RELATIVE DRYING RATES OF SELECTED SPECIES WITHIN THE HEM-FIR GROUP

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A number of species are harvested, processed, and marketed together within the hem-fir species group under the Western Wood Products Association grading rules (western hemlock, pacific silver fir, white fir, grand fir, California red fir, and noble fir). The out-of-kiln moisture content (MC) of these species varies considerably, both from board-to-board and within boards. This is usually attributed to wet pockets in the wood and compression wood. It is not known which of the hem-fir species, if any, are prone to high or low out-of-kiln MCs since the true firs are virtually indistinguishable after the foliage has been removed.

Differential drying rates for species within other species groups are well known. As examples, in the fir-larch group, western larch ends up at a higher MC than Douglas-fir. In the spruce-pine-fir group, alpine fir will leave the kiln at the highest MC and white spruce the lowest.

In this work, boards of six hem-fir species were dried and the MC of each board was measured as a function of time to investigate whether any one species contributes significantly to final moisture content variation. Knowing the initial weight and drying characteristics for each board also allowed us to determine how effective either pre- or post-sorting would be in reducing final MC variation.

PROCEDURE

Western hemlock, mountain hemlock, grand fir, noble fir, and pacific silver fir trees at the 3500' level in the Willamette National Forest[1] were identified and marked for cutting. Mountain hemlock is not listed in the grading rules as a hem-fir species, but often gets mixed into the grade. Samples of foliage from each tree were collected and the species verified by the university dendrologist. The trees were then felled. Because of the likelihood of wet wood, it was not desirable to have the butt log included in the study. Therefore, a 33' log was left in the woods for commercial logging and 8'6" bolts were cut up to a 6" top.

The logs were sawn into 2"x4" lumber. The lumber was wrapped in plastic, and stored under sprinklers until needed. Cutting occurred in late November to take advantage of the cold weather, keeping the lumber fresh for the drying experiments which occurred within two months of felling. Species, tree, and log were tracked for each board.

[1]The authors gratefully acknowledge Frank Lumber Company, Mill City, OR for allowing trees to be cut within their sale boundaries and arranging for log scaling with the Forest Service.

The white fir was obtained from the Klamath Falls area[2] because it was not available from the same site as the other species. It was harvested from a homogeneous stand of white fir as is common practice in Southern Oregon and Northern California. Tree and log data were not available for each white fir board.

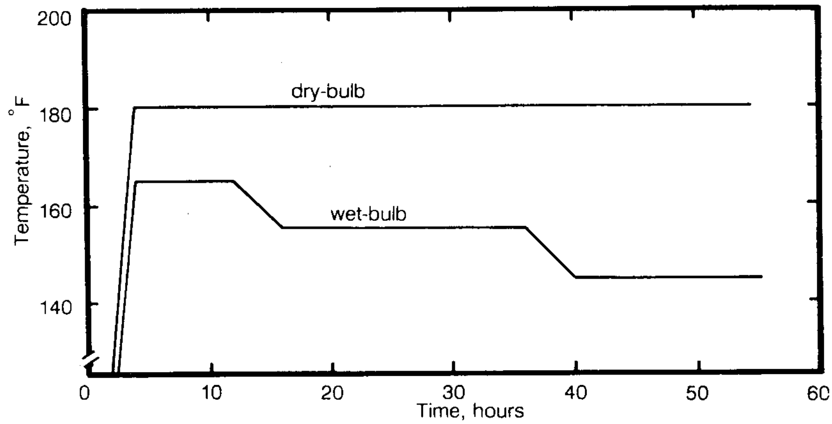

Figure 1

During drying, approximately 33 boards for a species were stacked 11 courses high, three boards per course on 3/4" stickers at a 2' spacing. Both ends of the boards were coated with an impermeable neoprene end coating. Two species were dried per charge, one at each end of a 16' lab kiln. The three boards in each course were separated by about a 1-foot space. This way no board received a leading edge effect for airflow from an adjacent board. The stack was only 3 boards wide to minimize the temperature drop across the load and give every board an equal treatment. The air velocity at the beginning of the each test was 700 ft/min and the temperature schedule in Figure 1 was used.

At selected time intervals (Table 1), a 10-inch piece was cut from the end of each board, the fresh end grain was recoated with neoprene, the kiln's end baffles were extended by 10 inches, and drying resumed. The interrupt to the drying process was approximately 35 minutes and was not counted in the drying time. Each 10-inch sample was immediately placed in a separate plastic bag to prevent further moisture change and allowed to cool.

