Defects and Grading after Kiln Drying Hardwood Lumber Sawn from Small-diameter Logs

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Close inspection of black cherry (*Prunus serotina*), sugar maple (*Acer saccharum*), and northern red oak (*Quercus rubra*) lumber, before and after kiln drying, revealed the factors that can affect the quality of kiln-dried lumber from small-diameter logs. Species-specific kiln drying schedules, with temperature and humidity modifications formulated by a kiln drying expert, were employed in this study to determine whether alternate drying protocols could improve the drying outcomes. Comparing lumber grades of individual boards before and after drying indicated that overall grade loss in the kiln was common but was affected by both species and the applied drying schedule. Most lumber defects were attributed to stresses that occurred during the drying process and were more prevalent in the post-drying inspection, with bow defects being the exception. The modified kiln schedules improved the drying defect outcomes for the black cherry and red oak compared with the conventional schedules for these species. For the sugar maple, the schedule-based improvement was less consistent. For the black cherry and red oak, the percentage of boards whose grade decreased using conventional kiln protocols was approximately 10% lower than that of the lumber that was dried using the modified kiln protocols. Sugar maple had a smaller change of 7%.

Keywords: Small-diameter hardwoods; Lumber recovery; Lumber grade; Dry kiln schedule; Drying defects

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INTRODUCTION

Lumber used for high-value appearance grade products must be dried to a moisture content that suits the interior environment where the final product will be used; in North America this usually means it must be kiln-dried to a moisture content of 8% to 10%. The stresses that arise during the drying process frequently lead to defects in the lumber that reduce its grade, value, and utility. When assessing the potential for using smaller diameter hardwood logs for the manufacturing of hardwood lumber, the quality and value of the kiln-dried lumber is the ultimate deciding factor.

A few studies on the lumber recovery potential of small-diameter hardwood logs (generally defined as logs with a diameter less than 11 at the small end) have evaluated the lumber volume and grade yields for "green" lumber (before drying) (Emanuel 1983; Hamner *et al.* 2006; Perkins *et al.* 2008). Green lumber recovery rates may be of interest to lower and mid-value lumber markets, such as pallet, container, and fencing manufacturers; however, the current green recovery information is not sufficient for lumber buyers who manufacture appearance-grade products that require kiln-dried lumber.

Scholl *et al.* (2008) studied the lumber grade yields and other quality characteristics of black cherry (*Prunus serotina*) lumber sawn from small-diameter logs and dried in a kiln. Scholl *et al.* (2008) identified the defects and grade/value losses that arose during the kiln drying process with both a conventional black cherry kiln schedule and two alternate schedules. Scholl (2006) evaluated the recoveries from small-diameter red oak (*Quercus rubra*), sugar maple (*Acer saccharum*), and black cherry logs, and many utilization characteristics were measured before and after the kiln drying process. Wiedenbeck *et al.* (2017) highlighted the overall lumber volume and value recovery results obtained by Scholl (2006) for all three species with both the green and kiln-dried moisture content conditions. After kiln drying, the distribution of the lumber grades was lower for all three species when compared with the lumber grades before it was dried (approximately 25% of the boards dropped to a lower grade value) (Wiedenbeck *et al.* 2017). *Eucalyptus globulus* harvested from 10-year-old plantations yielded a high proportion of low-grade sawn boards, but changes in grade after kiln drying were not examined (Yang *et al.* 2002). Changes in warpage amounts were compared before and after drying with bow-type distortions reduced in the kiln drying process while crook (spring)-type distortion results varied (Yang *et al.* 2002).

The principal goal of the research by Scholl (2006) was to develop information on the quality and value of the lumber produced from small-diameter hardwood logs of three important commercial species in the U.S. and many global markets, namely red oak, hard maple, and black cherry. Not only did that research produce original insights into basic lumber recovery from small-diameter logs after kiln drying (Wiedenbeck *et al.* 2017), it also explored the effects of different dry kiln temperatures and relative humidity schedules on the quality and value outcomes for each species.

