douglas-fir. Jozsa and Sawadsky (1990) reported a 21% increase in relative density at breast height for three years following a 40% live crown pruning of 8 year old Douglas-fir. Ring width decreased by 13% for two years following treatment. They concluded that ring density increased because of a combined increase in percent latewood and earlywood density. However, the 11 pruned trees were compared to only one control tree. Di Lucca (1989) reported the results from a 30% live crown pruning of two Douglas-fir in British Columbia. The trees, 45 and 51 years old, showed an increase in relative density at breast height and 10% height (approximately 3 m) following pruning at 15 and 21 years old. Polge et al. (1973) reported an increase in minimum and maximum wood density at breast height following a 50% live crown pruning of 13 year old Douglas-fir in France.

Results of the current study suggest that pruning intensity greater than one-third live crown removal is necessary in order to temporarily increase relative density. Pruning more than one-third of the live crown can reduce diameter growth and, to a lesser extent, height growth (O'Hara, 1991). The primary result is a decrease in earlywood width and increase in percent latewood in the lower stem (Marts, 1951;Cown, 1973; Jozsa and Sawadsky, 1990). Decreased earlywood width and increased percent latewood occurred at breast height and 5.27 m. A temporary increase in earlywood density was found at 5.27 m in this study. However, earlywood density did not increase at breast height.

Tracheid length increased briefly following pruning in age class 1. No research has investigated tracheid length variation following pruning in Douglas-fir. For *Pinus radiata*, Cown (1973) found no significant difference in tracheid length between pruned and control trees at breast height or 6.5 m. The trees had been severely pruned by removing approximately 76% of the live crown at age 6. In contrast, Gerischer and de Villiers (1963) found that heavy pruning caused an increase in tracheid length for approximately 3 years in *Pinus radiata*. Trees were pruned at age 9 to over 8 m, leaving only one-third of the live crown.

There are several important conclusions from this study. First, there did not appear to be an earlier transition to mature wood due to pruning. Relative density, even in the most severe treatment, only resulted in a temporary increase in percent latewood. Tracheid length increased for up to three years following pruning. However, within a short period, relative density and tracheid length were not appreciably different from those of unpruned trees.

For log grade and value recovery, the important results of pruning are the relationship between log diameter at harvest and the diameter of the defect core (Briggs, 1995). Therefore, pruning early in the rotation would benefit wood quality by shortening branch healing time, initiating clear wood formation sooner, and providing for a longer period of clear wood production. As suggested by Gerischer and de Villiers (1963), repeated pruning could have the effect of improving the properties of juvenile wood while reducing the size of the juvenile core. However, reduced growth rate from heavy pruning would reduce volume recovery and reduce the rate of branch stub occlusion (Petruncio et al., 1996). Therefore, pruning greater than 33% of the lower live crown is not recommended. Commercial thinning at the time of pruning is recommended to remove defective trees, recover the cost of pruning, and ensure rapid diameter growth.

Considering a 60-year rotation for Douglas-fir, the influence of a temporary change in wood properties is not crucial. There was more variation in wood properties due to annual variation than from the pruning treatments. The formation of clear wood on the bole of pruned trees will improve the quality of forest products by reducing weakness associated with knots and distorted grain. This improvement is much more important than an increase in wood density or tracheid length, especially considering a rotation length of 60 years or more.

CHAPTER 5. CONCLUSIONS REGARDING DOUGLAS-FIR WOOD QUALITY IN THE PACIFIC NORTHWEST

The wood quality of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) is a value judgement based on characteristics desired in the end product. Douglas-fir wood quality is dependent on many factors including genetics, site characteristics, silviculture, and rotation age. Wood quality is judged through log grading, wood processing, product performance and market acceptance. Therefore, actual and perceived Douglas-fir wood quality may change with time depending on these important variables.

The management of Douglas-fir forests represents a compromise between offsetting variables such as investment in intensive forest management practices, economic return, and noncommodity values such as biodiversity. Investment in activities that improve wood quality, such as pruning, have been overshadowed by efforts to increase volume growth. This emphasis has remained because of inadequate knowledge and awareness about opportunities to control wood quality through silviculture. In addition, the forest products industry has anticipated that technological improvements, such as advanced composite materials, will compensate or overcome wood quality problems. However, with increased regulation of timber harvesting and reservation of public timberlands, wood quality research and investment may be a viable strategy to improve future timber resources (Briggs and Smith, 1986; Oliver et al., 1986). This thesis provided research on the wood quality of Douglas-fir depending on such variables as initial tree density, rectangularity, and pruning intensity. Forest managers can manipulate initial stand density and pruning treatments in order to provide for a variety of different log characteristics.

Initial stand density was found to significantly affect mean and maximum branch size and the number of branches/m in the basal 5 m log. Although not quantified in this study, initial stand density has a tremendous impact on individual tree diameter and volume (Curtis and Reukema, 1970; Reukema and Smith, 1987; Smith, 1980). Log quality is primarily influenced by log size, growth rate (rings/in.), and branch size (NLRAG, 1998), all of which impact lumber grade and recovery (WWPA, 1998). All three of these factors are easily regulated through initial density, precommercial thinning, and commercial thinning. For structural lumber grades, there is an interaction among knot size, knot position, and lumber width. Wider boards have larger allowable knot sizes within a lumber grade. In this study, the largest branch measured was 47 mm outside bark, where initial tree density ranged from 309 trees/ha to 18,730 trees/ha. Although no conversion was made between branch diameter and knot diameter, it can be assumed that knot size would not exceed 63 mm. This would provide for at least No. 2 Sawmill logs, with pruning necessary for better recovery of clear wood (NLRAG, 1998). However, wide spacing will result in additional large and persistent knots and prevent the formation of clear wood long after branches die. There is also evidence that wide spacing combined with intensive management may exacerbate swelling at branch nodes, the number of double whorls, and stem sinuosity (Carter et al., 1986). This prediction is particularly crucial since the current trend is moving towards wider spacing, 469 trees/ha to 741 trees/ha

(Oliver et al., 1986; Reukema and Smith, 1987; Scott et al., 1998; Newton and Cole, 1999). Rectangularity had very little, if any effect on branch size. Therefore, management for wood quality should emphasize stand density over spacing geometry where rectangularity is 1:2 or less severe.

