

EFFECT OF SITE CHARACTERISTICS ON JUVENILE WOOD TRANSITION IN LODGEPOLE PINE IN THE INLAND NORTHWEST

*Thomas M. Gorman**†

Professor
Department of Forest
Rangeland and Fire Sciences
University of Idaho
Moscow, ID
E-mail: tgorman@uidaho.edu

David E. Kretschmann

President
American Lumber Standards Committee
Frederick, MD
E-mail: dkreschmann@alsc.org

David W. Green†

Research General Engineer, Emeritus
E-mail: levangreen@tds.net

Michael C. Wiemann†

Research Botanist
USDA Forest Service
Forest Products Laboratory
Madison, WI
E-mail: mwiemann@fs.fed.us

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Abstract. Juvenile wood (core wood) in softwood species is typically characterized as being less dimensionally stable and having lower mechanical properties than mature wood. Determining the age of transition between juvenile wood and mature wood is important when making judgments about utilization options for naturally occurring stands of trees in the intermountain west region of the United States. Lodgepole pine (*Pinus contorta* Dougl. ex. Loud.) trees were harvested from four different sites in the US Inland Northwest to include site variations that affect growth, such as elevation, precipitation, and length of growing season. Longitudinal shrinkage was measured in each sample as it dried from green to oven-dry conditions. Later, average microfibril angle was determined for the same samples. Although the two methods for estimating the juvenile wood transition period were not in agreement regarding the number of years to mature wood, there was agreement in a ranking of the four sites from shortest transition period to longest transition period. A significant difference in the juvenile wood transition period was found among sites; longer transition periods were attributed to stands in which trees exhibited persistent lower branches rather than to geographic influences. This work illustrates that stand conditions for sources of lodgepole pine can have a substantial influence on physical characteristics of this material when it is used as structural roundwood or solid-sawn products.

Keywords: Lodgepole pine, juvenile wood, mature wood, longitudinal shrinkage, microfibril angle, *Pinus contorta*.

INTRODUCTION

There are more than 10 trillion cubic meters (net) of softwood growing stock in the western

United States, excluding Alaska and the Great Plains (Smith et al 2009). Of the over 52 million hectares of western timberland that meet minimum productivity standards but are not reserved for timber harvest, it has been suggested that approximately 12 million hectares are

* Corresponding author

† SWST member

high-priority areas for fuel reduction treatments (Fig 1).

Most trees in these high-priority treatment areas are in diameter at breast height (dbh) classes less than 25 cm, although most of the biomass falls in dbh classes more than 25 cm (Woodall 2003). The species with the greatest percentage of their volumes in overstocked stands are lodgepole pine (*Pinus contorta* Dougl. ex. Loud.), whitebark pine (*Pinus albicaulis* Engelm.), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), and western larch (*Larix occidentalis* Nutt.). By far, the largest timber volume of these four species is the lodgepole pine, with western larch a distant

second. Most of the lodgepole pine are from 80 to 120 yr old. Thinning at-risk stands is often imperative to decrease fire risk, even for stands that will eventually to be subjected to controlled burns. Because the cost of fuel reduction treatments often exceeds the value of the material removed, finding higher value uses for the thinnings has been a major focus of Forest Service Research (Forest Service 2003).

Lodgepole pine (*P. contorta*) is usually divided into three geographical varieties (var. *contorta*, *latifolia*, and *murrayana*) (Flora of North America Editorial Committee 1993). *Pinus contorta* var. *latifolia* Engelm. is the inland form,

