Impact of Wood Variability on the Drying Rate at Different Moisture Content Levels

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Abstract

The impacts on drying behavior of basic density, initial moisture content, percentage and position of heartwood, ring count, rings from the pith, growth ring angle, and earlywood and latewood coverage on board faces were investigated for western hemlock (*Tsuga heterophylla*) lumber. Mathematical relations for the effects of wood properties and board geometric features related to position within its parental log were developed to predict the drying rate at four moisture content levels for drying temperatures of 80°C and 115°C. These relations were used for simulating wood drying as well as for predicting drying times of individual boards, which were used as a criterion for sorting green boards prior to entering their properties in the drying simulation.

Drying rate was affected by basic density, initial moisture content, percent heartwood, and growth ring angle at 80°C and only initial moisture content at 115°C. Presorting into two groups based on these wood properties reduced the standard deviation of the final moisture content distribution by 40 percent.

Removing large amounts of water from lumber is essential to achieve the desired quality (Mujumdar and Devahastin 2000), but it is difficult because wood is a natural biological material with nonuniform properties and a variable response to changes in its surroundings (Panshin and De Zeeuw 1980). Thus boards can dry at different rates, resulting in moisture levels, internal stresses, and defects that are not desirable (Berberović and Milota 2008). Overdrying lumber uses more energy than necessary and may result in excessive shrinkage and a tendency for the boards to degrade. Underdried boards may have mold growth and stains in a unit of lumber, which can result in warp after installation.

At present, some softwood mills sort prior to drying based on board weight, capacitance value, or gamma ray attenuation, each of which gives an indication of moisture content. For species such as western hemlock (*Tsuga heterophylla*), the moisture content after drying is not closely related to the initial moisture content (Milota and Wu 1997). Finding a relationship between board properties and the drying rate would allow presorting based on the boards' moisture content and predicted drying characteristics so that all boards in a batch would achieve the same final moisture content at the same time.

One objective of this research was to determine how drying rate is impacted by wood properties and geometric features of a board related to its position within the parental log. A second objective was to determine if these factors differentially affect drying at dryer temperatures above and below the boiling point. It is known that drying mechanisms vary above and below the boiling point (Hart 1964). Therefore, optimal presorting criteria might differ depending on the temperature at which the wood will be dried. A third objective was to establish if the same factors affect drying rate throughout the moisture content range. The final objective was to develop presorting criteria based on initial moisture content and board characteristics that allow a drying time to be predicted for each board. Sorting could then be based on the predicted drying time.

Materials and Methods

Sample preparation

Freshly sawn, rough, 2 by 6 nominal, 2.4-m-long western hemlock lumber was used to make 300 boards for drying. The lumber was acquired in two batches separated by several months. The 2.4-m pieces were cut in half (Fig. 1) to

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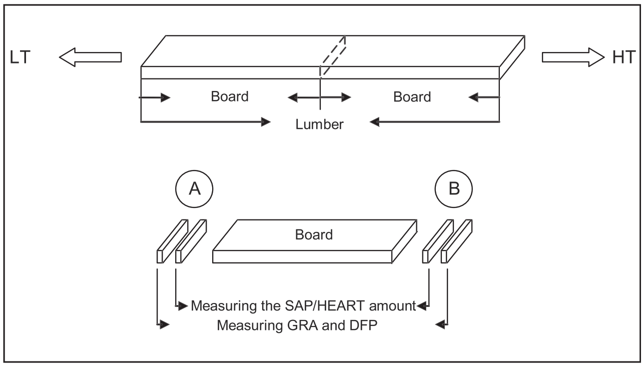

Figure 1.—Sample cutting diagram. SAP = sapwood; HEART = heartwood; GRA = growth ring angle; DFP = distance from the pith.

make matched charges each containing 10 boards. The boards were randomly assigned to different positions in the kiln, and charges were randomly assigned to the experimental treatments.

Two 10-mm-thick samples were cut from each end of the boards after removing a thin layer that was often damaged and dirty (Fig. 1). The samples were used for obtaining wood properties. If not used immediately, they were wrapped with aluminum foil, placed in a plastic bag, and stored at −10°C (14°F). The final board length was 1,014 mm. Each charge was wrapped in plastic and stored at 3°C.