A 3-inch sample was cut from the uncoated end (the end that had been furthest from the end of the board) of each 10-inch sample, weighed 1to the nearest 0.01g, ovendried at 220°F to a constant weight, and reweighed. The remainder of the sample was used for other experiments. The dry-basis MC for each sample was calculated at each sampling time. The dry specific gravity (SG) of each 3-inch

[2]The authors gratefully acknowledge Modoc Lumber Company, Klamath Falls, OR for obtaining, sawing, and delivering the white fir lumber.

Table 1. Sampling times and average moisture contents for each species.

Grand fir		Noble fir		Pacific Silver fir		White fir 1		White fir 2		Mountain hemlock		Western hemlock	
Time	MC	Time	MC	Time	MC	Time	MC	Time	MC	Time	MC	Time	MC
19.7	54.2	19.5	52.8	19.7	42.5	23.5	31.4	20.0	38.8	23.5	43.9	24.5	41.1
24.5	39.4	23.5	41.1	24.5	34.0	28.4	25.5	24.5	35.0	28.4	32.2	28.8	31.4
28.6	28.5	27.3	31.9	28.6	26.4	33.5	21.7	28.8	31.0	33.5	24.2	33.8	25.6
32.3	23.7	31.6	24.4	32.3	22.8	38.4	18.6	33.8	28.3	38.4	21.2	38.0	22.2
36.9	20.7	36.2	21.8	36.9	21.1	43.0	16.5	38.0	26.0	43.0	19.6	42.9	20.0
41.1	16.5	42.2	18.2	41.1	17.6	48.0	13.2	42.9	22.5	48.0	15.6	49.9	16.6
47.3	13.7	46.8	15.6	47.3	15.3	-	-	49.9	18.5	-	-	56.3	14.8

sample was determined by the water displacement[3] technique and an average specific gravity was calculated for each board.

The form of the data allowed a drying curve

$$M_t = e^{(C_1 * t + C_2)} \quad (1)$$

to be determined for each board where C_2 is the natural log of the initial MC and C_1 is an empirical constant determined by a least-squares fit. The drying curves are specific to the schedule used. The curves were used to reconstruct the drying behavior, interpolate between the data points, and predict MC as a function of time for each board. The fitting technique worked quite well with the lowest r^2-value equal to 0.87. The variation was due to high and low moisture values along the length of the board, not a failure or the curve to fit the shape of the data.

RESULTS AND DISCUSSION

Board Properties

Specific gravity varied significantly[4] between species. The average for each species and the Tukey groupings are shown in Table 2. The hemlocks tended to

Table 2. Experimentally-determined and published specific gravity by species. The letters represent Tukey groupings. Values associated with the same letter are not statistically different.

	Specific Gravity	
Species	Experimental	Published[1]
Mountain hemlock	0.52 A	0.45
Western hemlock	0.48 B	0.45
Pacific Silver fir	0.46 B	0.43
White fir	0.42 C	0.39
Noble fir	0.42 C	0.39
Grand fir	0.40 D	0.37

[1]Wood Handbook (USDA, 1987)

[3] Specific gravity is the sample weight minus the buoyant force of the submerged sample divided by the weight of the sample.

[4]The 95% confidence level was used for all statistical tests meaning that the probability of getting similar results from random data is 1 in 20.

have a higher SG than the true firs. The specific gravity of the experimental material for each species was 0.03 greater than that listed in the Wood Handbook (USDA, 1987) except for mountain hemlock which was 0.07 greater. The consistency of this difference indicates that the range of SG in the experiment is representative of the species group and the offset from the published values might be a measurement artifact. Within a species there were very few significant differences between trees and within a tree there were almost no cases in which SG varied by log.

The average initial MC by species is shown in Table 3. There was considerable variation between species; however, all of the values could be statistically separated into only two groups. It is difficult to compare our experimental to the sap/heart values from the Kiln Operator's Manual (Simpson, 1991) because of the variation in heart-sap mix in the experimental material. There were considerable differences in MC between trees within a species; however, differences of 20 to 50 percent MC were needed for statistical significance. MC differences between logs within a tree were expected and occurred because of the increasing proportion of sapwood higher in the tree.

Table 3. Experimentally-determined and published values for initial moisture content by species.

	Moisture Content		
Species	Experimental	Published[1]	
		Sup.	Heart
Noble fir	119.7 A	115	34
Mountain hemlock	109.7 A	-[2]	-[2]
Grand fir	105.6 A	136	91
Western hemlock	103.4 A	170	85
White fir	83.9 B	160	98
Pacific Silver fir	79.7 B	164	55

[1]Dry Kiln Operator's Manual (USDA, 1991)

[2]Not available

The specific gravity and initial MC data presented here should not be taken to represent species averages because the sample size and geographic representation are too limited to draw any general conclusions regarding species averages. This information was investigated and is presented because of its possible effect on drying.