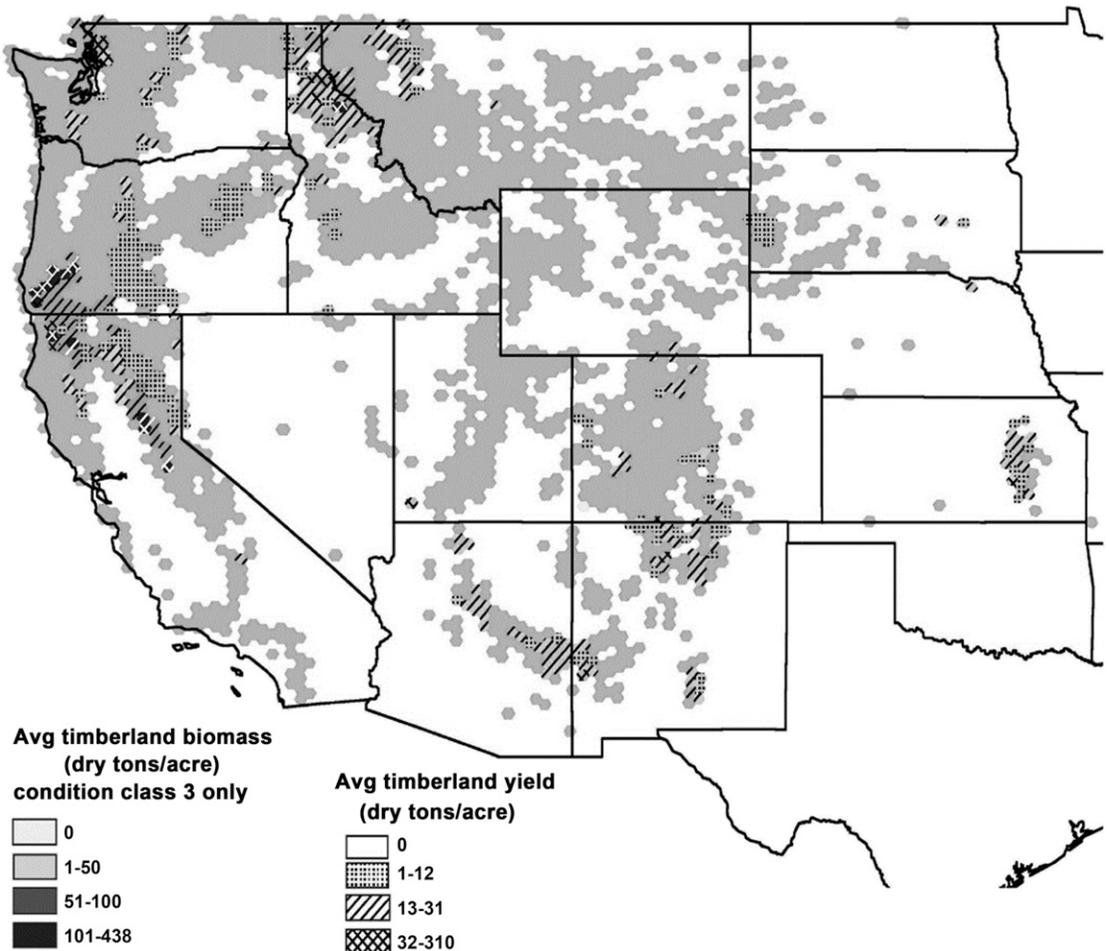


Figure 1. Potential high-priority fuel reduction thinning opportunities on timberland in the western United States (Vissage and Miles 2003).

growing mostly in Montana, Idaho, Wyoming, and eastern portions of Washington and Oregon. Lodgepole pine, as a species, grows in a wide variety of climate conditions, with temperatures ranging from 27°C along the coast and at higher elevations to -57°C in the Northern Rocky Mountains. At low elevations in the interior, lodgepole pine grows in sites receiving only 25 cm of precipitation per year. At higher elevations, snowfall supplies most of the soil water needed for germination and growth.

The mature size of lodgepole pine varies greatly with site. Mature trees in the Rocky Mountains are typically 46-84 cm dbh and 18-24 m high at 140 yr old. Lodgepole pine is very intolerant of shade and competition from other species. Fire regimes play an important role in lodgepole pine's successional continuum, especially in the case of repeated fires eliminating seed sources for other species. Closed lodgepole pine cones may accumulate for many years. The cones may then open following a fire, or a clear cut, resulting in very dense pure stands of seedlings; these cones may persist for more than 10 yr. The typical dense stands that naturally regenerate after fire result in self-pruning, such that the lower portion of the tree's stem is often free of branches. Growth and yield of lodgepole pine are very dependent on stand density.

Historical and contemporary studies have identified the prevalence of juvenile wood as a major impediment to efficient utilization. Juvenile core material shrinks longitudinally much more than does mature material, which can affect the dimensional stability of wood-based products. In addition, strength of juvenile wood is lower than that of mature wood, which is added later during tree growth. The effect of juvenile wood on properties has been widely studied for southern pine and western conifers (Koch 1972; Jozsa and Middleton 1994; Larson et al 2001). Although focused on southern pine, the discussion by Larson et al (2001) on juvenile wood formation and properties is relevant to the western pines. In that publication, the authors note that although there is extensive literature on juvenile wood, there has been little attempt to synthesize this

information from the viewpoint of solid-wood products and structural composites. For example, they point out that although summerwood percentages and specific gravity are often used to define the extent of the juvenile wood core, these characteristics provide little or no information as to how a board will react to drying. Determining the age of transition between juvenile wood and mature wood and some of the factors that could affect this transition are important when making judgments about utilization options for naturally occurring stands of trees in the Intermountain West.

Jozsa and Middleton (1994) noted that the juvenile wood of some species was not necessarily lower in relative density (ie specific gravity) than the mature wood. In some species, the relative density near the pith was higher than that of the mature wood (Fig 2). Other interesting transition patterns from juvenile to mature wood are also evident from Fig 2. For example, lodgepole pine appears to have a longer period of juvenility than Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco); however, the increase in relative density between juvenile wood and mature wood appears less than that of Douglas-fir. Abdel-Gadir and Kraemer (1993) reported a wide range (11-37 yr) in the period of juvenile wood production based on density. Koch (1996) noted that the magnitude of the difference between properties (strength, shrinkage, etc.) of juvenile wood and mature wood in lodgepole pine is less than in most other western species. Unlike the dominant pattern shown in Fig 2, in which relative density initially decreased and then either remained constant or increased, the relative density of western larch increased continually with age.

