EFFECTS OF EARLY PRUNING ON RING SPECIFIC GRAVITY IN YOUNG LOBLOLLY PINE TREES

*Harold E. Burkhart**

University Distinguished Professor of Forestry
E-mail: burkhart@vt.edu

Ralph L. Amateis

Senior Research Associate
Department of Forest Resources and Environmental Conservation
Virginia Polytechnic Institute and State University
310 West Campus Drive
Blacksburg, VA 24061
E-mail: ralph@vt.edu

(Received June 2019)

Abstract. Juvenile wood is not well suited for use in many forest products. Understanding factors that affect the formation of juvenile and mature wood is important when managing commercially important conifer species. The purpose of this investigation was to determine the contribution of ring age, relative height in the stem, and crown position (within or not within the green crown) on ring specific gravity of loblolly pine trees pruned at young ages. A designed experiment consisting of five treatments, control; prune at age 3 yr, age 6 yr, or age 9 yr; and at ages 3, 6, and 9 yr, was established at two locations in the Piedmont region of Virginia. Wood samples were acquired at three heights along the stem 15 yr after planting. Results showed that differences in ring specific gravity of the treated plots (half of green crown removed at each scheduled pruning) were significantly higher than that of the control plots. All variables of ring age, relative height, and ring position of within or not within the green crown, were statistically significant. The results suggest that cambial age, maturation, and proximity to green crown are important for controlling whole-ring specific gravity in loblolly pine trees.

Keywords: Pruning, wood density, juvenile wood, mature wood, *Pinus taeda*.

INTRODUCTION

Variation in wood properties within the stem has major implications for processing and using wood for specific products. Patterns of variation differ among species, sites, genotypes, and for specified wood characteristics. Variation within the stem occurs from the pith to bark and at heights along the stem for a given ring number. In hard pines, within-tree variation in wood properties is often very pronounced, with pith-to-bark trends being particularly marked (Megraw 1985; Zobel and Sprague 1998; Larson et al 2001). The consistent radial variation within the stem can be related to cambial age. However, variation in wood properties along the stem for a given ring age, although generally less prominent than the pith-to-bark variation, is also important. Wood of a given ring age near the base of southern pine trees is denser than that of young trees. This pattern of density variation in the vertical direction is generally attributed to the botanical concept of maturation in woody plants. However, as noted by numerous authors (eg Zobel and Sprague 1998; Greenwood 1995; Burdon et al 2004; Dahlen et al 2018), the processes involved in this increase in density in conifers have not been elucidated. The most commonly included variables for estimating ring specific gravity are tree ring age and height along the tree bole (eg Tasissa and Burkhart 1998a; Auty et al 2014; Dahlen et al 2018).

Wood specific gravity is affected by a host of factors, including climate properties, genetic variability, and silvicultural practices such as thinning, pruning, and applying fertilizer. All of

* Corresponding author

Wood and Fiber Science, 52(2), 2020, pp. 139-151
https://doi.org/10.22382/wfs-2020-013

these factors influence height growth and crown development, which in turn affect wood properties. The transition phase between formation of juvenile and mature wood has been reported to be related to site characteristics (Gorman et al 2018), genetic control (Hayatgheibi et al 2018), initial planting density (Larocque and Marshall 1995), fertilizer applications (Mörling 2002; Antony et al 2009), thinning (Schneider et al 2008), crown size (Amarasekara and Denne 2002; Mansfield et al 2007), culmination of height increment (Kučera 1994), and other variables. Multiple interacting factors preclude establishment of cause and effect, but the relative influence of variables such as ring age, height along the tree stem, and proximity to the green crown can be evaluated with appropriate data from field trials.

Juvenile Wood

Juvenile wood is formed in the central core of the stem (Fig 1). This stem portion is also commonly referred to as corewood or crown-formed wood. The zone of juvenile wood extends outward from the pith; wood characteristics change rapidly in successively older growth rings and then eventually level off. Differences in properties of juvenile and mature wood tend to be pronounced in conifers. A radial cross-section of mature loblolly pine typically contains three zones: a core or zone of crown-formed wood, a zone of transition wood, and a zone of mature wood.

The task of establishing the boundary between juvenile and mature wood is complicated because the transition is gradual, not abrupt, and the inherent variability is large. Because of the lack of a clearly defined border between juvenile and mature wood, visual inspection of data plots has sometimes been used (eg Bendtsen and Senft 1986; Clark and Saucier 1989). Several investigators, however, have successfully applied statistical modeling for estimating the demarcation between the juvenile and mature zones (Abdel-Gadir and Krahmer 1993; Tasissa and Burkhart 1998b; Sauter et al 1999; Mutz et al 2004; Koubaa et al 2005; Clark et al 2006; Mora et al 2007). The most commonly used variable for analyzing the transition is specific gravity, but other wood characteristics, such as ring average microfibril angle (Clark et al 2006; Jordan et al 2007), have also been used. Comprehensive compilations of published works on the importance and characteristics of juvenile wood have been published by Megraw (1985), Zobel and van Buijtenen (1989), Zobel and Sprague (1998), and Larson et al (2001).

Specific Gravity

Specific gravity is the most widely used criterion for evaluating the quality of wood and its strength properties. Although specific gravity has great utility as a predictor of the quality and strength properties of wood, it is highly variable by species, within and among trees of a given species, environmental factors, and silvicultural treatments. Initial efforts were aimed at estimating