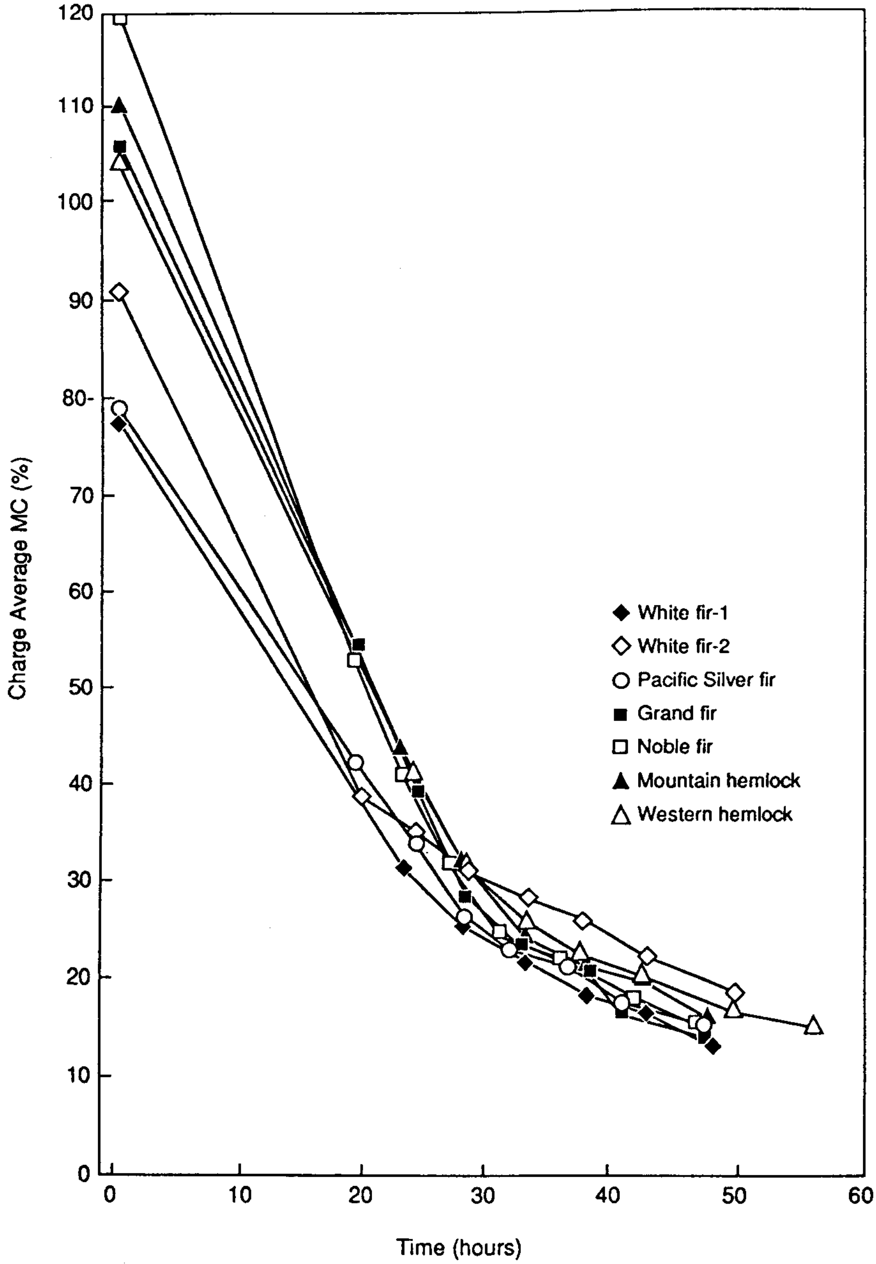

Figure 2. Drying curves. All MC-time data were averaged by species to obtain data points.