The objective of this research was to discover whether newly devised, alternate dry kiln schedules for drying lumber recovered from small-diameter hardwood logs result in similar or different levels of drying caused defects as compared to results obtained when conventional dry kiln schedules are used in drying black cherry, sugar maple, and red oak.

EXPERIMENTAL

Log Samples

The log samples were obtained from small-diameter trees harvested in northern and central Pennsylvania. The tree selection was neither random nor deliberate. Logs were provided by cooperating sawmills and were delivered to the collection/processing site over a period of several weeks. All of the stems delivered to the study team were included in the sample. The stems had various lengths when received. They were then bucked into lengths of 8 ft 4 in, numbered for tracking purposes, and end-sealed. One or two 8-ft logs were obtained from each stem. The overall sample consisted of 159 logs from 130 black cherry trees, 132 logs from 113 sugar maple trees, and 87 logs from 70 red oak trees. The small-end diameters inside of the bark (scaling diameter) of the study logs were less than or equal to 12 in. The proportion of logs with diameters of less than 10 in was the highest for the black cherry (63%) and lower for the sugar maple and red oak (31% and 40%, respectively).

Log Breakdown and Kiln Drying

The logs were sawn on a portable sawmill (Timber Harvester, Waterloo, NY) at Penn State University (University Park, USA) by a single experienced sawmill operator. The opening face of each log (*i.e.*, the placement of the first sawline) was the log face opposite from the highest quality face on the log. Each sawn board was numbered so that it could be tracked throughout the study. Within 24 h of being sawn, each board was evaluated for the full set of stress-induced defects, which are often exacerbated by the lumber drying process. These defects include end checks, surface checks, shakes, bows, twists, crooks, and cups. The boards were also graded using the grade rules of the National Hardwood Lumber Association (NHLA 2014).

The lumber was hand stacked into packs that were 8 ft (length) × 4 ft (width) × 4.5 ft (height). The kiln used was a steam-heated kiln (Custom Built in 1965, with Irvington-Moore and Allen-Bradley monitoring and control systems) with a capacity of 1500 board feet (BF). A conventional and two experimental kiln schedules were used in this project. When the logs were sawn into lumber, it was apparent that the red oak sample had a bacterial infection, which is not uncommon. Bacterially infected red oak must be dried more carefully to prevent deep surface checks, honeycomb, and ring failure. A dry kiln schedule for BI red oak was used according to the *Dry Kiln Operator's Manual* (Simpson 2001) and was incorporated into this study as the conventional schedule for the red oak.

The first modified kiln (MOD-1) schedule used for each species lowered the final dry- and wet-bulb setting, while the second modified (MOD-2) schedule decreased both the initial and final dry- and wet-bulb settings. It was hypothesized that the lower final dry- and wet-bulb temperatures slowed the rate of warping in the lumber during the final stages of drying because of the premature release of drying stresses. It was proposed that lumber dried using the lower initial dry- and wet-bulb setting would increase the tension set, and therefore the lumber should better resist the forces that cause warping in the later stages of drying. In addition to the changes made to the initial and final dry- and wet-bulb temperatures and the number of steps applied in the modified kiln charges, the conditioning times for the modified schedules were increased as well. Scholl (2006) details the applied drying schedules. Kiln samples were used to check the moisture content throughout each kiln charge, with a target final moisture content of 8%.

In total, 10 kiln charges using lumber sawn from the small-diameter logs were processed and analyzed. The available number of black cherry and sugar maple logs produced a sufficient volume of lumber to allow for the conventional schedules of each species to be applied to two kiln charges. Because of the BI red oak logs, only two red oak drying treatments (one kiln charge each) were performed. Details on the drying procedures are further elaborated on in Table 1.