Measurements taken before drying

The percentages of sapwood and heartwood in each board were determined by applying ferric nitrate or ferrous ammonium sulfate solutions on opposite faces of end samples to cause color changes in the two regions (Kutcha and Sachs 1962). Sample images were then analyzed using ImageJ (National Institutes of Health 2010), and sapwood and heartwood areas were calculated based on pixel colors. The individual results for both ends were averaged to obtain the heartwood percentage within a board.

Ring count was determined using scanned pictures of end samples. Within ImageJ the width of two consecutive growth rings was measured (Fig. 2). Two such measurements were taken along each of the three dashed lines at each end of the board and averaged. This average value was used to obtain the ring count for the board.

Growth ring angle and distance from the pith were determined from the same images by using custom software written by the lead author. The growth ring angle was averaged from measurements at 10 locations at each end of the board (Fig. 3). The distance from the pith was the radius of curvature of the growth rings at the center of the board, assuming the growth rings were circular in a method similar to Booker (1987).

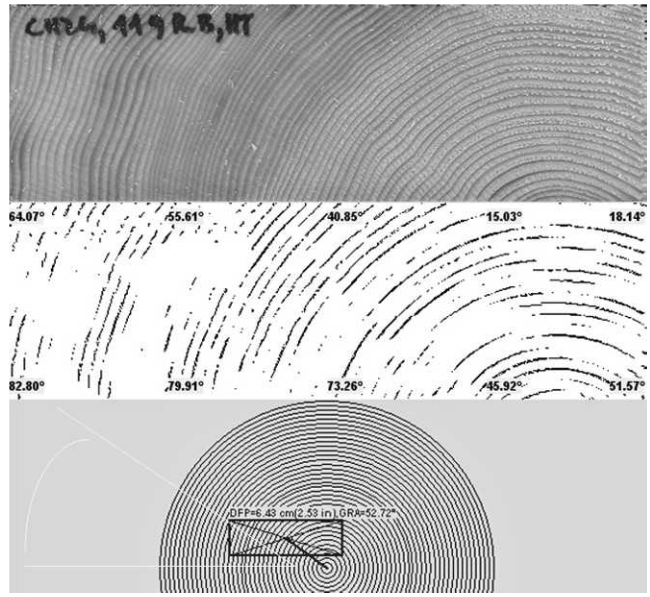

Figure 3.—The output from the image processing program used for calculations of the growth-ring angle and distance from the pith.

The position of heartwood within a board was denoted as T or F. T meant that one face was predominately heartwood and the other face sapwood, causing moisture movement to possibly be asymmetric. Boards denoted T had a growth ring angle of less than 30° (flat sawn) and contained less than 30 percent heartwood, which covered or almost covered one face (Fig. 4). The rest of the boards were denoted as F.

Earlywood and latewood coverage of board faces was determined using 3.2 megapixel images of board faces. Counts of pixels with dark and light color were converted into percentages of earlywood and latewood (Fig. 5). Results for each face were averaged to represent the whole board.

Drying

Each board was weighed, and its width and thickness were measured at the middle of the board. The measuring location was marked with crayon in order to take the measurements at the same location after drying. Ten boards were then loaded into the kiln. One of the matched charges was dried at 80°C and the other at 115°C (Table 1). Each board was hung from two load cells, and its weight was continuously measured during drying using the system

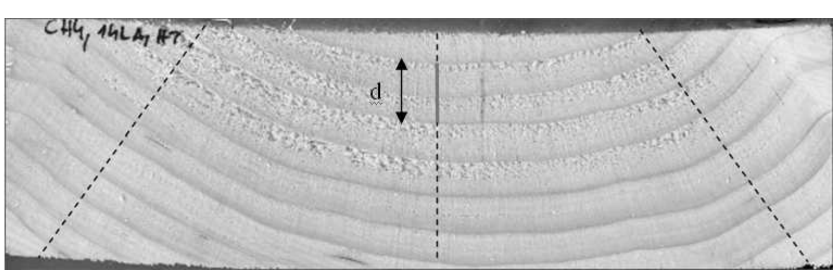

Figure 2.—Ring count measurements.