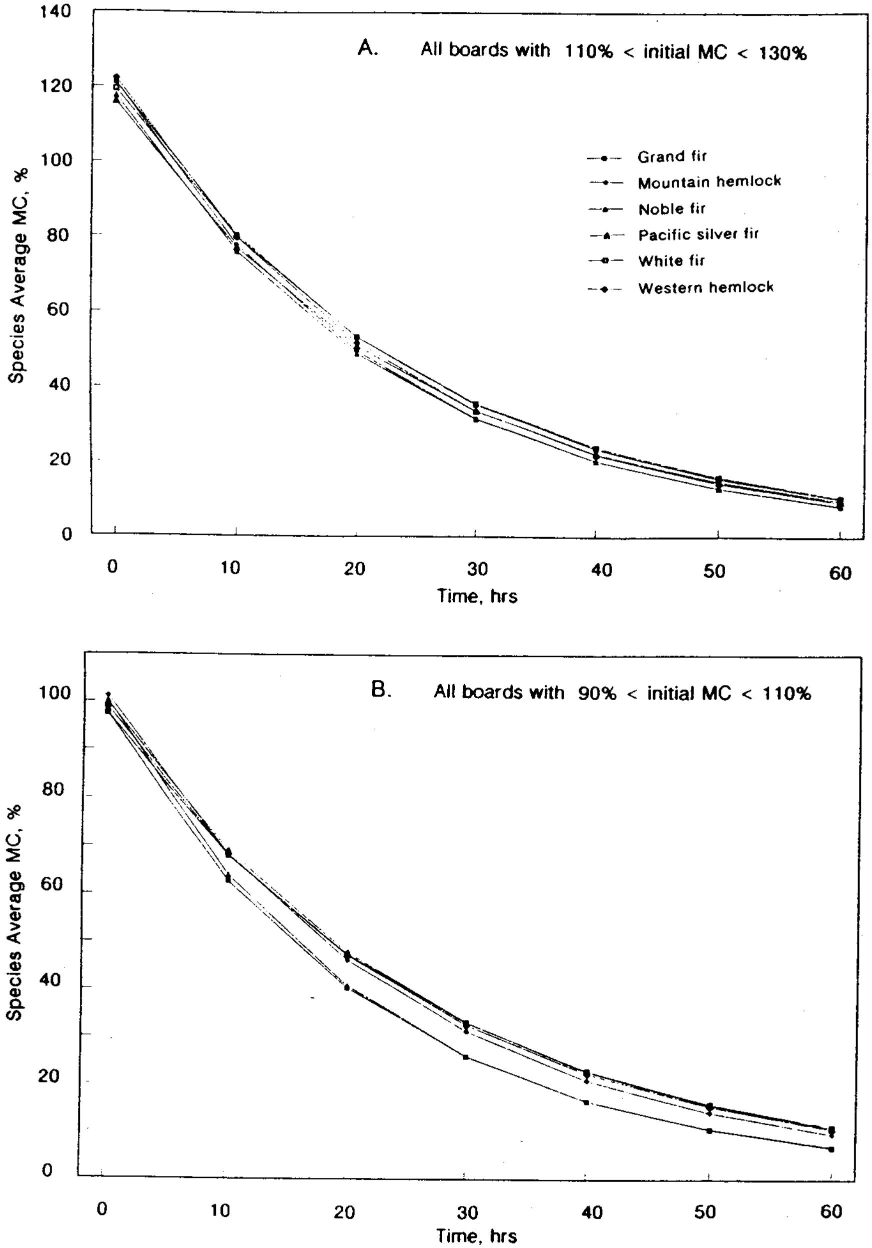

Figure 3. The average drying characteristics are similar for boards with similar initial MCs even when the boards are from different species.

Drying rates by species

Moisture contents for all boards on a species-averaged basis at each time point clearly showed a high initial drying rate for the species with a high initial MC (Fig. 2). As a result moisture variation decreased as time in the kiln increased. Despite tremendous variation in initial MC, the average final MC for each species tends to fall into a fairly narrow range.

Additional evidence that the species dry similarly can be seen in Figure 3 in which the drying curves for all of the boards with initial MCs of 90-110 and 110-130 are averaged and plotted by species. Similar plots were prepared for each 20 percent MC interval. The lack of any substantial differences in the drying curves suggest that there is no need to do a sort based on species when drying hem-fir.

Pre-sorting by Weight

Before concluding that sorting is not needed, however, it is useful to examine the moisture distribution on a board-by-board basis instead of using species averages. To do this, Equation 1 was used to simulate drying for individual boards. In one case, all of the boards were dried as one charge. In the second case, the boards were divided into light, medium, and heavy sorts and each dried as a separate charge. The schedule in Figure 1 was used (the drying curves are only valid for the schedule in Figure 1) and the drying time was varied so that 95 percent of the boards would have an MC less than 19 percent.

In the first case, t in equation 1 was set to 57.5 hours and MC_t determined for each board. The MC distribution in this case was quite wide while the mean MC was 10.5 percent (Fig. 4e). This indicates that considerable over drying was required to achieve the 95 percent distribution below 19 percent MC. A number of very slow drying boards in the charge tended to skew the distribution towards the right. If these boards could be sorted out, overdrying might be prevented on the rest of the charge.