Lumber Defect Status Post-kiln Drying

When the kiln drying schedules were completed, the lumber was immediately removed from the kiln and reexamined. The kiln-dried lumber grade was determined, and the presence and extent of stress-caused lumber defects were identified and tallied. The board surface measure used to calculate the green lumber grade was used to determine the kiln-dried grade. This standardization allowed for the effects of the drying defects on the lumber grade to be distinguished from grade changes in the board surface measure caused by shrinkage. Next, each of the original cuttings, which had been drawn on the board surface prior to drying, were examined for defects and dimensional changes that could affect the lumber grade. Finally, all four types of warping were carefully remeasured using the accepted procedures detailed in Scholl *et al.* (2008).

Table 1. Overview of Dry Kiln Treatments Applied for Drying Lumber Sawn from Small-diameter Logs

Species	Schedule	Initial Dry-bulb (°F: °C)	Final Dry-bulb (°F: °C)	Initial Wet-bulb (°F: °C)	Final Wet-bulb[a] (°F: °C)	No. of Steps[b]	Time in Kiln (h)	No. of Boards	Volume of Boards (BF)	No. of Parent Logs[c]
Black Cherry	Conventional (T8-B4)[d]	130: 54	180: 82	123: 51	130: 54	8	91	497	1825	77
	Mod-1	130: 54	160: 71	123: 51	110: 43	8	117	254	927	40
	Mod-2	110: 43	160: 71	103: 39	110: 43	9	110	242	873	41
Sugar Maple	Conventional (T8-C3)[d]	130: 54	180: 82	125: 52	130: 54	9	119	319	1216	35
	Mod-1	130: 54	160: 71	125: 52	110: 43	9	72	297	1234	47
	Mod-2	110: 43	160: 71	105: 41	110: 43	9	76	325	1278	49
Red Oak	Conventional (BI)[e]	105: 41	180: 82	102: 39	130: 54	12	470	347	1319	47
	Mod-1	100: 38	160: 71	97: 36	110: 43	13	614	312	1274	40

[a] before the equilibration and conditioning stages; [b] refers to changes in the dry kiln temperature and humidity settings during a particular kiln drying schedule; [c] No. of parent logs = the number of logs that yielded lumber in the kiln charges (batch); all of the lumber from a log was dried in the same charge; [d] *Dry Kiln Operator's Manual* (Simpson 2001); [e] BI schedule from the *Dry Kiln Operator's Manual* (Simpson 2001).

Statistical Analysis

Closer inspection of how the dry kiln schedule modifications impacted specific lumber quality attributes was done using a binary logistic regression with the schedule as the predictor variable and the presence of a drying defect as the response variable. For this analysis, the sample was comprised of all of the red oak (n = 659) and black cherry boards (n = 1005) and only 65% of the sugar maple boards (n = 595). The sugar maple boards sawn from the lowest quality logs (Forest Service grade F4; Rast *et al.* 1973) were unevenly distributed among the dry kiln treatments because the log batches arrived at different points in time. To overcome this problem, the boards from this group of logs were excluded from the analysis.

Logistic regression allows for a discrete outcome from a set of variables, which may be continuous, discrete, or mixed. In binary logistic regression there are only two values: 1, which indicates the board has a defect, and 0, which indicates a defect was not found on the board. The most important piece of information provided from a binary logistic regression is the odds ratio (OR). An OR is the increase (or decrease, if the value is less than 1) in the odds that a defect will occur in a treatment when compared with the control. This statistic allowed for the comparison of drying degradation results obtained with the conventional kiln schedules for each species (control schedule) with those from the modified kiln schedules. The OR provided information on whether a treatment (in this case a modified kiln schedule) increased the risk of an outcome of interest, as well as a rough estimate of the magnitude of the introduced risk compared with the baseline levels.