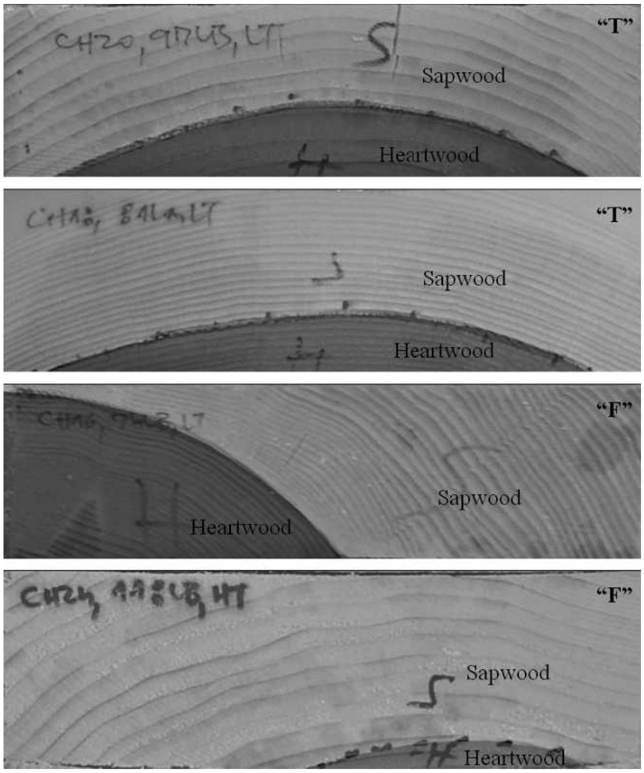

Figure 4.—Examples of end samples for determining the heartwood position.

shown in Figure 6. Load cell accuracy was within 0.25 percent of full scale or 0.03 kg per board. The drying process was stopped after the wettest board had reached approximately 12 percent moisture content. This was estimated by the rate of weight change.

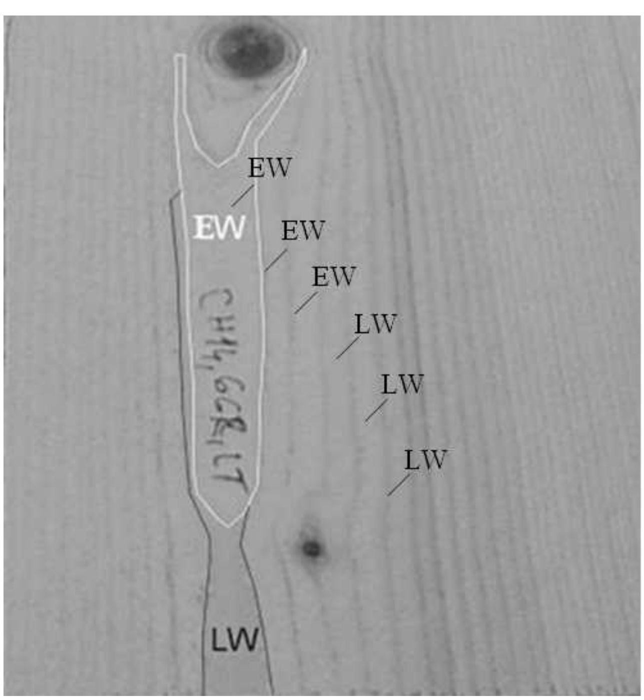

Figure 5.—Earlywood (EW) and latewood (LW) coverage measurements

Table 1.—Dryer conditions.[a]

	Low-temperature (80°C) schedule (°C)		High-temperature (115°C) schedule (°C)	
Time, h	Dry-bulb	Wet-bulb	Dry-bulb	Wet-bulb
0	43	35	43	35
3	80	70	115	85
End[b]	80	70	115	85

[a] The air velocity was 3.8 and 5.1 m/s for the low- and high-temperature schedules, respectively.
[b] Approximately 50 and 15 hours for the low- and high-temperature schedules, respectively.

After drying, each board was weighed, and its width and thickness were measured at the location of the crayon mark. Board shrinkage was calculated as a percentage of the original dimension. They were then oven dried (D4442, American Society for Testing and Materials 1997) and weighed again (m_{OD}). All moisture contents were calculated on a dry basis. The basic density (ρ_B) was calculated as

$$\rho_B = \frac{m_{OD}}{V_G} \quad (1)$$

where the green board volume (V_G) was adjusted to account for any wane.