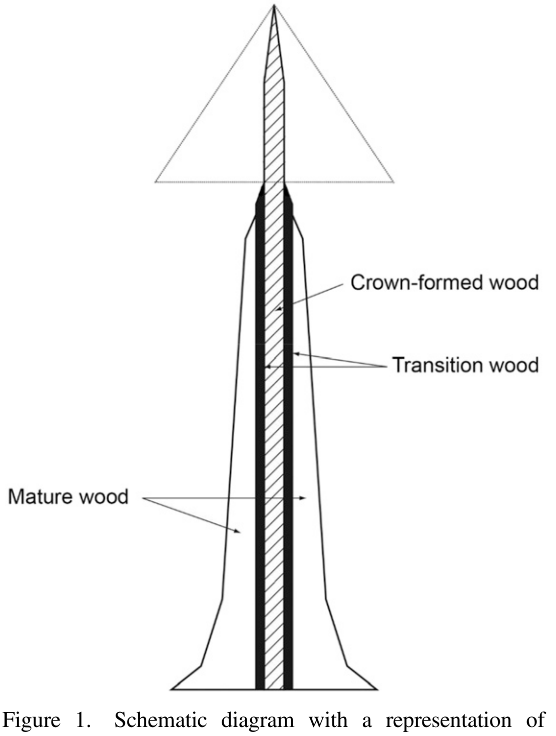

Figure 1. Schematic diagram with a representation of crown-formed, transition, and mature wood in relation to crown base in a loblolly pine tree (adapted from Clark and Saucier 1991).

average tree specific gravity from easily measured variables, such as tree age. With the advent of X-ray densitometry techniques (Cown and Clement 1983; Jacquin et al 2017), determination of ring densities for large samples became commonplace.

Specific gravity is defined as the ratio of the weight of wood to the weight of an equal volume of water at a standard temperature; it is dimensionless and in this article is expressed on an oven-dry weight and green volume basis (sometimes referred to as "basic specific gravity").

Objective

The overall aim of this field trial was to gain insight into the relative importance of ring cambial age (number of rings from pith), maturation (relative height in the stem), and whether the ring was formed within the green crown on whole-ring specific gravity of young loblolly pine trees. Cambial age and maturation have consistently been shown to be related to ring specific gravity in hard pines. Although these variables cannot be experimentally manipulated, height to the base of the green crown can be controlled by pruning, allowing for assessment of influence of proximity to the green crown on ring specific gravity.

The objective of this study was to determine the relative importance of ring cambial age, expressed by number of rings beyond the pith, maturation, represented by the height along the stem, and crown position (whether formed within or not within the green crown) on whole-ring specific gravity of loblolly pine trees pruned with a single lift or with multiple lifts at tree ages 3, 6, and 9 yr.

MATERIALS AND METHODS

Establishment of Early Pruning Field Trials

Field trials were established in harvested areas at two locations in the Piedmont region of Virginia. The two locations in this study are in the same physiographic region at the Appomattox Buckingham (AB) State Forest (latitude 37.418 N, longitude 78.669 W, elevation 213 m) and at the Reynolds Homestead (RH) Forest Resources Research Center (RH) (latitude 36.643 N, longitude 80.146 W, elevation 340 m). Differences in juvenile to mature transition and in wood specific gravity can result from varied genetic, environmental, and management factors. These sources of variability were mitigated to the extent possible when this pruning trial was installed. Both locations were planted with a common genetic family of 1-0 open-pollinated seedlings at the same initial planting density.

Each location consisted of four replicates with five treatments: 1) control (no pruning), 2) removal of half of the live crown length on all trees at age 3 yr, 3) removal of half of the live crown length on all trees at age 6 yr, 4) removal of half of the live crown length on all trees at age 9 yr, and 5) removal of half of the tree live crown length at ages 3, 6, and 9 yr. Age is defined as number of years since planting. Early treatments consisted of herbaceous and woody vegetation control through the first 2 yr following planting and one fertilizer treatment of 225 $kg \cdot ha^{-1}$ of elemental nitrogen and 22 $kg \cdot ha^{-1}$ of phosphorous applied at age 2 yr on all plots; no additional silvicultural treatments were applied following the initial planting stage. The treatments were randomly assigned to square treatment plots of six rows with six trees per row planted at a spacing of 3×3 m. The interior 16 trees were measurement trees. Pruning treatments were applied during the dormant seasons between the third and fourth, the sixth and seventh, and the ninth and tenth growing seasons. All pruning treatments occurred before crown closure; live and dead branches removed were cut flush with the stem and left on the plots. The study was measured annually from age 3 yr during the dormant season. Data collected on each tree consisted of diameter at breast height (dbh), total tree height, and height to live crown. Additional details about the trial establishment, tree measurements, and impact of timing and intensity of pruning on subsequent tree growth can be found in Amateis and Burkhart (2011).

Selection and Processing of Sample Trees

With four blocks, five treatments, and 16 trees per treatment, each location consisted of 320 measured trees. Before tree felling, dbh, total height, and height to the base of the live crown were measured on each tree designated and marked for wood sampling.

The felled-tree sampling, implemented after 15 growing seasons, involved felling four undamaged trees in each treatment plot. Thus, $4 \times 5 \times 2$ or 80 trees were felled at each of the two locations. For logistical purposes, one row from each plot was randomly selected for removal. Only well-formed, undamaged trees were felled for wood sampling to avoid problems with compression wood in the stem, partial removal of part of the live crown because of wind, snow or ice damage, and other damages that would modify wood properties. When a mortality spot or a tree that did not qualify for felling was encountered, a qualifying tree in an adjacent row was selected; if there were two qualifying trees, one on each side, the tree selected for felling was determined randomly. Summary data on means and standard deviations of sample tree dbh and total heights for the five treatments at each location are provided in Table 1.

Felled trees were removed from the plots and laid out at landings adjacent to or near to the pruning trial. For each felled tree, three disks were cut near the midpoint of the height internode of years 2, 5, and 8, ie cuts were made as close as possible to the midpoint between the tip of the terminal leaders at ages 1 and 2 yr (disk 1), 4 and 5 yr (disk 2), and 7 and 8 yr (disk 3). The location for disk removal was adjusted slightly upward or downward to avoid branches from intermediate flushes of height growth within the year (loblolly pine typically has 2-5 height flushes each year; Trincado and Burkhart 2009). Figure 2 illustrates the general position of the three sample disks; mean heights and standard deviations of the three sample disks by location and treatment are given in Table 2. All disks were labeled as to location, block, treatment, tree, and sample disk number and placed in cold storage before drying and specimen preparation for X-ray densitometry.