Within operational planting densities, 469 trees/ha (4.6 m x 4.6 m) to 1682 trees/ha (2.4 m x 2.4 m), it took between 13 and 17 years, and averaged 14.7 years, until one-third or less of the live crown was below 5.27 m. Once a branch falls into the lower one-third of the live crown, approximately 88% of its cumulative radial growth has been completed. Within another two years radial growth will cease on these branches, followed within approximately a year by the end of terminal elongation. The maximum percent of life spent without ring production (%NORING) did not vary with initial tree density. Maximum %NORING averaged 22.5% at the Alsea site and 30% at the Valley site. In this study several variables were able to categorize over 70% of missing-ring branches correctly. In general, missing-ring branches were found in the lower one-third of the live crown, had small terminal buds, and short terminal shoots; it is unlikely that they export an appreciable amount of carbohydrate for bolewood growth. The cumulative evidence suggests that pruning the lower one-third of the live crown appears to be a reasonable compromise between wood quality and volume growth loss. Any minor decrease in growth would be compensated for by higher value logs.

There was not sufficient evidence to conclude that initial stand density influenced wood density or tracheid length at breast height, while holding age constant. Individual tree and crown variables did provide better prediction of wood density or tracheid length. There was evidence that wood density increased with increasing initial tree density at 5.27 m, although a majority of variation was left unexplained. These findings support the literature that concludes for a given age and site, ring width, or growth rate, has no significant effect on wood density (Smith, 1956; Kennedy, 1961; McKimmy, 1966; Megraw, 1986a ; Jozsa et al., 1989). Although initial spacing directly influences crown structure (Curtis and Reukema, 1970; Eversole, 1955; Reukema and Smith, 1987), young trees are "sufficiently vigorous and healthy regardless of spacing", with little difference in wood properties until later in life (Briggs and Smith, 1986). Despite these findings, information is still lacking on the effect of initial spacing on the transition from juvenile to mature wood. In this study there was no evidence in the outer-wood zone that trees with more advanced crown recession had higher density wood or longer tracheid length. As the trees age, differences may become more pronounced.

The influence of initial tree density on branch number, size, and persistence needs to be balanced with volume production. The current management trend is towards wider initial spacing (Oliver et al., 1986; Reukema and Smith, 1987; Scott et al., 1998; Newton and Cole, 1999). Wide initial spacing decreases planting cost and eliminates precommercial thinning cost, while providing for rapid early growth. However, as observed in this study, wide spacing also guarantees additional large and persistent knots and a higher juvenile wood volume (Maguire et al., 1991). This suggests that wide spacing is most appropriate if rotations are relatively long, providing both large sized trees and high quality (Newton and Cole, 1987). Precommercial thinning, once crown recession has advanced beyond 5 m, would provide for logs with smaller knots and less taper than trees grown at wide initial spacing (Oliver et al., 1986). However, precommercially thinned stands take longer to reach a certain diameter compared to trees at an initially wide spacing. If widely spaced trees are pruned, rapid diameter growth will provide for faster branch stub occlusion (Petruncio et al., 1996) and higher clear wood volume. Oliver et al. (1986) estimated that 185 trees/ha could be pruned when stands are at an initial spacing of 3.7 m x 3.7 m at a lower cost than precommercial thinning trees from 2.4 m x 2.4 m to the wider spacing. The precommercially thinned trees would take longer to reach a given size and would not produce clear wood. In addition, the widely spaced trees would reach merchantable size sooner, providing an earlier return on the investment.

Wide initial spacing, combined with pruning appears to be the best choice for improving wood quality of Douglas-fir. Pruning is cost effective when applied early in the rotation and combined with wide spacing (Fight et al., 1995). Narrow spacing cannot adequately control branch diameter to grow clear wood on shorter rotations without pruning. There was no evidence that wide initial spacing reduced wood density or tracheid length. In addition, there was no evidence that pruning the lower 33% of the live crown significantly reduced diameter growth. Therefore, the combination of wide initial spacing and pruning appears to have many advantages. The primary disadvantage of this management approach is an increase in juvenile wood volume. Considering a rotation length of 60 years, an increase in juvenile wood volume would not be important if pruning occurred early in the rotation. In addition, maintaining good diameter growth would ensure a larger volume of clear mature wood over the juvenile core. Continued thinning and extended rotation lengths could provide logs with old-growth characteristics (Newton and Cole, 1987).

There are many competing factors that influence Douglas-fir wood quality. Future forest practice regulation may limit silvicultural options that are currently available to forest managers. Practices such as pruning have not been extensively utilized because of doubt in future markets and resource needs. The Pacific Northwest will become more reliant on young-growth Douglas-fir as the available timber supply declines because of increased reservation of public forest lands and environmental restrictions (Briggs, 1997). Increased demand for wood products, combined with a decreasing supply of fiber from a dwindling timberland base, will increase the need for efficient management of forests for high quality timber products.

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