Bendtsen and Senft (1986) used regression analysis to identify potential sources of improvement in mechanical properties of southern pine using specific gravity, cell length, and microfibril angle (MFA) (Fig 3) as predictor variables. After dropping out the first three years of measurements, for which no change was observed in mechanical properties, scatter diagrams appeared linear. With data from the first three

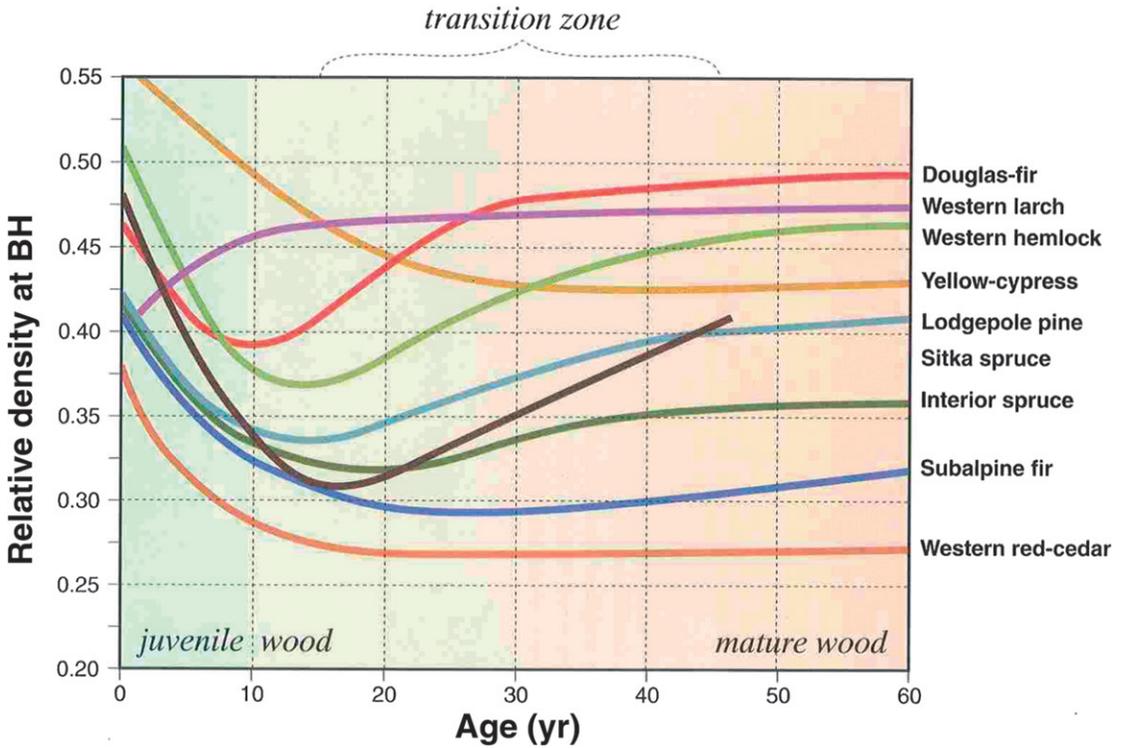


Figure 2. Relative density of wood at breast height (BH) for western species as a function of age within a tree (Jozsa and Middleton 1994). The transition from juvenile to mature wood ranges from 15 to 30 yr.

years omitted, coefficients of determination (R^2) from multiple regression analysis showed that these three variables could explain about 80% of the variation in mechanical properties. Mansfield

et al (2009) determined that the fiber traits MFA and tracheid length were related. They also determined that these traits defined the transition of juvenile wood to mature wood, rather than density, which is influenced by climate.

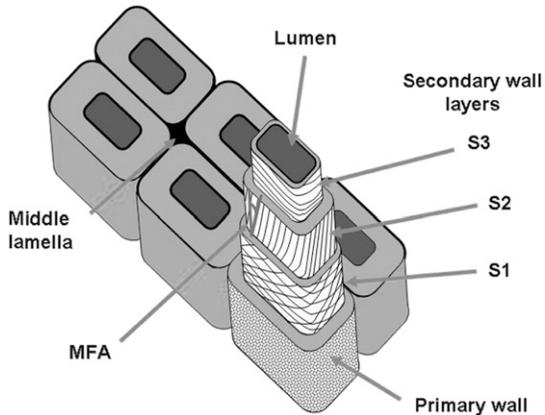


Figure 3. Microfibril angle (MFA) is defined as the angle of the microfibril bundles with respect to the cell axis in the S2 wall layer.

Clark and Saucier (1989) concluded that the period of juvenility in slash and loblolly pine was influenced by environmental factors, such as temperature (length of growing season) and seasonal rainfall patterns, associated with geographic location. Their study also showed that although planting density did not alter the length of the juvenile period, it did influence the size of the juvenile core by controlling radial growth. Mansfield et al (2007) found that proximity to crown affected juvenile wood transition, which is why some authors refer to juvenile wood as “crown wood.” Larson et al (2001) pointed out that, in young trees, pruning of branches tended to accelerate the transition from juvenile wood to

Table 1. Annual precipitation and duration of snow-free season for the four sites selected for this study (Koch 1996).