Determining Ring Density

Sample disks were placed into a conditioning chamber until the MC stabilized at 12%. A standard table saw was used to cut one specimen from each disk. Two blades were mounted on the saw mandrel separated by a spacer in such a way that specimens of approximately 1.7 mm thick and 2 cm wide could be cut spanning edge to edge through the center of the disk. Thus, each growth ring was represented by two observations, one on either side of the pith. After removal from the disk, each specimen was labeled with a six-digit number identifying the location, replication, plot, tree, and disk from which it came. It was then placed in a paper envelope and stored in the conditioning chamber until the time of scanning.

Table 1. Means and standard deviations of tree diameter at breast height (cm) and total height (m) by treatments (1-5) at each of the two study locations (1-2).

Location[a]	Treatment[a]	Mean dbh	Standard deviation of dbh	Mean Height	Standard deviation of Height
1	1	21.91	4.647	15.33	1.644
1	2	20.94	2.291	15.31	0.856
1	3	20.21	2.253	15.17	0.711
1	4	21.51	3.536	15.02	1.080
1	5	19.30	2.718	14.83	0.782
2	1	22.76	3.709	16.77	1.069
2	2	23.65	3.180	17.45	1.419
2	3	21.99	3.001	17.21	1.018
2	4	23.07	1.876	16.66	0.788
2	5	21.72	2.688	16.29	1.384

[a] Location 1, Appomattox Buckingham; 2, RH; Treatment 1, control; 2, pruning at age 3 yr; 3, pruning at age 6 yr; 4, pruning at age 9 yr; 5, pruning at ages 3, 6, and 9 yr.

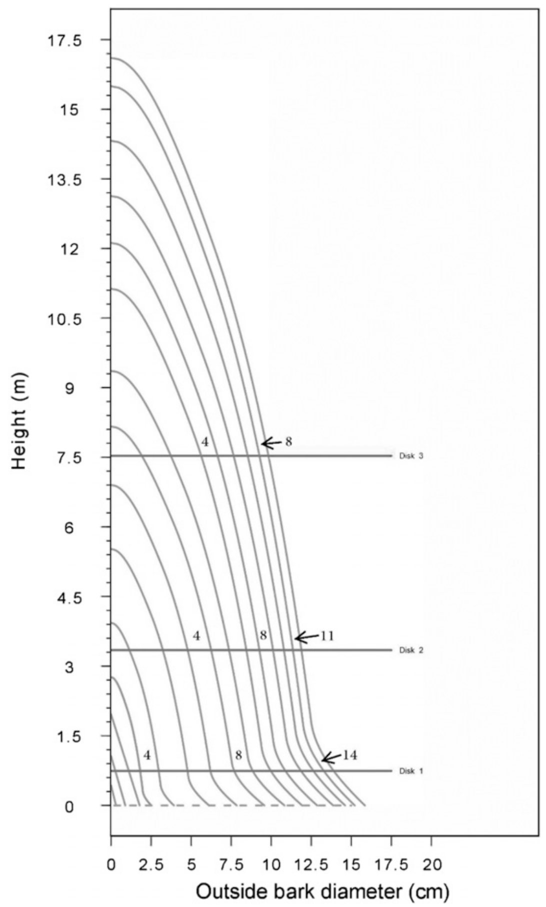

Figure 2. General position of three sample disks and identification of selected ring ages in the three disks of a representative tree age 15 yr, diameter at breast height 26.6 cm, and total height 16.4 m. Years 1-3 depicted by cones; ring profiles for ages 4-15 yr generated by the taper function of Max and Burkhart (1976) using measured values of tree diameter at breast height and total height.

A model QTRS-01X (QMS 1999) tree ring analyzer was used to scan each specimen following the procedures of Mirabile and Zink-Sharp (2017), who used the same analyzer for their work with Douglas-fir and southern pines. Measurements of the X-ray attenuation, ring by ring, were collected every 0.120 mm along the specimen from edge to edge and stored in ASCII file format along with the ring number, sample disk, tree, treatment, block, and location identifiers. Each scan was visually inspected to verify that the proper number of rings, which were 14, 11, and 8 for disks 1, 2, and 3, respectively, were included.

RESULTS AND DISCUSSION

Data Plots and Preliminary Analyses

Graphs of ring specific gravity vs ring age for disk 1 showed that, as expected, density decreased from ring age 1 yr to ring age 3 yr and then generally increased from ring ages 4 to 14 yr. The more-or-less monotonic increase in specific gravity from ages 4 to 14 yr showed a shift in level with higher specific gravity at the RH location than at the AB site and undulations in the trend from year to year (Fig 3[a]). Variability in genetics, soils, and management inputs were controlled to the extent possible in the design and installation of the study plots, but there were climate differences between the two locations. Summer precipitation (June-September) data from nearby weather stations for the two sites showed a general shift toward higher rainfall (10 of 13 yr) at the RH than at the AB site (Fig 3[b]). This observation of higher wood specific gravity being associated with higher levels of summer rainfall is in agreement with Cregg et al (1988) who, following a 2-yr study with loblolly pine, reported that the year with high summer rainfall resulted in wood with higher specific gravity than wood produced in the year with low summer rainfall. Locally weighted loess curves were developed for the two study sites (Fig 4) to elucidate the general trends of specific gravity and summer season rainfall in Fig 3(a) and (b) in a single graph.

A regression analysis was conducted to predict ring specific gravity using ring age (years beyond the pith) and relative height (disk height divided by total tree height) as predictors, as well as an indicator variable to account for the general shift in the level observed in the data plots of ring specific gravity at the two locations. Climate variables of temperature and precipitation were not statistically significant predictors when entered into the regression model following inclusion of location, ring age, and relative height. Accordingly, it was assumed that the influence of

Table 2. Mean heights (m) and (standard deviations [m]) by location and treatment for three sample disks illustrated in Fig 2.