The ORs were calculated using the following rules. First, for end checks, surface checks, and shakes, the boards that contained these defect types before being kiln dried were discarded from the analysis. The boards for which the green board did not contain these defects, but the kiln-dried board did were assigned a value of 1. Boards that did not develop these defects were assigned a value of 0. When analyzing the principal causes for lumber grade reductions after drying, a value of 1 was assigned to any board that decreased in grade because of the cited cause (surface checks, pith-related surface checking, or shrinkage in width); otherwise, a value of 0 was assigned. After analyzing the wood before and after kiln drying for the presence (or absence) of warp-type defects, the boards that did not have cups, crooks, bows, or twists before kiln drying, but exhibited the specific warp defect after drying were assigned a value of 1 for warp degradation because of kiln drying. However, a second set of ORs was also calculated for the four warp defects. This alternate analysis was conducted because warping does not always decrease the quality of the wood after kiln drying, but can in some instances, improve it (for example, a green board with bow distortion becomes less distorted after drying). The OR tests for improvements in the cup, crook, bow, and twist defects assessed only those boards that were determined to have a warp defect before drying to determine if they were still warped in the post-drying quality inspection.

While the ORs derived from logistic regression provided insights about the likely changes in the frequency of the different types of defects after drying under various drying schedules (temperature and humidity regimes), they did not address the lumber grade changes. This was accomplished by ranking the lumber grades (NHLA 2014), where the best grade was ranked as 1 (FAS-1F), the next best grade was ranked as 2, *etc.*, with below grade boards ranked as 9. The lumber grades assigned after drying (post-drying grade) were compared with the grades assigned before drying (pre-drying grade), and the integer representations of these grades were used to derive the variable *GradeChange*. Thus, the boards with no change in grade had a *GradeChange* of 0, the boards that fell into the next lower grade category had a *GradeChange* of 1, *etc*.

A generalized linear mixed model (GLMM) employing a negative binomial distribution with the log link function was used to examine the response variable *GradeChange* for each species given the classification variables drying schedule, log, boards (nested within log), and pre-drying lumber grade, which is shown as Eq. 1 below.

$$GradeChange = schedule/dist = negbin\ link = log \qquad (1)$$

The least squares means were evaluated using the Tukey adjustment. The residuals for the four classification variables were examined using a linear mixed model, which indicated that the homogeneity of the variance assumption was met for residuals in the model. The significance level for all of the tests was an α of 0.05.

This same GLMM model was run a second time with a reduced data set, which only contained the lumber graded as No. 2AC or better (grade ranks 1 through 5) before being dried to determine if the results of the higher grade/value lumber paralleled those derived from the test that included all of the lumber grades.

RESULTS AND DISCUSSION

Lumber Defect Status Post-kiln Drying

After drying, the incidence rate of defects typically associated with drying stresses increased, as was expected. There were two notable exceptions. For the black cherry, the percentage of boards with end checks decreased slightly, and for all three species, the incidence of bowing decreased after drying, which is shown in Fig. 1. For all of the kiln treatments and species, the incidences of fiber/wood separation-type defects after drying compared with before drying increased for end checks (6%), surface checks (20%), and shakes (separation between annual growth rings; 5%). The overall changes in the occurrence of warp-type defects after kiln drying were an increase in twists (70%), decrease in bows (34%), increase in cups (23%), and increase in crooks (21%). These post-drying defect occurrence rates were high, particularly the rates of twists, cups, and crooks. The tendency of drying-related stresses to occur in boards sawn from small-diameter logs was expected to make drying these boards without incurring warp defects difficult. The curvature of the growth rings in these boards leads to differences in the shrinkage rates across and along the grain, as a result of the radial and tangential grain orientations being highly variable throughout the boards.