National Forest	Annual precipitation (cm)	Elevation (m)	Duration of snow-free season
Helena	51	1531	Early June to late October
Panhandle	140	1736	Mid-July to early October
Payette	71	1978	June 1 to late November
Kootenai	89	1280	Mid-April to mid-November

mature wood below the new crown. Shuler et al (1989) noted that MFA in young-growth ponderosa pine did not vary significantly with either site index (from 55 to 100) or dbh (from 23 to 36 cm). It has generally been found that the largest variation in MFA in softwoods occurred in the butt log (Voorhies and Groman 1982; Shuler et al 1989; Jozsa and Middleton 1994), which is usually the most valuable log in a stem.

Longitudinal shrinkage (LS) and MFA are strongly correlated, and they can be used as indicators for demarcation of the juvenile wood–mature wood transition (Harris and Meylan 1965; Ying et al 1994; Clark et al 2006). Given its relatively low-cost means of determination, LS may offer a better opportunity for demarcation of the juvenile wood–mature wood transition than MFA.

Koch and Barger (1988) identified 28 stands of lodgepole pine on public forests in the western United States where increased utilization was desired by forest managers. Eleven of these 28 stands are located in the interior northwestern region, within the states of Idaho and Montana, where interest in value-added utilization opportunities has led to studies related to structural roundwood grading and allowable stress estimates (Green et al 2004, 2005, 2006) for small-diameter lodgepole pine.



Figure 4. Four sites selected for sampling included 1) dry site, intermediate growing season (Helena National Forest [NF]); 2) wet site, short growing season (Panhandle NF); 3) midrange precipitation, intermediate growing season (Payette NF); and 4) midrange precipitation, long growing season (Kootenai NF).

Processing structural roundwood components to a uniform diameter facilitates their use in construction, because this doweling step eliminates a log's natural taper and provides standard-dimension building components. In general, however, the doweling process also removes portions of outer mature wood and exposes more of the juvenile wood core. The net effect of the

machining is a decrease in both modulus of rupture (MOR) and modulus of elasticity (MOE) (Larson et al 2004; Green et al 2005). In a study comparing the effect of doweling on flexural properties of small-diameter (7.5-15 cm) logs, MOR was decreased by about 8% and MOE was decreased by about 15% for Douglas-fir (*P. menziesii*), and MOR was decreased by about



(a)



(b)



(d)



(c)

Figure 5. National Forest (NF) sites where trees were harvested for this study included (a) Helena NF, (b) Panhandle NF, (c) Payette NF, and (d) Kootenai NF.

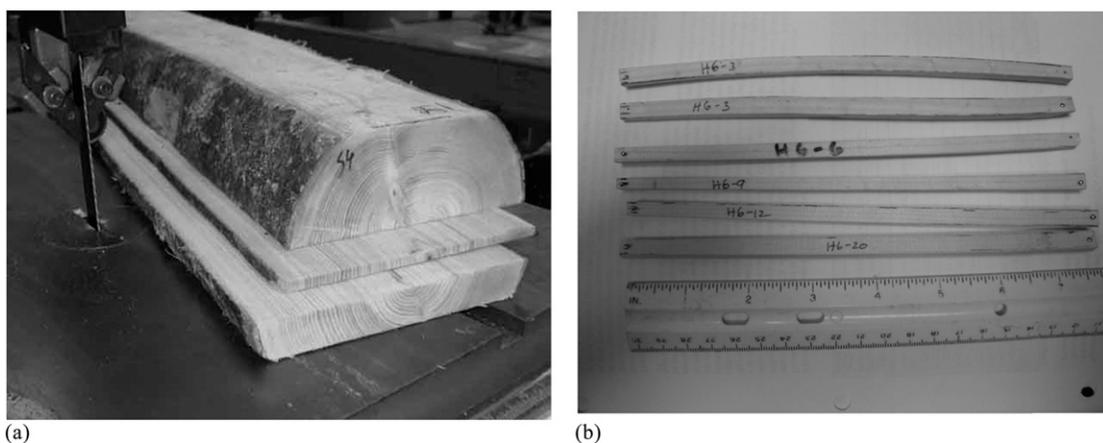


Figure 6. Sample preparation consisted of (a) sawing a single, radially oriented board from each bolt, then (b) extracting samples to measure green to oven-dry shrinkage.

12% and MOE was decreased by about 33% for ponderosa pine (*Pinus ponderosa*) (Green et al 2005). A better understanding of the factors that control the juvenile wood period in natural stands of lodgepole pine could help determine the relative volume of juvenile wood contained in logs harvested from specific locations.

The objective of this study was to measure LS and MFA to estimate the juvenile wood–mature wood transition in lodgepole pine across a range of growing conditions in the US Intermountain West. Better understanding of the factors contributing to juvenile wood transition could improve utilization options for small-diameter lodgepole pine, especially when seeking markets for trees harvested from stand thinnings intended to improve forest health and decrease fire hazards.