Location[a]	Treatment	Disk 1	Disk 2	Disk 3
1	1	0.663 (0.185)	3.271 (0.690)	6.654 (1.104)
	2	0.613 (0.144)	2.863 (0.370)	6.408 (0.572)
	3	0.733 (0.167)	3.292 (0.435)	6.694 (0.386)
	4	0.705 (0.148)	3.380 (0.573)	7.094 (0.639)
	5	0.684 (0.226)	2.953 (0.665)	6.390 (0.810)
2	1	0.659 (0.180)	3.705 (0.767)	7.323 (1.047)
	2	0.754 (0.120)	4.040 (0.556)	7.786 (0.764)
	3	0.772 (0.169)	4.115 (0.714)	7.782 (0.752)
	4	0.739 (0.129)	4.174 (0.596)	7.729 (0.599)
	5	0.733 (0.150)	3.759 (0.568)	7.264 (0.900)

[a] Location 1, Appomattox Buckingham; 2, RH; Treatment 1, control; Treatment 2, pruning at age 3 yr; Treatment 3, pruning at age 6 yr; Treatment 4, pruning at age 9 yr; Treatment 5, pruning at ages 3, 6, and 9 yr.

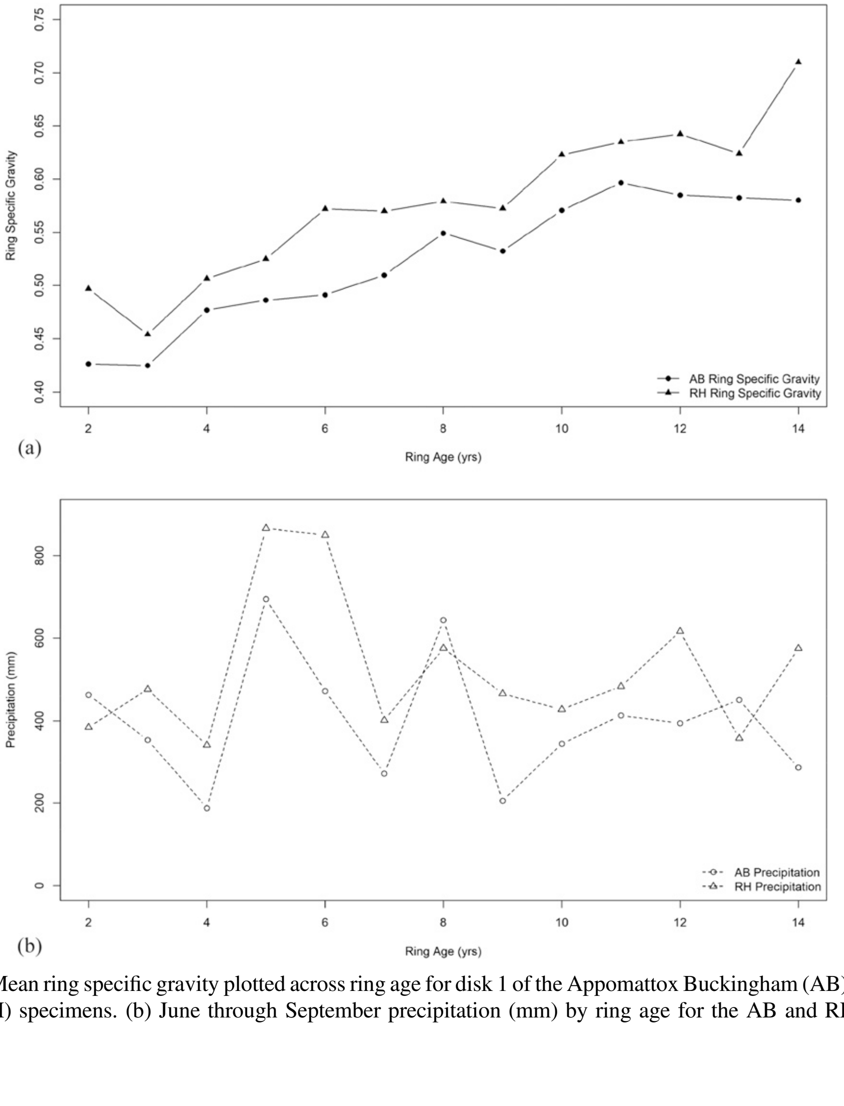

Figure 3. (a) Mean ring specific gravity plotted across ring age for disk 1 of the Appomattox Buckingham (AB) and Reynolds Homestead (RH) specimens. (b) June through September precipitation (mm) by ring age for the AB and RH locations.

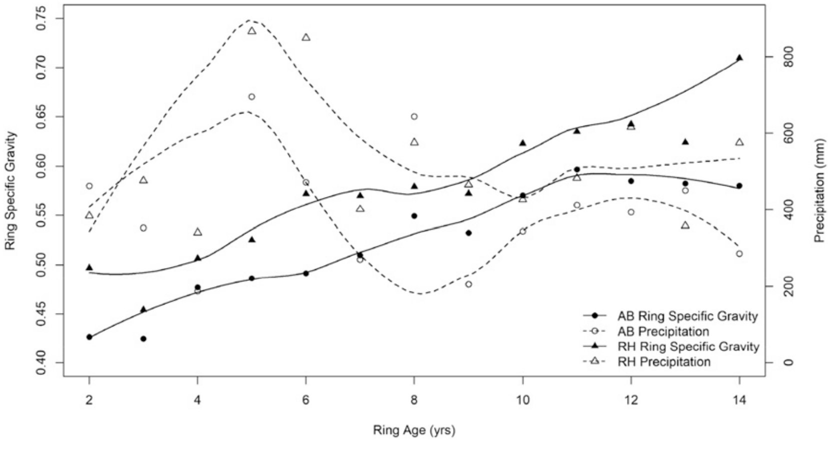

Figure 4. General pattern of ring specific gravity and precipitation at the two study locations generated by nonparametric locally weighted loess curves.

climate differences between the two locations were adequately accounted for by a shift in the level via a location indicator variable.

Height to base of green crown for the control plot trees was graphed against the four pruning treatments to compare self-pruning crown recession rates against pruned crown height. Figure 5 shows this relationship using the thrice-pruned plot trees as an example. When removing one-half of the green crown through pruning, it took about 3 yr for self-pruning of the control trees, on average, to reach the same height to green crown.