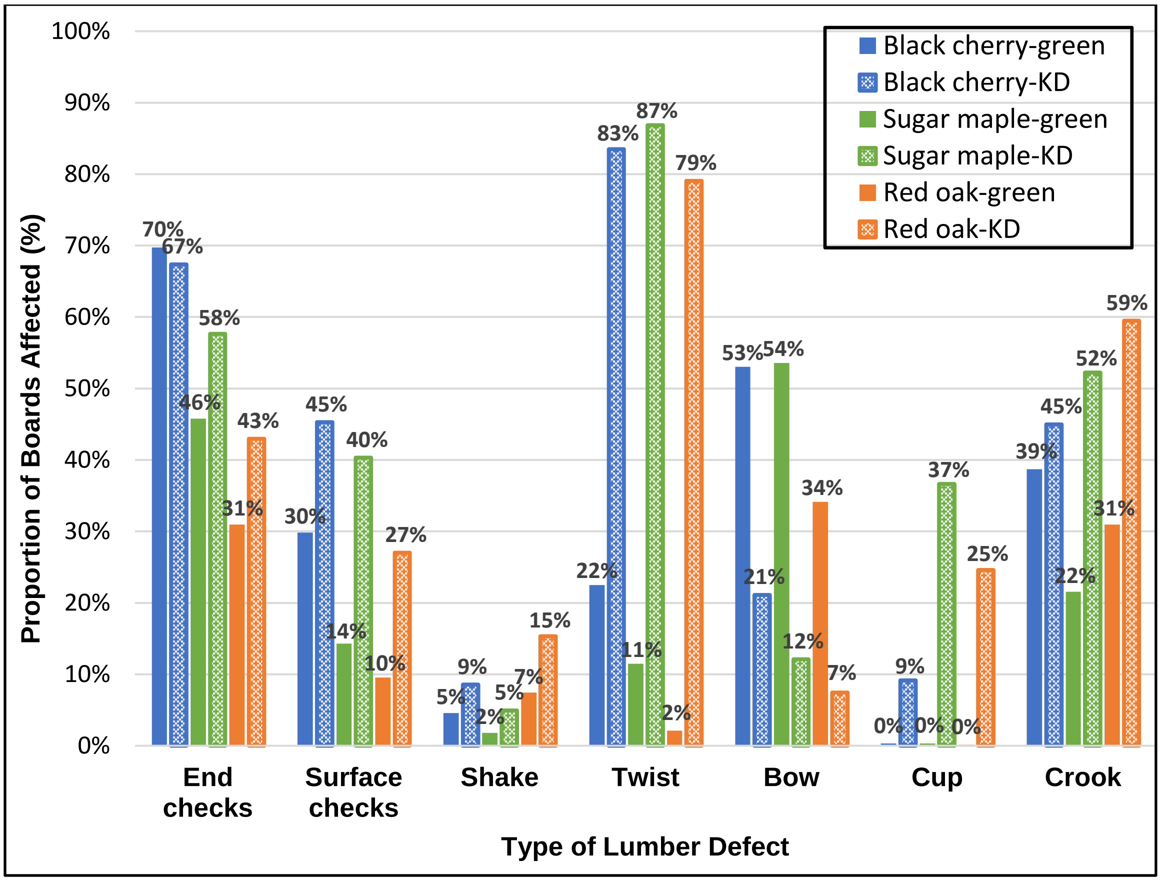

Fig. 1. Percentage of boards sawn from small-diameter logs containing seven types of drying-related defects before and after kiln drying

The defect occurrence rates measured after kiln drying for the three species and three dry kiln treatments are visually depicted in Figs. 2 (wood separation-type defects) and 3 (warp-type defects). The figures give an indication of how the different dry kiln temperatures and humidity protocols affected the defect rates. The increase or decrease in the percentage of boards exhibiting defects after kiln drying compared with before drying was portrayed. There were two main differences among the dry kiln treatments that were most evident upon inspection of the figures. First, for the black cherry and red oak, the cumulative category "all split defects" was distinctly lower for the Mod-1 and Mod-2 kiln treatments than it was for the conventional treatment (Fig. 2). Second, for the black cherry and red oak, the cumulative category "all warp defects" was lower for the Mod-1 and Mod-2 kiln treatments, but for sugar maple, the alternative kiln treatments (schedules) appeared to increase the occurrence of the dry lumber having twists, bows, cups and crooks when compared with the conventional dry kiln treatment (Fig. 3).