MATERIALS AND METHODS

Sampling was limited to lodgepole pine trees growing in four of the 11 National Forests (NF) in Idaho and Montana identified by Koch and Barger (1988) as underutilized, unmanaged stands. Our intent was to select stands with significantly different geographic locations, representing a wide range of annual precipitation and growing seasons. We sampled and assessed trees 13–33 cm dbh from 1) a relatively dry site with an intermediate growing season (Helena NF in Montana), 2) a relatively wet

site with a short growing season (Panhandle NF in Idaho), 3) a midrange precipitation site with an intermediate growing season (Payette NF in Idaho), and 4) a site with midrange precipitation and a long growing season (Kootenai NF in Montana) (Table 1; Figs 4 and 5). All the sites were naturally regenerated after stand-replacing fires that occurred between 1910 and 1920.

Six trees were harvested at the Helena NF and Panhandle NF sites, and five trees were harvested from the Payette NF and Kootenai NF sites. Trees were selected based on straightness of bole and absence of defects. In addition, we selected trees with diameters that would allow us to create a sufficient number and size of test samples needed for the study. At the time of harvest, the ends of the boles were examined to eliminate trees containing signs of compression wood, including eccentric growth rings or irregular wide bands of latewood. A 1.5-m bolt was cut from the large end of each tree and processed to extract a single, radial-sawn board from each bolt (Fig 6[a]).

Table 2. Number of sections taken from each tree to extract longitudinal samples from both sides of the pith.

National Forest	Tree 1	Tree 2	Tree 3	Tree 4	Tree 5	Tree 6
Helena	3	3	3	3	3	3
Panhandle	3	3	2	3	3	2
Payette	3	3	4	2	3	—
Kootenai	3	3	3	3	3	—

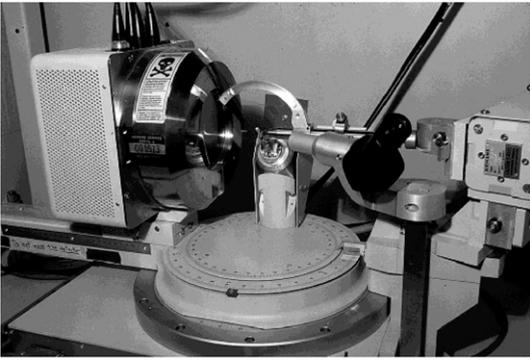


Figure 7. Testing equipment setup for X-ray diffraction microfibril angle measurements.

The radial-sawn boards were cut into shorter sections, usually less than 40 cm long and 1 cm thick, by crosscutting clear sections between knots. This allowed us to obtain two to four

clear sections from each bole (Table 2). Each clear section was then sawn longitudinally to extract narrow samples that were centered at the 3rd, 6th, 9th, 12th, 15th, 20th, 40th, and 60th annual growth rings from both sides of the pith, with each measuring approximately 5 by 5 mm in cross section. To avoid grain deviation caused by knots, the lengths of the samples ranged from 125 to 350 mm (Fig 6[b]). All samples were kept in the green condition by immersing them in water immediately after sawing.

LS Method

LS was determined for each sample by measuring the change in length between green and oven-dry conditions. To ensure precise length