Table 3 displays a summary of mean wood specific gravity by ring position (1 = within green crown, 2 = below green crown) for ring ages 4 yr and above for each of the three disks obtained

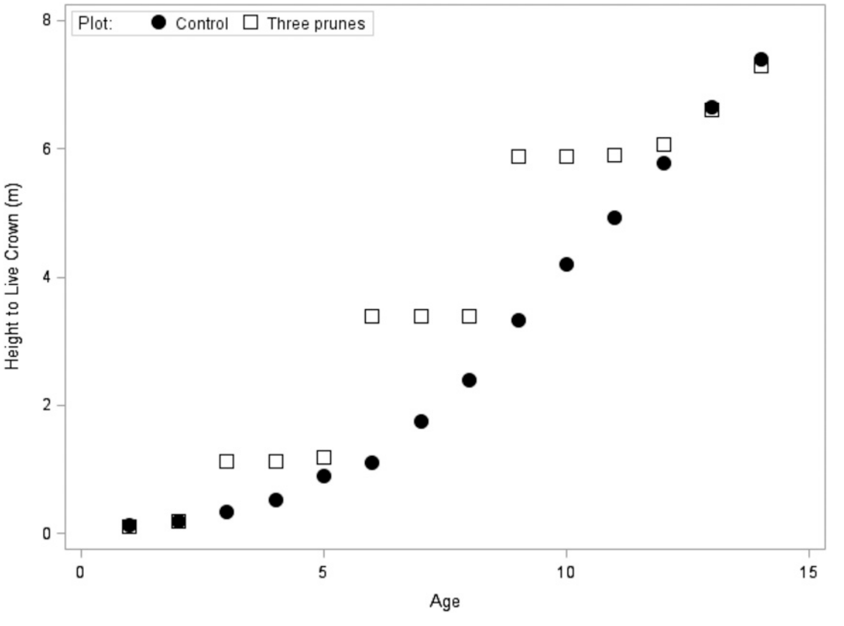

Figure 5. Rate of crown recession for the control plots vs the three-lift treatment plots.

from 160 sample trees (4 trees × 5 treatments × 4 blocks × 2 locations). Loblolly pine self-prunes and typically carries around 10 yr of branches in the green crown after initial crown rise following planting. For disk 1 and ring age 4 yr, 59% of the 160 rings were below the green crown; this figure increased to 100% by ring age 8 yr and older. By comparison, for disk 2, none of the 4- or 5-yr-old rings were below the green crown, but 21% of the observations at age 6 yr were below the green crown, with the distribution reaching 99% by ring age 11 yr. All rings in disk 3 (ring ages 4-8 yr) were laid down within the green crown.

Differences within and between Locations

Models were defined to test for differences in mean specific gravity among blocks at each location and between locations. A full model (1) accounting for location, block, and treatment effects was specified. Reduced models (2) and (3) were specified to reflect combining blocks within locations and across locations, respectively.

$$Y_{ijk} = b_0 + b_1 L_i + b_2 B_j + b_3 T_k + \varepsilon, \qquad (1)$$

$$Y_{ik} = b_0 + b_1 L_i + b_3 T_k + \varepsilon, \qquad (2)$$

$$Y_k = b_0 + b_3 T_k + \varepsilon, \qquad (3)$$

where Y is mean specific gravity; L_i is the location (i = 1,2); B_j is the block (j = 1,4); T_k is the plot (k = 1,5); b_0, b_1, b_2, and b_3 are the parameters; and ε is the error term.

Results of tests for differences between and within treatments and controls indicated that there was no significant difference in average specific gravity at the $\alpha = 0.05$ level among blocks at a

Table 3. Mean whole-ring specific gravity and standard deviation by ring position and ring age (4 yr and older) for the three sample disks illustrated in Fig 2. Data are for the control plots and all pruned plots.

		Ring position 1[a]			Ring position 2[a]		
Disk	Ring age	Mean density	Standard deviation	Number of observations[b]	Mean density	Standard deviation	Number of observations[b]
1	4	0.480	0.0335	65	0.502	0.0485	95
1	5	0.485	0.0372	36	0.506	0.0376	124
1	6	0.488	0.0372	17	0.546	0.0554	143
1	7	0.476	[c]	2	0.563	0.0523	158
1	8	—	—	—	0.575	0.0442	160
1	9	—	—	—	0.561	0.0517	160
1	10	—	—	—	0.604	0.0550	160
1	11	—	—	—	0.626	0.0520	160
1	12	—	—	—	0.609	0.0554	160
1	13	—	—	—	0.601	0.0555	160
1	14	—	—	—	0.643	0.0807	160
2	4	0.468	0.0394	160	—	—	—
2	5	0.478	0.0369	160	—	—	—
2	6	0.454	0.0405	131	0.468	0.0467	29
2	7	0.499	0.0472	129	0.527	0.0533	31
2	8	0.519	0.0464	126	0.545	0.0514	34
2	9	0.516	0.0425	57	0.530	0.0482	103
2	10	0.483	0.0457	14	0.522	0.0544	146
2	11	0.437	[c]	1	0.563	0.0722	159
3	4	0.455	0.0334	159	—	—	—
3	5	0.470	0.0391	159	—	—	—
3	6	0.474	0.0355	159	—	—	—
3	7	0.463	0.0440	159	—	—	—
3	8	0.508	0.0679	159	—	—	—

[a] 1, formed in green crown; 2, formed below green crown.
[b] Sum of number of observations in ring positions 1 and 2 for any given ring age for each disk = 160; except for disk 3 where a sample strip was lost.
[c] = not computed because of inadequate sample.
—, no observation for the disk, ring age, and ring position combination.