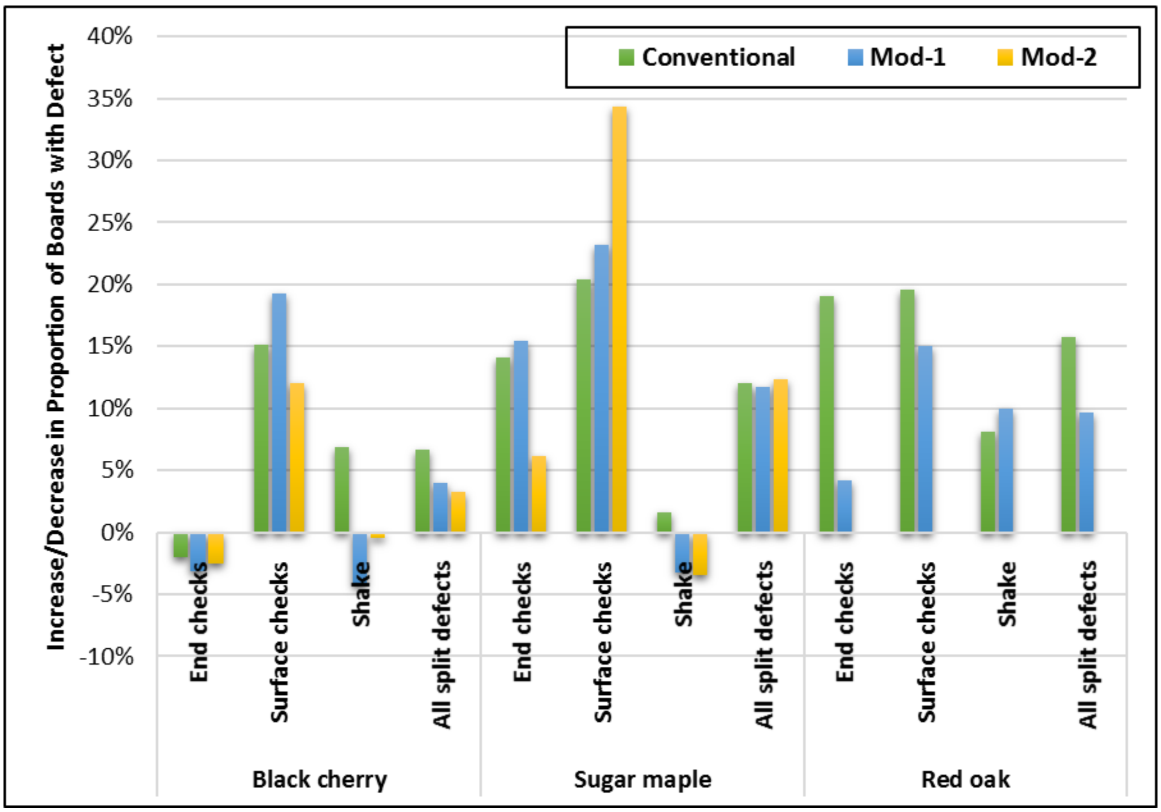

Fig. 2. Change in the wood separation-type defect occurrence rate after kiln drying