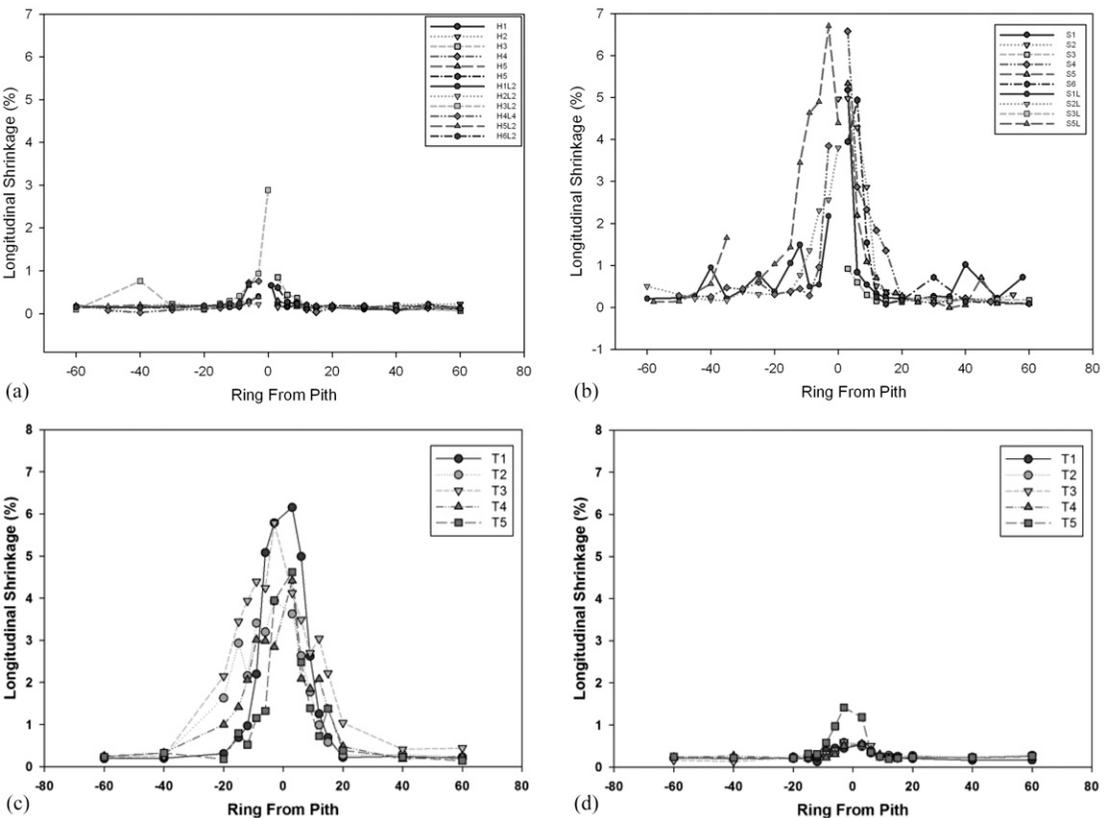


Figure 8. Longitudinal shrinkage values at various ring positions for the trees sampled from the (a) Helena National Forest, (b) Panhandle National Forests, (c) Payette National Forest, and (d) Kootenai National Forest sampling locations.

measurements, small pins were inserted near the ends of each sample to serve as reference markers. The initial green length of each sample was measured by clamping it to a moveable stage equipped with a position indicator that monitored distance to the nearest 0.0254 mm and measuring the distance between the pins. The samples were then placed in frames designed to allow airflow and longitudinal movement, and to prevent bowing during drying. The frames containing the samples were placed in a drying oven set at 102°C. Periodic weighing ensured that the samples had reached oven-dry conditions when the length of each sample was remeasured after 48 h in the oven. The change in length for each sample was

divided by its initial green length then multiplied by 100 to determine percentage LS.

X-Ray MFA Method

The average MFA for earlywood and latewood for a given ring position was determined using X-ray diffraction techniques as described by Verrill et al (2006, 2011). In general, because of reflections from the 002 crystallographic planes in the cellulose microfibrils, two back plane bright spots are produced per wood cell face. Thus, cells with rectangular cross sections yield eight back plane bright spots, whereas those with hexagonal cross sections produce 12 bright spots. These bright spot patterns are broadened by

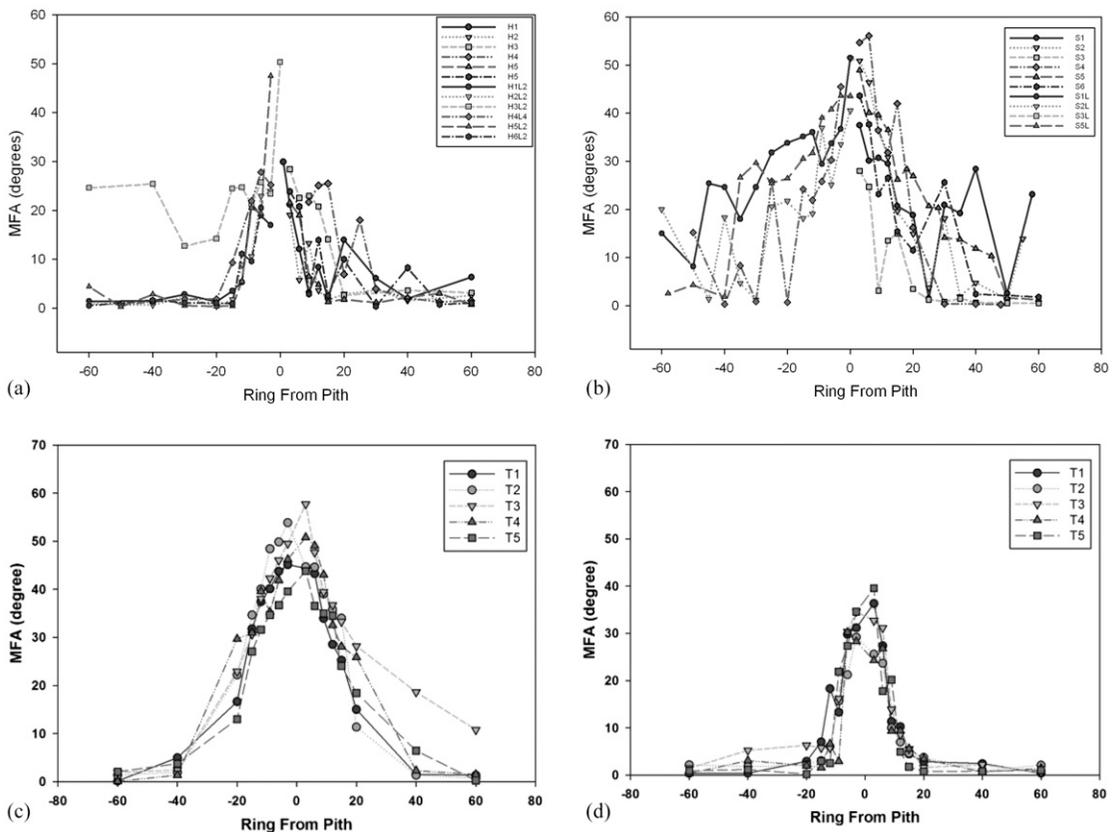


Figure 9. Microfibril angle (MFA) values at various ring positions for the trees sampled from the (a) Helena National Forest, (b) Panhandle National Forests, (c) Payette National Forest, and (d) Kootenai National Forest sampling locations.