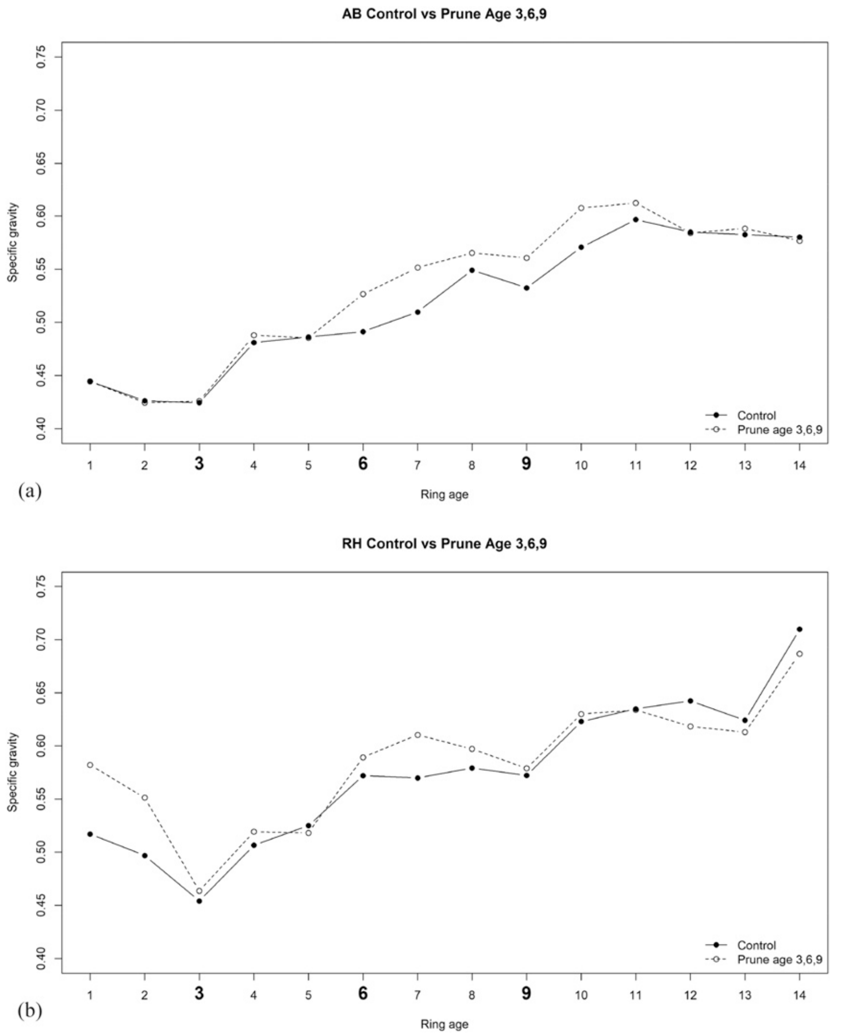

Figure 6. Data plots of mean ring specific gravity for treatment 5 (pruned at ages 3, 6, and 9 yr) and for the control plots at (a) the AB site and (b) the RH site. Years when pruning treatments were applied are shown in bold type.

given location, but there was a significant difference between locations.

Soils at the two sites are similar, and the site quality, as indicated by average total height of sample trees felled on the control plots at age 15 yr, is also similar (mean height AB = 15.3 m, RH = 16.8 m; Table 1).

Differences between Treatments and Control

Models (1) and (2) were also used to test for differences among treatments where L and T are specified as fixed effects and B, a random effect within L, in a mixed model context. The design of the study affords the use of Dunnett's test of the treatment means against the control appropriate.

Table 4 indicates that the least squares mean of specific gravity for all treatment plots (pruning once at age 3 yr, age 6 yr, or age 9 yr and pruning thrice at ages 3, 6, and 9 yr) was significantly higher than that of the control plots at the two locations. Environmental conditions were the same for the control and for the treated plots at

Table 4. Differences (pruned minus control) of least squares means of whole-ring specific gravity between pruning treatments 2-5 and control plots, treatment 1, using the Dunnett-Hsu test for significance.

Treatment plot	Estimate	Standard error	DF	*t*-Value	Pr > *t*	Adj *P*
2	0.04713	0.005073	1071	9.29	<0.0001	<0.0001
3	0.05386	0.005039	1071	10.69	<0.0001	<0.0001
4	0.06225	0.005262	1071	11.83	<0.0001	<0.0001
5	0.05952	0.004695	1071	12.68	<0.0001	<0.0001

Treatment 1, control; 2, pruning at age 3 yr; 3, pruning at age 6 yr; 4, pruning at age 9 yr; 5, pruning at ages 3, 6, and 9 yr.

each location; thus, we interpret this difference to result from the pruning treatments. The nature of the transient increase in specific gravity following pruning is illustrated in Figure 6.

Partitioning Variance

Preliminary analyses indicated that the two locations were significantly different; this divergence apparently stems from climate differences at the two sites. Consequently, an indicator variable for sites was specified. Although past work has shown that cambial or ring age is a primary variable to include when predicting ring-level specific gravity, with height along the stem (maturation) also being an important factor, these two continuous variables were included in a model to partition the total variation in ring specific gravity into sources. After accounting for these three variables, all of which are expected to be important predictors for these data, we tested for the significance of position in the tree crown (ie whether the ring was formed within or not within the green crown).

A general linear model (GLM) (4) was specified to partition the overall variance in mean ring specific gravity into significant components.

$$Y_{ij} = b_0 + b_1 L_i + b_2 \mathrm{RA} + b_3 \left(\frac{h}{H}\right) + b_4 \mathrm{RP}_j + \varepsilon, \quad (4)$$

where Y_{ij} is the ring mean specific gravity, L_i is the location AB or RH ($i = 1{,}2$), RA is the ring age, h/H is the relative height, disk height h/total tree height H, and RP_j is the ring position within or not within green crown ($j = 1{,}2$).

When testing the effect of ring position on ring specific gravity, the height to the base of the live crown (HCR) for each ring age was compared with the disk height to create a dichotomous variable, indicating whether a particular ring was formed below or within the live crown. All rings below the green crown were included whether the crown rise resulted from self-pruning or removal of branches by pruning. When HCR was less than the disk height, the ring at that age and height was formed within the live crown (RP = 1). When HCR was greater than the disk height, the ring at that age was formed below the live crown (RP = 2) (Table 3). Ring ages 1-3 yr form the juvenile core and were not considered in this analysis.