Analysis

Drying rate.—The load cell weight data were visually inspected for electrical noise. In two cases warp caused boards to touch, which affected the weights, and these data were not used. The drying rate (DR) for a board was then calculated from moisture content (X) and time (t) as

$$\mathrm{DR}_{X_1-X_2} = \frac{X_1 - X_2}{t_2 - t_1} \quad (2)$$

for moisture content ranges of 90 to 140, 60 to 90, 40 to 60,

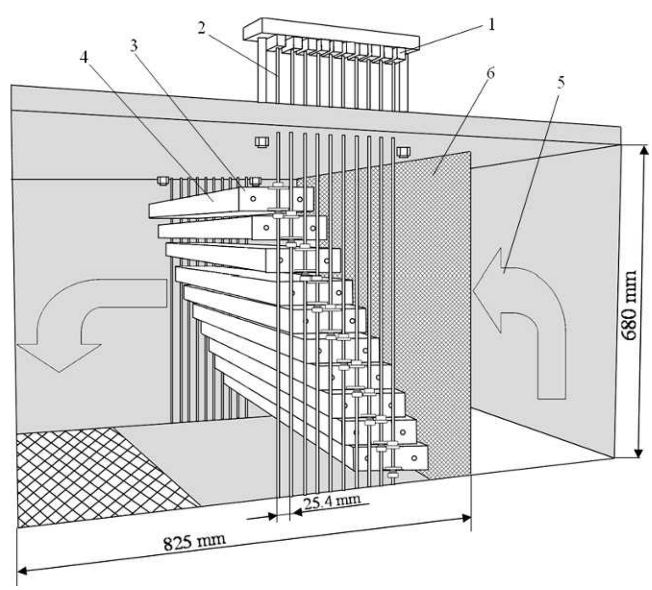

Figure 6.—The interior of the kiln with weighing apparatus: (1) load cell, (2) rod attached to load cell for holding the board, (3) bracket screwed in the board for connecting the board and rod, (4) board, (5) air flow direction, (6) perforated metal screen.

and 16 to 40 percent for low-temperature (80°C) drying and 80 to 120, 60 to 80, 30 to 60, and 10 to 30 percent for high-temperature (115°C) drying. Ranges were chosen based on the measured board moisture contents and the observations found in Berberović (2007).

The drying ranges were adjusted to have the number of green boards equally distributed across the different moisture content ranges. Matched boards dried at high or low temperature did not have the same initial moisture content although they came from the same lumber piece. Therefore, the moisture content ranges for low- and high-temperature drying were slightly different. Boards with an initial moisture content lower than a range were not included in that range. A filtering transformation was used to adjust for serial correlation because the drying rate versus moisture content characteristic represented a time series.

Effect of wood properties.—Multiple linear regression and regression inference about the regression parameters were conducted for the basic density (BD, kg/m^3), initial moisture content (IMC, %), heartwood percentage (HW, %), ring count (RC, no./cm), distance from the pith (DFP, cm), growth ring angle (GRA, degrees), and latewood coverage of board faces (ELC, %) as the independent variables. The average value of the drying rate (DR, $kg_{H_2O} \cdot kg_{wood}^{-1} \cdot h^{-1}$) was calculated over a moisture content range using Equation 3.

$$DR_{calculated} = a \cdot BD + b \cdot IMC + c \cdot HW + d \cdot RC + e \cdot DFP + f \cdot GRA + g \cdot ELC + n \qquad (3)$$

where n is the constant term ($kg_{H_2O} \cdot kg_{wood}^{-1} \cdot h^{-1}$). The analysis was conducted for each moisture content range and drying temperature.

A two-sample t test was conducted to estimate the effect of the heartwood position on the drying rate. A paired t test on the difference in the drying rate between matched boards was used to estimate the effect of temperature on the drying rate. The initial moisture content used for the test was based on the paired board with the lowest initial moisture content.

Simulation.—Final moisture content distributions for drying with and without presorting were compared. Final moisture contents were based on Equation 3 and the time to dry the charge to an average moisture content of 20 percent. This charge average was selected so no boards were below 16 percent, the lower limit for Equation 3. In addition, coefficients of determination were calculated for linear regressions applied on the board ranks based on the calculated drying time of individual boards, and board ranks were based on wood properties to calculate how much each property accounted for variations in drying time. Boards that were dried using the low-temperature drying schedule were used for the simulations.

Results

Board properties

The basic density (Table 2) of the boards was slightly less than, but not statistically different from, the published value of 420 kg/m^3 (Forest Products Laboratory 2010), which agreed well with 408 kg/m^3 reported by Pong et al. (1986). Jozsa et al. (1998) and Simpson (1991) also reported values of 420 kg/m^3. Basic density was normally distributed.