In the second case, the undried boards were divided into three equal-sized sorts based on their green density (board weight divided by board volume). The average initial MCs of the light, medium, and heavy sorts were 66.1, 99.4, and 129.3 percent, respectively (Table 4). Drying in three separate kiln charges was simulated by setting t equal to 55, 65, and 47.5 hours. At these times, 95 percent of the pieces in each sort were under 19 percent MC, corresponding to 95 percent of the total production under 19 percent MC. The resulting MC distributions are shown in Figures 4a, 4b, and 4c.

Presorting reduced the total drying time by approximately 1 hour [3*57.5/3=57.5 versus (47.5+55+65)/3=55.8], probably not enough to justify sorting just to decrease drying time. The heavy sort took less time to dry than either the light or medium sorts. At first this looks like an error; however the MC distribution (Figure 4d) helps to explain the results. The average MC for this sort was 15.6% and the distribution was narrow. None of the slow-drying material was present in this sort; hence, it was not necessary to overdry most of the charge to get 95 percent of the pieces under 19 percent MC. Most likely, all of the boards in this sort were heavy sapwood boards. Sapwood loses its moisture quickly and the lack of wet pockets of heartwood eliminates the problem of severe overdrying.

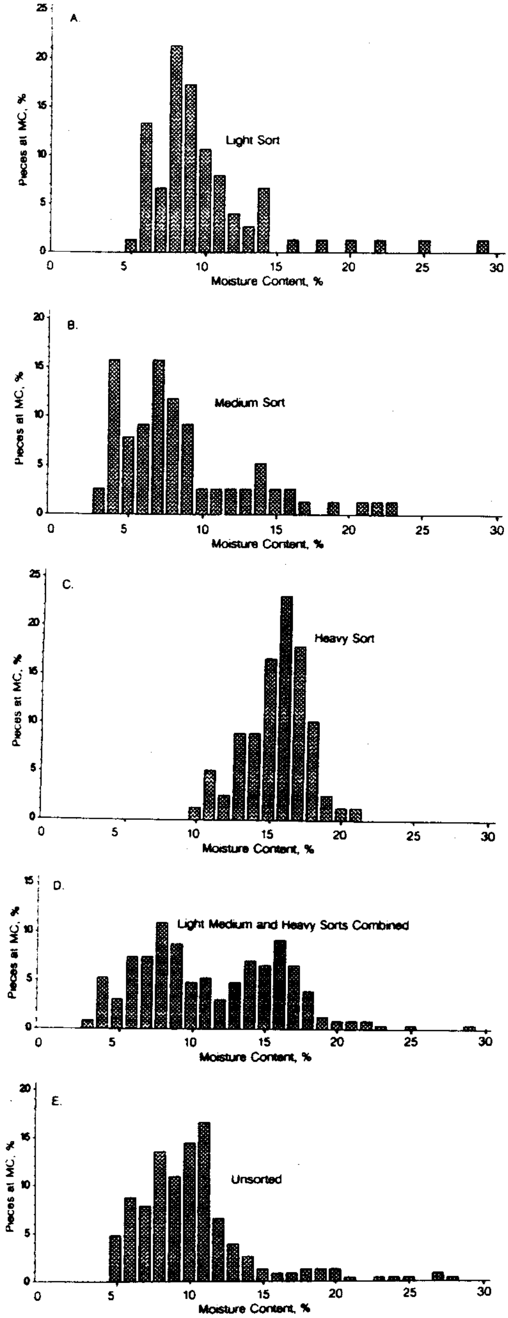

Figure 4. Effect of pre-sorting by weight on the final MC distribution. Parts A, B, and C show the MC distribution for the light, medium, and heavy sorts. These are combined in part D. Part E shows the MC distribution for the unsorted charge.

Table 4. Comparison of average boards in sorted and unsorted charges

	Sorted			Unsorted
	Light	Medium	Heavy	
N, -				229
MC_o, %	66.1	99.4	129.3	98.3
MC_f, %	9.9	8.9	15.6	10.5
Time, hr	55	65	47.5	57.5
Rate, %/hr	1.0	1.4	2.4	1.5
SG, -	0.43	0.45	0.46	0.45
HtCap, $^{BTU}/ft^3\,^{\circ}F$	24.7	35.3	44.6	34.9

The sapwood boards in the unsorted charge would have been overdried and suffered the degrade associated with overdrying. This clearer material represents the highest grade and highest dollar value boards. Overall the sorted charges average 11.5% MC, only 1% higher than the unsorted charge, while moisture distribution was not significantly reduced.