In Table 5, part a) shows that the overall model is statistically significant ($R^2 = 0.5638$; standard error of estimate = 0.05019). Part b) indicates that Type I sums of squares for the four sources are all significant with the location accounting for 11.5% of the total variation accounted for, ring age 71.8% after location, relative height 15.9% after location and ring age, and ring position 0.849% after the first three variables are entered. Despite the relatively small portion of the model sum of squares accounted for by ring position after all other variables have been entered, the reduction in error sum of squares is significant and suggests that proximity to the green crown is an important factor for determining wood specific gravity.

As a matter of interest, the GLM was run again with the ring position entering after accounting for location (representing site and environmental influences) and followed by the ring age and then the relative height (h/H), two "biological" variables that have consistently been shown to have significant statistical correlation with the wood density of conifers. The Type I sums of squares are all statistically significant regardless of the

Table 5. 5a) Overall test for significance of the general linear model (GLM) and 5b) Type I sums of squares for the individual components of GLM (4).

5a

Source	DF	Sum of squares	Mean square	*F* Value	PR > *F*
Model	4	12.472920	3.118230	1237.70	<0.0001
Error	3830	9.649189	0.00251937		
Corrected total	3834	22.122109			

5b

Source	DF	Type 1 SS	Mean square	*F* Value	PR > *F*
Location	1	1.434274	1.434274	569.30	<0.0001
Ring age	1	8.952143	8.952143	3553.33	<0.0001
Relative height	1	1.980627	1.980627	786.16	<0.0001
Ring position	1	0.105876	0.105876	42.02	<0.0001

order of entry of the four variables, but the partitioning of the sums of squares accounted for by the model varies. With the stated order of entry of variables, location accounted for 11.5%, ring position 59.9%, ring age (cambial age) 23.3%, and relative height in the stem (maturation) 5.3% of the overall variability. The three factors, crown position, ring age, and height along the stem, are interacting and their effects cannot be separated, but results suggest that all play a role.

Gartner et al (2002) tested the assumption that conifers produce juvenile wood within the crown and mature wood below by comparing wood properties of the three outer growth rings in disks sampled from different vertical positions in 18 to 34-yr-old Douglas-fir trees. These authors did not find an effect of crown position on the transition from juvenile toward mature wood as measured by wood density. By contrast, Gartner et al (2005) did find that pruning young Douglas fir in an intensively managed plantation resulted in a small, temporary increase in wood density in samples acquired at a sampling height of 5.5 m following removal of 50% of live crown in trees pruned at age 13 yr. The response in this instance, which is consistent with the responses from pruning loblolly pine reported here, was attributed to the removal of presumably vigorous branches in the vicinity of the bole where the 5.5-m sample disk was cut.

Early pruning of the green crown promoting a temporary shift in transition toward formation of mature wood has been previously noted (Megraw 1985; Zobel and Sprague 1998; Larson et al 2001). Evidence presented here indicates a duration of around 3 yr for loblolly pine that is pruned at young ages.

CONCLUSIONS

The experiment reported here was designed to determine the impact of early pruning on ring specific gravity in young loblolly pine trees. As part of the design, factors such as geographic region, site factors, and genetics—all known to affect wood density—were controlled or held constant to the extent possible. There was, however, an overall trend of higher ring specific gravity at the RH site when compared with that at the AB site. Hence, an indicator variable was included in the analyses to account for locational differences. Principal findings from this study include the following:

1. Mean ring specific gravity of the treated plots (pruned once at age 3 yr, age 6 yr, or age 9 yr or thrice at the ages 3, 6, and 9 yr) was significantly higher than that of the control plots.
2. Partitioning the overall variance in mean ring specific gravity showed that after accounting for location differences, the ring age, height in the stem (a surrogate for maturation), and whether the ring was formed in the green crown or below the crown were all statistically significant with p values less than 0.001.
3. Early pruning of loblolly pine by removal of half of the green crown increased the ring specific gravity over that of unpruned control trees. This effect typically lasted for around 3 yr before self-pruning by the control trees

reached the same height to base of the green crown.

Although cause and effect cannot be established with an empirical analysis of this nature, the results indicate that proximity to the green crown, cambial age, and maturation, are important factors controlling whole-ring specific gravity in loblolly pine. The transition to higher ring specific gravity in the pruned-tree treatments typically persisted for 3 yr, after which the base of the green crown for trees in the control plots rose to the same level as that of the trees in the pruned plots.

ACKNOWLEDGMENTS

Financial support for this project provided by the Forest Modeling Research Cooperative at Virginia Polytechnic Institute and State University and by the USDA McIntire-Stennis Program (Project VA-136630) is gratefully acknowledged. The Reynolds Homestead Forest Resources Center and the Virginia Department of Forestry made space available for planting the early pruning trials and assisted with the logistics of sample tree felling and wood sampling at the study locations. Special thanks to professor Audrey Zink-Sharp in the Department of Sustainable Biomaterials at Virginia Polytechnic Institute and State University for helpful guidance with the X-ray densitometry work and to David Jones with the Brooks Forest Products Center for preparing sample strips from the disks for X-ray densitometry and to Dr. Brian Bond for use of the conditioning chamber.

REFERENCES

Abdel-Gadir A, Krahmer RL (1993) Estimating the age of demarcation of juvenile and mature wood in Douglas-fir. Wood Fiber Sci 25:242-249.

Amarasekara H, Denne MP (2002) Effects of crown size on wood characteristics of Corsican pine in relation to definitions of juvenile wood, crown formed wood and core wood. Forestry 75:51-61.

Amateis RL, Burkhart HE (2011) Growth of young loblolly pine trees following pruning. For Ecol Mgmt 262: 2338-2343.

Antony F, Jordan L, Daniels RF, Schimleck LR, Clark A III, Hall DB (2009) Effect of midrotation fertilization on growth and specific gravity of loblolly pine. Can J Res 39: 928-935.

Auty D, Achim A, Macdonald E, Cameron AD, Gardiner BA (2014) Models for predicting wood density variation in Scots pine. Forestry 87:449-558.

Bendtsen BA, Senft J (1986) Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly pine. Wood Fiber Sci 18: 23-38.