The average value of the initial moisture content calculated over all the boards was 107 percent (Table 2), which was in good agreement with the 108 percent reported by Pong et al. (1986). The ''Dry Kiln Operator's Manual'' (Simpson 1991) suggests a mean moisture content of 124 percent, calculated from the measured heartwood content and the US Department of Agriculture values of 85 percent for heartwood and 170 percent for sapwood. Initial moisture content showed a slight positive skewness.

Table 2.—Summary of board measurements.

Property[a]	Average value (SD)
Basic density, (kg/m^3)	401 (42.2)
Initial moisture content (%)	107 (44.6)
Heartwood amount (%)	53.1 (32.5)
Shrinkage in width, HT (%)[b]	6.3 (2.0)
Shrinkage in thickness, HT (%)[b]	5.9 (2.1)
Shrinkage in width, LT (%)[b]	6.3 (2.2)
Shrinkage in thickness, LT (%)[b]	5.7 (1.6)
Ring count (no./cm)	3.8 (2.5)
Distance from the pith (cm)	8.1 (3.3)
Growth ring angle (°)	33.7 (12.2)
Earlywood/latewood face coverage (%)	22.3 (9.4)
Thickness (mm)	42.38 (1.87)
Ending moisture content, HT (%)	7.3 (4.0)
Ending moisture content, LT (%)	14.6 (4.8)

[a] HT = high temperature (115°C); LT = low temperature (80°C).
[b] Expressed as shrinkage from 0 to 30 percent moisture content assuming a linear relationship between shrinkage and moisture content below fiber saturation.

Similarly, the shrinkage coefficients (Table 2) were between the published values of 4.2 percent radially and 7.8 percent tangentially (Forest Product Laboratory 2010). Shrinkage in width was greater than in thickness because the material was predominately flat sawn. There was no difference due to drying temperature. Other board properties are summarized in Table 2. A two-sample t test comparing the wood collected at different times indicated that there were no differences in the mean values of basic density, initial moisture content, and heartwood percentage.

Factors affecting drying rate at a low temperature

Basic density, initial moisture content, heartwood percentage, and growth ring angle affected the drying rate at the lower temperature of 80°C (Table 3). Ring count and distance from the pith had no effect.

Basic density was negatively correlated with drying rate within the drying range of 16 to 90 percent with no effect above 90 percent. This suggests that basic density begins to affect the drying rate as surface layers reach a low enough moisture content for diffusion to occur within the wood. The drying may be externally controlled above 90 percent. The 95 percent confidence intervals of the basic density regression coefficients overlap for the 60 to 90 percent and 40 to 60 percent moisture content ranges. The mean value of the regression coefficient for basic density in the 16 to 40 percent moisture content range was statistically different from those calculated for higher drying moisture content ranges.

The amount of heartwood was negatively correlated with a drying rate from 40 to 140 percent moisture content (Table 3). Similar results were obtained by Morrell et al. (2003), Keey and Nijdam (2002), and Perre and Turner (1997). The lower permeability of heartwood to free water may be attributed to aspirated pits and pits encrusted with

Table 3.—Effects of significant factors indicated by multiple linear regression for drying at the low temperature (80°C).

Property (coefficient)[a]	Moisture content range (%)[b] 90–140	60–90	40–60	16–40
Basic density (a)	0 (0, 0)	−1.15 (−1.68, −0.61)	−0.94 (−1.27, −0.61)	−0.21 (−0.29, −0.14)
Initial moisture content (b)	2.65 (1.84, 3.46)	0.04 (0.01, 0.08)	0	0.33 (0.25, 0.4)
Heartwood percentage (c)	−0.81 (−1.36, −0.26)	−0.76 (−1.35, −0.16)	−0.89 (−1.35, −0.42)	0 (0, 0)
Growth ring angle (f)	(0, 0)	(0, 0)	(0, 0)	−0.37 (−0.6, −0.13)
Constant (n)	210	−930	−710	−160
Coefficient of determination, r^2 (%)	64	42	42	69

[a] Coefficients are for Equation 3.
[b] All values are coefficient × 10^4. Values in parentheses are 95% confidence intervals.

extractives present in heartwood. At lower moisture contents the sapwood pits aspirate and the effect of heartwood percentage on the drying rate decreases. The 95 percent confidence intervals overlap, suggesting that there is no statistically significant difference between the mean values of the coefficients for all three moisture content ranges in which the heartwood percentage was found to affect drying rate (Table 3).