It's common in commercial operations for the heavy sort to take longer to dry than the light sort. Since the opposite occurred here, some discussion is needed. The heavy sort contains more water per cubic foot and the coil capacity of the kiln might not be great enough to heat the charge quickly and maintain the drying rate. This problem did not exist in the experimental set-up. Also, the high drying rate increases the temperature drop across the load, another problem that did not exist in the experimental set-up. The average rate of moisture content change in the heavy sort was 2.4 percent per hour compared to 1.0 and 1.4 in the light and medium sorts. Thus the kiln must supply approximately twice as much energy per unit of time. If a commercial kiln is unable to do this and maintain the desired dry- and wet-bulb temperatures, the drying might indeed take longer.

Both, the light and medium sorts contained boards that dried very slowly. To actually lower the MC enough to have less than 5 percent wet pieces, most of the charge must be overdried, as in the unsorted charge. This is evident in Figures 4a and 4b by distributions that are skewed way to the right. Interestingly these boards were not in the heavy sort. Based on these results, pre-sorting would achieve only a marginal success at narrowing the final moisture distribution. Comparisons between green density and final MC on a board-by-board basis for an unsorted charge, show no relationship between the weight of a board going into the kiln and its MC coming out (Fig. 5).

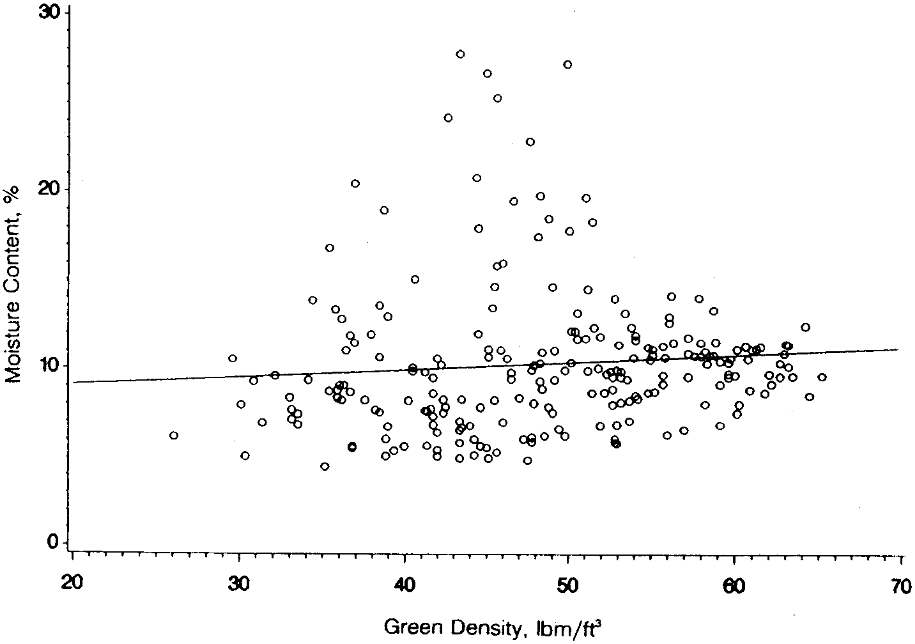

Figure 5. Moisture content at 57.5 hours as a function of the green density of the board.

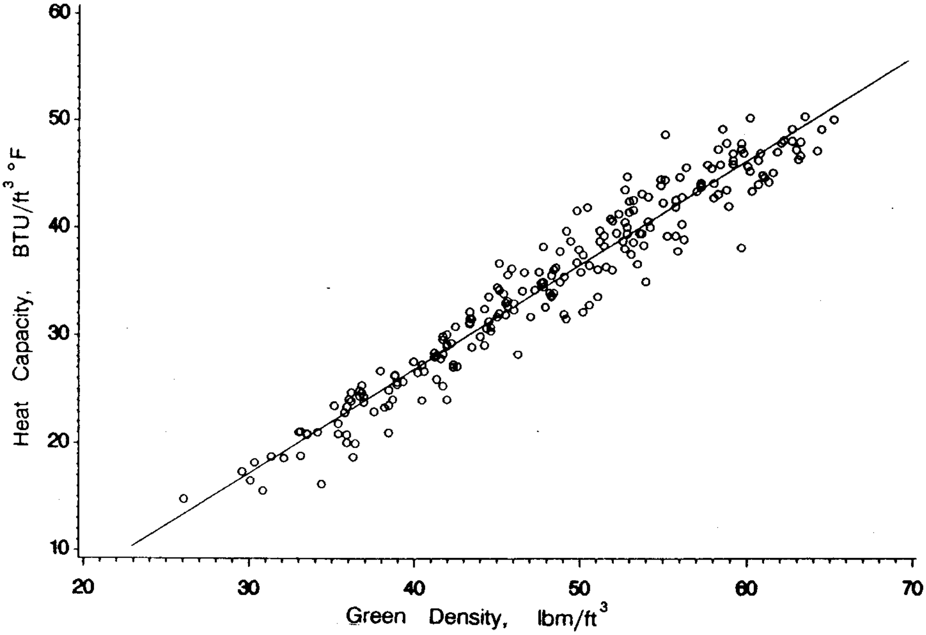

Figure 6. Volumetric heat capacity as a function of green density.