(among other factors) MFA variability and variabilities in cell rotation and tilt. These broadened intensity patterns can be evaluated along the 2θ circle on the back plane (where θ is the Bragg angle) to determine MFA using an 11 parameter nonlinear least squares fit.

The existing lodgepole pine blocks used for LS measurements were cut in odd–even ring pairs. Therefore, for each tree, there were blocks cut that centered around rings 3, 6, 9, 12, 15, 20, and 60. The blocks were cut down to a uniform thickness perpendicular to the radial cell wall orientation. Our previous trials of radial and tangential face exposures (Kretschmann et al 1997) indicated little difference between X-ray–predicted MFAs from radial and tangential faces. Therefore, the radial faces (the most likely scan orientation in a commercial device) of these samples were exposed. The resulting specimens were approximately 2 mm thick and 3 mm wide.

An X-ray scattering system (Kristalloflex 710D X-ray generator, 2-dimensional Siemens [Munich, Germany] HI-STAR area detector system, with Siemens general area detector diffraction software

[GADDS] version 3.310 for Windows NT) was used to collect X-ray diffraction data (Fig 7). Each specimen was placed in a specially prepared mounting bracket and attached to the X-ray diffraction goniometer. The specimens were perpendicular to the incident X-ray beam path. The X-ray beam passed through the radial face near the center of the specimen. The radiation source was $\text{CuK}\alpha$ ($\lambda = 1.54 \text{ \AA}$), 40 kV, 20 mA, and a 0.5-mm aperture incident beam. The exposure time was 60 s.

A 2-dimensional intensity pattern was then captured by the area detector. The diffracted X-ray beams passed through the beryllium window of the area detector into a chamber that held xenon gas under four bars of pressure. The xenon atoms were ionized by incident X-rays, producing charged particles as the X-rays passed through the gas. These charged particles were then electrically attracted to a multiwire electrode assembly array in the detector. An electrical signal was then generated, indicating the original x, y position of the X-ray on the detector. The intensity of the complete 2-dimensional diffractogram was recorded digitally and integrated over an azimuthal angle with 0.1° resolution over

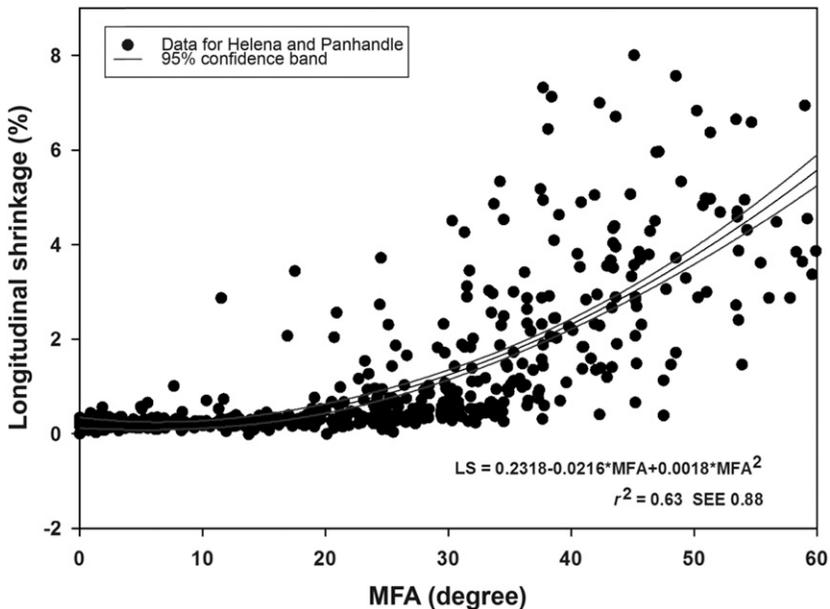


Figure 10. Quadratic regression fit between longitudinal shrinkage (LS) and microfibril angle (MFA) for all measurements from the Panhandle and Helena National Forests.

the 002 crystal plane arcs of the diffractogram. The average MFA for earlywood and latewood for a given ring position was then determined using the aforementioned X-ray diffraction techniques described by Verrill et al (2006).

Each small, individual sample we examined represented a combination of earlywood and latewood for the given ring position. Because of the tight ring structure, the samples typically contained more than one annual ring of growth.

RESULTS AND DISCUSSION

The LS information clearly showed distinctions between the four harvest locations sampled (Fig 8). Both length of time for the juvenile zone and magnitude of LS varied by location, with the greatest shrinkage occurring in samples collected from the Panhandle NF of Idaho. The samples with the least shrinkage were collected from the Helena and Kootenai NF in Montana, and these samples also exhibited the shortest periods of larger LS values.

The MFA measurements also showed a distinction between the four geographic sampling locations

(Fig 9). Again, the length of time for the juvenile zone and magnitude of MFA varied by location, with the greatest juvenile zone occurring in the samples collected from the Panhandle and Payette NF of Idaho. The smallest juvenile zone occurred in the samples collected from the Helena and Kootenai NF in Montana, suggesting that the juvenile wood period was shorter at these two locations than at the two locations in Idaho.