The growth ring angle was negatively correlated with drying rate in the moisture content range of 16 to 40 percent (Table 3). The same behavior was found by Hao and Avramidis (2004) and Pang (2002a). Gas diffusion in the tangential direction is lower than in the radial direction Pang (2002a). Drying mainly occurs along the thickness direction of a board, and therefore boards with a lower growth ring angle (flat sawn) dried faster than boards with a higher growth ring angle (quartersawn). The 95 percent confidence interval of the growth ring angle regression coefficient for the moisture content range of 16 to 40 percent can be seen in Table 3.

Initial moisture content was positively correlated with drying rate within all moisture content ranges in which it had an impact on drying (Table 3). Cabardo et al. (2006) and Innes and Redman (2003) presented similar results. A possible reason for this finding could be a negative relationship between initial moisture content and basic density. A weak negative correlation was found for all boards, in agreement with Pang (2002b), Oliveira and Zhang (1994), and Walker (1993). The relationship was stronger for boards containing only sapwood (n = 29, slope = $0.78\%\cdot kg^{-1}\cdot m^3$, $r^2 = 0.46$). A multiple linear regression with only initial moisture content, amount of heartwood, and an interaction term did not indicate that drying rate was dependent on heartwood percentage or the interaction term over the moisture content ranges of 90 to 140 percent and 60 to 90 percent.

Factors affecting drying rate at a high temperature

Initial moisture content was the only property that affected the drying rate during high-temperature (115°C) drying (Table 4). It had an effect over the entire moisture content range. The 95 percent confidence intervals suggest there is no difference between the coefficients for 80 to 120 percent and 60 to 80 percent moisture content ranges (Table 4). The mean values of the regression coefficients for 30 to 60 percent and 10 to 30 percent moisture content ranges were statistically different from coefficients for the other ranges. The wood temperature during high-temperature drying can reach and exceed the water boiling point, leading to significant changes in pressure inside the wood. At 115°C, the increase in pressure may mask possible effects from other wood properties on the drying rate. This was observed by Pang (2002a) who found a clear effect of sawing pattern on drying rate with the temperature lower than the water boiling point and no effect with the temperature greater than the boiling point.

This result contrasts with the results of Keey and Nijdam (2002) and Perre and Turner (1997), who reported that sapwood and heartwood percentage affected drying rate at high-temperature drying. It also contrasts with the work of Milota and Tschernitz (1994) and Kayihan (1985) in which an important modeling assumption was that at a certain moisture content, a board dries at a certain rate independent of how wet it was initially. A likely explanation is that sapwood percentage increases as moisture content increases. This explanation is supported by the decreasing coefficient as moisture content decreases. Also, while other factors may not significantly impact the drying rate individually, they may combine to cause the moisture content effect. Besides being related to heartwood percentage, initial moisture content is related to most other properties. Within the sapwood samples, initial moisture content is weakly related to basic density. Ring count may be related to basic density. Flat-sawn boards are more likely to come from the outside of the log where the initial moisture content is higher. Boards from a greater distance from the pith are more likely to contain sapwood. A factorial experiment using a 2-way ANOVA to reveal the interaction effects would allow a valid comparison. However, it would be very difficult or impossible to select the samples prior to drying.

A strong linear relationship was found between the drying rate ranks of boards dried at high and low temperatures (Fig. 7). Boards dried at a 46 to 67 percent greater rate at the higher temperature, but if a board dried at a greater than average rate at the higher temperature, its matched board at the lower temperature tended to also dry at a greater than average rate. This occurred even though the previous analysis indicated different properties affect rate at different temperatures.

Sensitivity analysis results

A sensitivity analysis for Equation 3 using the coefficients in Table 3 for low-temperature drying indicated that a 1-hour drying time increase is caused by a 10.2-kg/m^3 increase in basic density, a 9.7 percent increase in initial moisture content, a 23.3 percent increase in heartwood percentage, or a 10° increase in the growth ring angle. The base case was a basic density of 400 kg/m^3, 110 percent initial moisture content, 50 percent heartwood, and a 45°

Table 4.—Regression coefficients and 95% confidence intervals for different moisture content ranges at high-temperature (115°C) drying.

Property[a]	Moisture content range (%)[b]			
	80–120	60–80	30–60	10–30
Initial moisture content (*b*)	9.36 (6.52, 12.19)	8.1 (6.54, 9.65)	2.22 (1.54, 2.89)	0.79 (0.66, 0.91)
Constant (*n*)	4	46	269	106
Coefficient of determination, r^2 (%)	55	58	33	57

[a] Coefficients are for Equation 3.
[b] All values are coefficient $\times 10^4$. Values in parentheses are 95% confidence intervals.

growth ring angle. The increase in drying rate caused by a greater initial moisture content change is not great enough to offset the time required to remove more moisture.