Sorting by Specific Heat

Some sorting systems currently available sort by comparing the temperature of the board before and after a fixed amount of energy is applied to the surface. Although heat capacity, thermal conductivity, surface emissivity, surface roughness, and convective heat transfer coefficient can affect this method, heat capacity is probably the dominant effect. The potential for sorting based on heat capacity was evaluated by calculating the heat capacity on a volumetric basis for each board according to

$$C = (0.27 + MC/100) *SG*62.4 \tag{2}$$

where C has units of $BTU/ft^3 {}^\circ F$. Since heat capacity is a function of green density (Figure 6), sorting by either method would appear to achieve similar results.

Post-sorting

As an alternative to pre-sorting, post-sorting after the wood comes out of the kiln but before the planer could permit redrying the wet pieces. This practice is common in plywood manufacturing to prevent overdrying, increase dryer capacity, and reduce costs. Bassett (1973) discussed the practice for lumber but it has never been implemented except to remove a very small fraction of wet pieces from production. The goal has been to minimize this fraction, not optimize it.
To simulate a redry operation it was assumed that no pre-sorting was done and that a post-sort dropped out all pieces with a MC greater than 22% at a low redry percentage reducing to 19.25% as the redry percentage increases. The percentage was selected to allow 3 to 5 percent wet pieces in the primary production. The basis for the calculations is one charge in the primary dryer. For simplicity, the percent wets in the redry was limited to less than 5%, although in practice, it would be desirable to redry some of the production from the secondary dryer, particularly as the redry rate increases.

The experimentally-determined drying curve for each board (Equation 1) was used to simulate primary and secondary drying. It was assumed each board in the secondary dryer continued to dry along the same drying curve. That is,

$$M_t = e^{(C_1*(t'+t'')+C_2)} \tag{3}$$

where t' is the time in the primary dryer and t" is the time in the secondary dryer. Drying was continued in the secondary dryer until more than 95% of the pieces were under 19% MC (i.e. no redry from secondary dryer).

The results of this analysis are shown in Table 5 for several redry percentages. The redry percentage is the percent of the pieces from the primary dryer that are greater than the cut-off MC. Also shown are the drying times and the percent of the pieces that were greater than 19% but allowed to remain in the production (not redried). The average moisture content is shown for the production from each dryer (not counting redry) and for the overall production. If the redry percentage was 20%, it would take 5 primary dryer charges to

Table 5. Summary of post-sorting and redry calculations

% Redry	Cut-off MC	Primary Dryer			Secondary Dryer			Overall	
		Time	MC	% Wet	Time	MC	% Wet	Time	MC
0	-	57.5	10.3	-	-	-	-	57.5	10.3
3.1	22	55.0	10.8	4.3	21	16.3	4.6	55.6	11.0
4.8	21	52.0	11.9	3.1	22.5	15.8	4.8	53.0	12.1
9.2	20	48.0	13.5	3.0	25	13.4	4.5	50.3	13.5
11.7	19.9	46.5	14.2	3.9	26.5	12.5	4.2	49.6	13.9
13.1	19.9	46.0	14.4	4.1	26.7	12.1	3.5	49.5	14.1
15.3	19.8	45.5	14.5	3.8	27.5	11.2	2.8	49.7	14.0
17.5	19.6	45.0	14.7	4.2	27.5	10.8	4.9	49.8	14.0
22.2	19.5	44.0	15.0	5.0	27.0	10.3	5.0	50.0	13.9
34.9	19.3	43.0	14.9	4.0	26.0	9.6	4.8	52.0	13.0

accumulate enough material for one charge in the secondary dryer. Thus 20% of the time in the secondary dryer needs to be added to the time in the primary dryer to get the overall kiln time per charge.

$$t = t' + (Redry\%/100)*t'' \tag{4}$$

The overall drying time and average MC from Table 4 are plotted in Figure 7. Total production is maximized at approximately 13.1% redry, although the curve is actually fairly flat to 20% redry. Thus, a mill short on kiln capacity could use redry to reduce the total drying time for a charge of lumber by 10 to 15%.