Figure 10 shows the relationship between LS and MFA for the test data from the Helena and Panhandle NF. A quadratic fit to the test data were also plotted. Similar trends in the MFA and LS relationship were observed for the Payette and Kootenai NF. It can be seen that there was less variability in the MFA–LS relationship at smaller values of LS and MFA. As MFA exceeded 20°, there was a considerable increase in variability of corresponding LS measured values.

A segmented regression between age and MFA for all samples was fit for each of the four sites to estimate the juvenile transition point. Figure 11 shows an example graphical representation of the segmented regression technique for determining

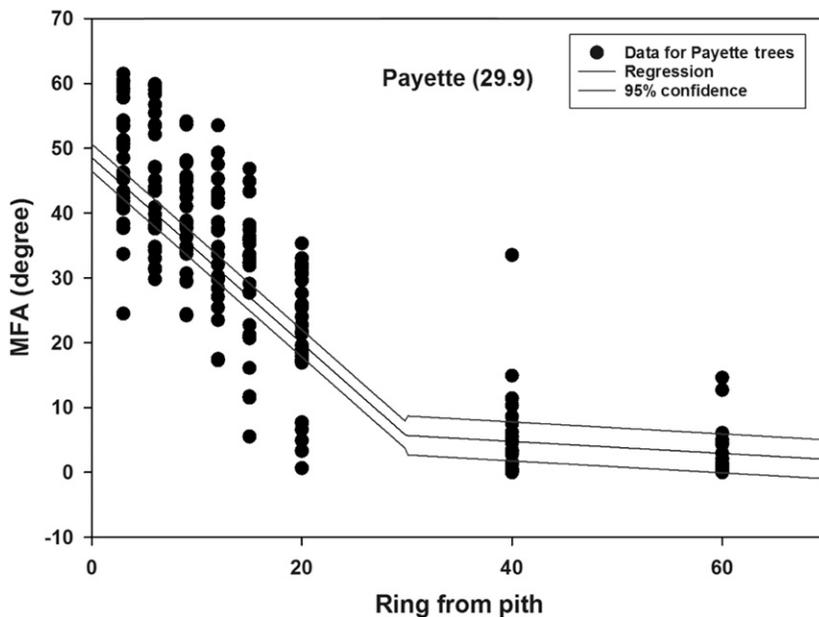


Figure 11. Segmented regression of microfibril angle (MFA) and tree age to determine juvenile transition period in lodgepole pine harvested on the Payette National Forest, Idaho.

Table 3. Summary of segmented regression prediction of juvenile wood transition.

National Forest	Years to reach mature wood							
	Based on longitudinal shrinkage	Adjusted R^2	Standard error of estimate	p	Based on microfibril angle	Adjusted R^2	Standard error of estimate	p
Helena	10.7	0.48	0.11	<0.0001	15.9	0.64	5.8	<0.0001
Panhandle	12.9	0.64	0.93	<0.0001	21.0	0.61	9.4	<0.0001
Payette	20.8	0.54	1.27	<0.0001	29.9	0.79	8.3	<0.0001
Kootenai	10.0	0.40	0.18	<0.0001	13.3	0.78	5.8	<0.0001

juvenile wood–mature wood transition period for data collected from material harvested on the Payette NF in Idaho. Table 3 provides a summary of the segmented regression prediction of juvenile wood transition for each of the four sites.

Although the two methods for estimating the juvenile wood transition period were not in agreement regarding the number of years to mature wood, there was agreement in a ranking of the four sites from shortest transition period to longest transition period.

Although precipitation and length of growing season difference at each site did not appear to influence the transition period from juvenile to mature wood, we did observe a trend toward increasing shrinkage with increased elevation, although the correlation was not strong, given the limited data points. Persistent branching in the lower portions of trees in natural stands of lodgepole pine may be a better indicator of a prolonged juvenile wood transition period than geographic indicators, however. Those stands with persistent lower branches (Figs 5[b] and [c]) exhibited the longest juvenile wood period, whereas stands without persistent lower branches (Figs 5[a] and [d]) had the shortest juvenile wood period. This observation is consistent with the responses reported after pruning lower branches in conifers (Larson et al 2001).

CONCLUSIONS

Although the LS and MFA measurement methods for estimating the juvenile wood transition period were not in agreement regarding the number of years to mature wood, there was agreement in the ranking of the four sites from the shortest transition period to the longest transition period.

In addition, our results suggest that persistent branching in the lower portions of trees in natural

stands of lodgepole pine is a better indicator of a prolonged juvenile wood transition period than geographic factors such as precipitation, elevation, or climate. Thus, it appears that when stand growing conditions result in early, wider spacing between trees, thereby extending the life of the lower branches, the juvenile wood transition period will be extended.

When considering value-added opportunities for lodgepole pine obtained from forest thinnings to improve forest health, stands containing trees with relatively small crown ratios will provide material that is better suited for structural applications than stands exhibiting large crown ratios.

This study illustrates that stand conditions for sources of lodgepole pine can have a substantial influence on the physical characteristics of this material when it is used as structural roundwood or solid-sawn products.

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