A similar analysis of high-temperature drying using the coefficients in Table 4 indicates that a 1-hour change in drying time is caused by a 40 percent change in moisture content when the base case moisture content is 90 percent. An increase of initial moisture content above 90 percent did not cause an increase in drying time because the greater drying rate throughout drying offset the extra time one would expect for additional moisture to be removed. While this seems implausible, the high moisture content boards are likely to be sapwood and have much greater permeability than heartwood boards. The few boards in the study starting at very high moisture content (180% to 200%) did dry in the same or less time as many of the boards starting at 100 percent moisture content.

The drying times calculated from the sensitivity analysis for the low-temperature drying agree favorably with drying times obtained by using the drying rate function from Berberović and Milota (2008). The relative error between the two ranged from 0.25 to 21 percent, depending on the combination of wood properties that were found to affect the drying rate in this study. The function is valid for western hemlock from 71°C to 107°C and does not take any wood properties into account except initial moisture content.

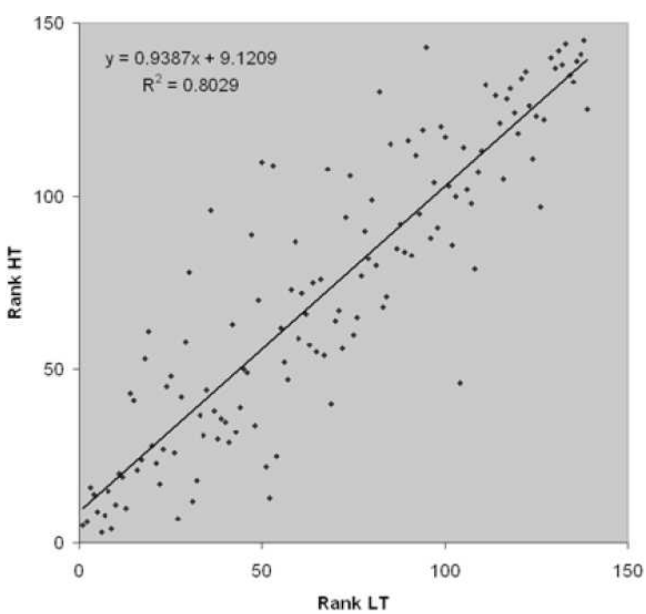

Figure 7.—High-temperature (HT; 115°C) drying ranks versus low-temperature (LT; 80°C) drying ranks.

Variability after drying

The purpose of presorting is to reduce the board-to-board moisture content variability in the dried product. Eighty-eight boards were assigned to one charge to simulate unsorted drying. The same boards were assigned to one of two charges based on their predicted drying time to 20 percent moisture content to simulate sorted drying. Drying time was obtained from Equation 3 and the coefficients in Table 3. Drying was then simulated to determine the time required for each of the three charges to reach an average of 20 percent moisture content. The low-temperature drying schedule was used.

The standard deviation of the moisture content after simulated drying with presorting (2.2%) was 40 percent less than when the boards were not presorted (3.7%; Fig. 8D). For comparison, unsorted hemlock dried by Berberović (2007) at similar conditions resulted in a standard deviation of 4.4 percent for a 14 percent final moisture content. One would expect greater variability in a real measurement because of temperature and humidity variations in the dryer. Regressions based on the rankings of drying time for the 88 boards indicated that that basic density and initial moisture content explained 23 and 20 percent of drying time variations, respectively. Heartwood percentage and growth ring angle showed a very weak impact on the drying time. One reason for the importance of basic density and initial moisture content is that each directly contributes to how much water must be removed from the board.

Drying without presorting yielded the widest final moisture content distribution (Fig. 8). Slightly better results were achieved with two presort groups based on basic density or initial moisture content where both methods generated the same distributions (Figs. 8A and 8B). Sorting by board initial mass resulted in a distribution with a standard deviation that was lower than that of previously described sorting methods (Fig. 8C). This suggests that green density sorting, often called weight sorting, would be more effective than trying to measure and sort based on green moisture content or basic density. Finally, using the predicted drying time sorting method proposed here, it was possible to reduce the standard deviation by an additional 13 percent compared with presorting based on the board initial mass. This suggests that the predicted drying time captures the impact of the properties on drying rate the best and that sorting based on a single property may not be the most optimal approach.