Perhaps more important than production is the overall average moisture content. At 13.1% redry, the average MC of the lumber leaving the mill is approximately 4% MC higher than with no redry and the MC distribution is much tighter (Figure 8). The higher overall moisture content will allow the lumber to pass through the planner with less degrade and possibly at a higher speed. The tighter MC distribution means that the customer will receive fewer overdried pieces. The wets that the customer does receive are very close to 19%. In fact, it quite likely that all of the pieces would be under 19% after shipping.

As the redry percentage is increased, the cutoff moisture content becomes very critical. Thus the moisture meter would have to be used consistently to monitor and calibrated often.

As the redry rate increases, the time in the primary dryer to maintain a given redry rate becomes critical. An hour either way makes a large difference in the redry percentage. This seems like a significant problem; however, an exact redry rate does not appear critical to optimize production since the curves in Figure 7 flatten out. It must be remembered, however, that as the redry rate increases, the variable cost associated with handling increases. For a given mill it would be possible to reproduce Figure 8 with cost on the ordinate instead of MC and select the redry rate which minimizes cost.

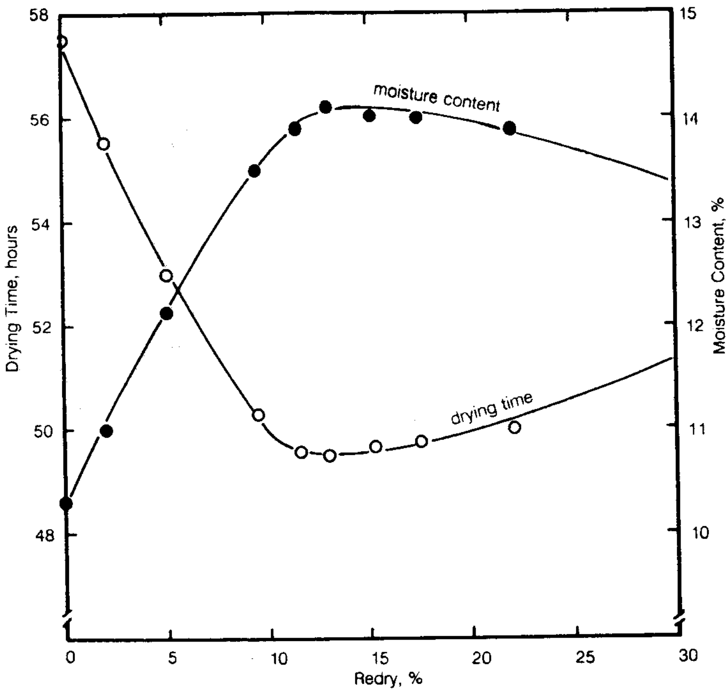

Figure 7. Average MC of production and total kiln time as a functional of redry percentage.

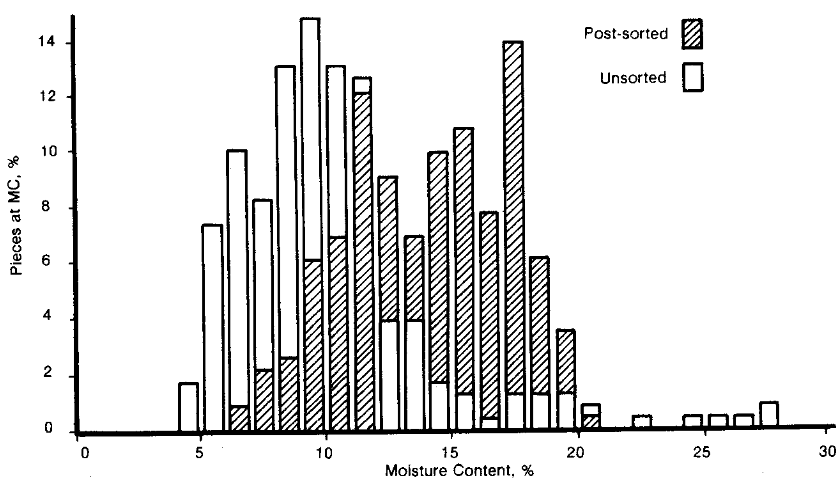

Figure 8. MC distributions for post-sorting with a redry rate of 13.1% and for no sorting. In each case, 95% of the pieces are less than 19% MC.

CONCLUSIONS

Species sorting within the hem-fir group has little impact on drying efficiency. Presorting based on weight or heat capacity would have a marginal effect on overall drying time because the rate at which a board dries has at least as much effect on its final MC as its initial MC. Green sorts, however, might be effective for grade recovery because the sapwood boards would not be overdried.

Post-sorting and redrying the wet pieces might increase dryer capacity by 10 to 15%, tighten the final MC distribution, and increase the final average MC. This process should also lead to a reduction in degrade, overdried pieces, and wet pieces.

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