Burdon RD, Kibblewhite RP, Walker JCF, Megraw RA, Evans R, Cown DJ (2004) Juvenile versus mature wood: A new concept, orthogonal to corewood versus outerwood, with special reference to *Pinus radiata* and *P. taeda*. Forest Sci 50:399-415.

Clark A III, Saucier JR (1989) Influence of initial planting density, geographic location, and species on juvenile wood formation in southern pine. Forest Prod J 39(7/8):42-48.

Clark A III, Saucier JR (1991) Influence of planting density, intensive culture, geographic location, and species on juvenile wood formation in southern pine. Ga Forest Res Pap 85, Georgia Forestry Commission, Macon, GA. 13 pp.

Clark A III, Daniels RF, Jordan L (2006) Juvenile/mature wood transition in loblolly pine as defined by annual ring specific gravity, proportion of latewood, and microfibril angle. Wood Fiber Sci 38:292-299.

Cown DJ, Clement BC (1983) A wood densitometer using direct scanning with X-rays. Wood Sci Technol 17:91-99.

Cregg BM, Dougherty PM, Hennessey TC (1988) Growth and wood quality of young loblolly pine trees in relation to stand density and climatic factors. Can J Res 18:851-858.

Dahlen J, Auty D, Eberhardt TL (2018) Models for predicting specific gravity and ring width for loblolly pine from intensively managed plantations, and implications for wood utilization. Forests 9:292.

Gartner BL, Robbins JM, Newton M (2005) Effects of pruning on wood density and tracheid length in young Douglas-fir. Wood Fiber Sci 37:304-313.

Gartner BL, North EM, Johnson GR, Singleton R (2002) Effects of live crown on vertical patterns of wood density and growth in Douglas-fir. Can J Res 32:439-447.

Gorman TM, Kretschmann DE, Green DW, Wiemann MC (2018) Effect of site characteristics on juvenile wood transition in lodgepole pine in the inland northwest. Wood Fiber Sci 50:180-192.

Greenwood MS (1995) Juvenility and maturation in conifers: Current concepts. Tree Physiol 15:433-438.

Hayatgheibi H, Forsberg NEG, Lundqvist S-O, Mörling T, Mellerowicz EJ, Karlsson B, Wu HX, García-Gil MR (2018) Genetic control of transition from juvenile to mature wood with respect to microfibril angle in Norway spruce (*Picea abies*) and lodgepole pine (*Pinus contorta*). Can J Res 48:1358-1365.

Jacquin P, Longuetaud F, Leban JM, Mothe F (2017) X-ray microdensitometry of wood: A review of existing principles and devices. Dendrochronologia 42:42-50.

Jordan L, He R, Hall DB, Clark A III, Daniels RF (2007) Variation in loblolly pine ring microfibril angle in the southeastern United States. Wood Fiber Sci 39:352-363.

Koubaa A, Isabel N, Zhang SY, Beaulieu J, Bousquet J (2005) Transition from juvenile to mature wood in black spruce (*Picea mariana* (Mill.) B.S.P.). Wood Fiber Sci 37: 445-455.

Kučera B (1994) A hypothesis relating current annual height increment to juvenile wood formation in Norway spruce. Wood Fiber Sci 26:152-167.

Larocque GR, Marshall PL (1995) Wood relative density development in red pine (*Pinus resinosa* Ait.) stands as affected by different initial spacings. Forest Sci 41: 709-728.

Larson PR, Kretschmann DE, Clark A III, Isebrands JG (2001) Formation and properties of juvenile wood in southern pines: A synopsis. Gen Tech Rep FPL-GTR-129. USDA Forest Service, Forest Products Laboratory, Madison, WI. 42 pp.

Mansfield SD, Parish R, Goudie JW, Kang K-Y, Ott P (2007) The effects of crown ratio on the transition from juvenile to mature wood production in lodgepole pine in western Canada. Can J Res 37:1450-1459.

Max TA, Burkhart HE (1976) Segmented polynomial regression applied to taper equations. Forest Sci 22:283-289.

Megraw RA (1985) Wood quality factors in loblolly pine. Tappi Press, Atlanta, GA. 88 pp.

Mirabile KV, Zink-Sharp A (2017) Fundamental bonding properties of Douglas-fir and southern yellow pine wood. Forest Prod J 67:435-447.

Mora CR, Allen HL, Daniels RF, Clark A III (2007) Modeling corewood-outerwood transition in loblolly pine using wood specific gravity. Can J Res 37:999-1011.

Mörling T (2002) Evaluation of annual ring width and ring density development following fertilisation and thinning of Scots pine. Ann Sci 59:29-40.

Mutz R, Guilley E, Sauter UH, Nepveu G (2004) Modelling juvenile-mature wood transition in Scots pine (*Pinus syvestris* L.) using nonlinear mixed-effects models. Ann Sci 61:831-841.

Systems QM Inc. (QMS) (1999) QMS tree ring analyzer users guide. QMS, Knoxville, TN. 55 pp.

Sauter UH, Mutz R, Munro BD (1999) Determining juvenile-mature wood transition in Scots pine using latewood density. Wood Fiber Sci 31:416-425.

Schneider R, Zhang SY, Swift DE, Bégin J, Lussier J-M (2008) Predicting selected wood properties of jack pine following commercial thinning. Can J Res 38:2030-2043.

Tasissa G, Burkhart HE (1998a) Modeling thinning effect on ring specific gravity of loblolly pine (*Pinus taeda* L.). Forest Sci 44:212-223.

Tasissa G, Burkhart HE (1998b) Juvenile-mature wood demarcation in loblolly pine trees. Wood Fiber Sci 30:119-127.

Trincado G, Burkhart HE (2009) A framework for modeling the dynamics of first-order branches and spatial distribution of knots in loblolly pine trees. Can J Res 39:566-579.

Zobel BJ, Sprague JR (1998) Juvenile wood in forest trees. Springer-Verlag, Berlin, Germany. 300 pp.

Zobel BJ, van Buijtenen JP (1989) Wood variation its causes and control. Springer-Verlag, Berlin, Germany. 363 pp.