Conclusions

Basic density, initial moisture content, heartwood percentage, and growth ring angle affect drying rate at a low temperature. Only initial moisture content affects drying rate at a high temperature.

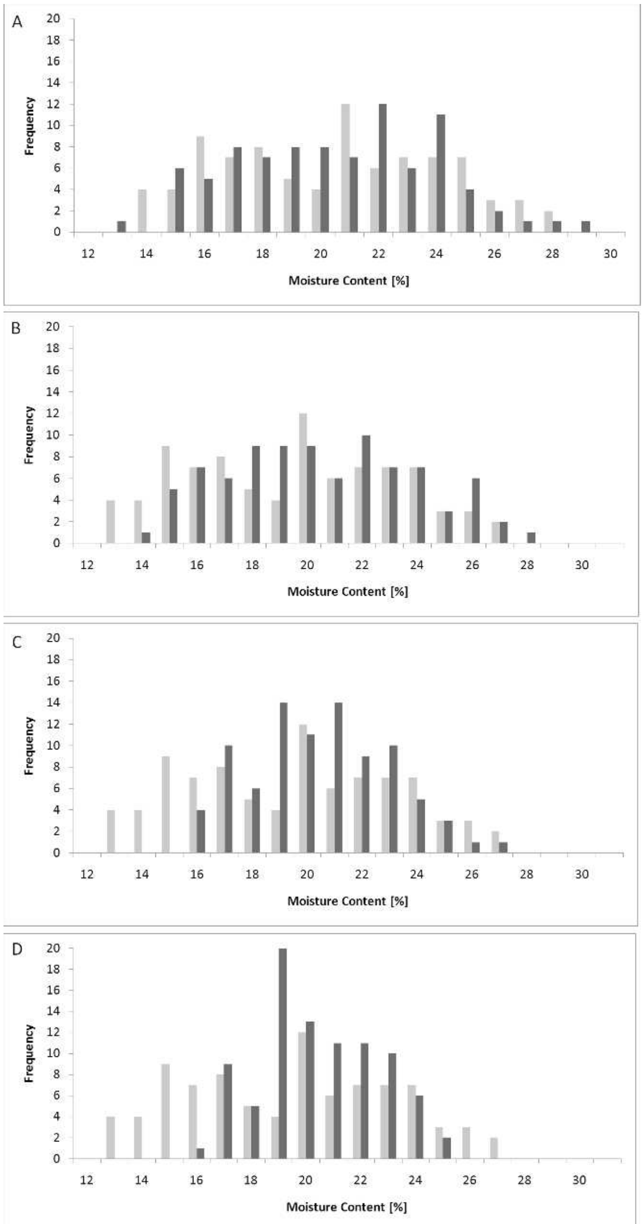

Figure 8.—Simulated final moisture content distributions for drying without and with presorting. Light gray bars = unsorted boards (mean MC = 20%, SD = 3.72%). Dark gray bars = boards presorted by (A) basic density (mean MC = 20%, SD = 3.45%); (B) initial moisture content (mean MC = 20%, SD = 3.42%); (C) initial mass (mean MC = 20%, SD = 2.49%); and (D) predicted drying times (mean MC = 20%, SD = 2.17%).

Initial moisture content is positively correlated to drying rate, while basic density, heartwood percentage, and growth ring angle are negatively correlated. Their impact on drying rate varies as the board dries to a lower moisture content. For low-temperature drying, basic density affects drying rate below 90 percent, heartwood percentage above 40 percent, and growth ring angle below 40 percent. Results indicated that initial moisture content had an effect at all moisture contents except 40 to 60 percent. For high-temperature drying, initial moisture content affected the drying rate at all moisture contents. The results indicate that sorting by basic density or initial moisture content could be used as the presorting criteria but that green density would be more effective. With the appropriate technology in a mill, the results demonstrate that sorting on multiple wood and board properties could reduce the final moisture content distribution even further.

Boards that dry at higher rates at a low temperature would also dry at higher rates at a high temperature, even though the mechanisms for drying differ above and below the boiling point. This means that different sorting criteria may not be necessary for different drying temperatures.

The drying time for a board can be predicted from wood properties. It is then possible to sort based on this expected drying time and greatly reduce the moisture content variability in dried hemlock lumber.

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