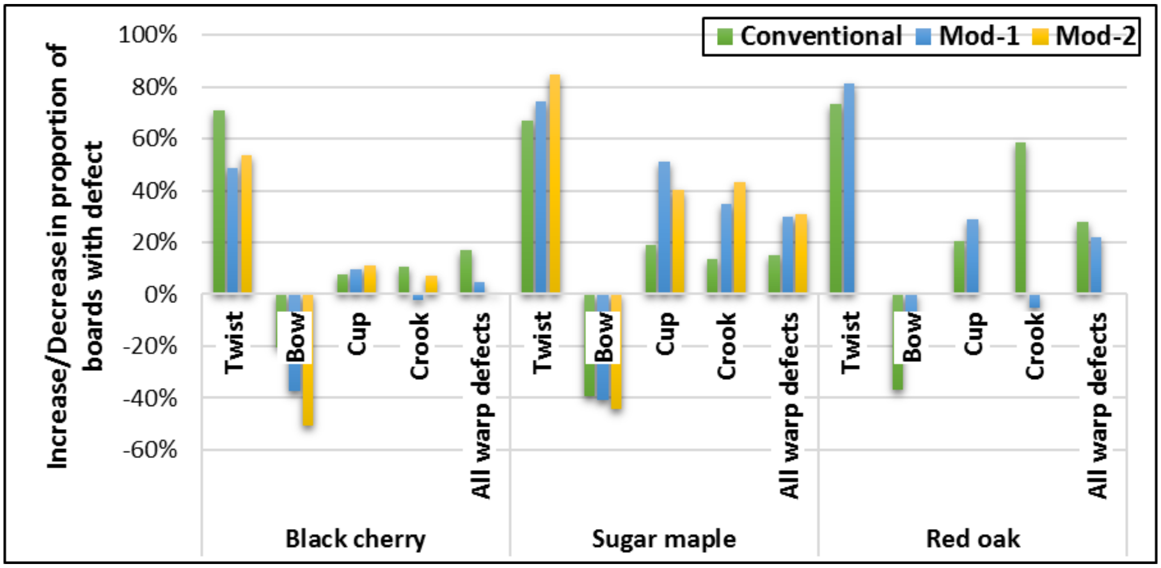

Fig. 3. Change in the warp-type defect occurrence rate after kiln drying

The statistical examination of these results using the ORs developed through logistic regression provided a comparison for the occurrence rates of drying-related defect types in the modified drying treatments with those of the conventional treatment.

For the black cherry, both of the modified schedules led to a statistically significant reduction in the shake (Table 2, OR < 1) and bow defects (Table 3, OR < 1). Additionally, Mod-1 reduced the odds of crook defects occurring during drying (Table 3).

Table 2. Lumber Drying Defect ORs for Lumber Dried with the Modified Kiln Schedules Compared with the Conventional Schedules for Each Species

Species	Black Cherry		Sugar Maple		Red Oak
Kiln Schedule	Mod1	Mod2	Mod1	Mod2	Mod1
Defect Present on Board					
End Check	2.00	1.60	**2.68**	**2.52**	0.65
Surface Check	1.13	0.71	1.38	**3.23**	0.91
Shake	**0.30**	**0.39**	0.52	0.50	1.46
Defect Causing Grade Reduction					
Surface Check	0.95	0.66	1.2	1.84	1.34
Surface Check with Pith	0.62	0.65	1.73	0.66	0.48
Shrinkage (Width)	0.66	0.87	**0.62**	**0.62**	0.82

Defects with significantly different odds of being present in the kiln charges compared with the control charge are shown in **bold red font**

Table 3. Lumber Drying ORs for Warp-type Defects Dried with the Modified Kiln Schedules Compared with the Conventional Schedules for Each Species

	Black Cherry				Sugar Maple				Red Oak	
	Mod-1		Mod-2		Mod-1		Mod-2		Mod-1	
Warp Defect	Worse	Better	Worse	Better	Worse	Better	Worse	Better	Worse	Better
Twist	N.S.	N.S.	N.S.	N.S.	**2.28**	N.S.	**5.75**	N.S.	**0.64**	N.S.
Bow	**0.28**	N.S.	**0.33**	**2.81**	N.S.	**1.79**	N.S.	**3.82**	N.S.	N.S.
Cup	N.S.	--	N.S.	--	**5.05**	--	**3.43**	--	**1.89**	--
Crook	**0.64**	N.S.	N.S.	N.S.	N.S.	**0.50**	**1.90**	N.S.	**0.57**	**3.12**

Defects with significantly different odds of being present in the modified charges compared with the conventional schedule are shown in **bold red font** in the columns labeled "Worse"; Defects with significantly different odds of being absent after drying with the modified schedule compared with the conventional schedule are shown in **bold red font** in the columns labeled "Better"; N.S. – not significant

For the sugar maple, the modified schedules appeared less effective based on the OR results. The odds for the end checks were statistically higher for both of the modified kiln schedules compared with the conventional schedule. Also, the lumber quality outcomes for the lumber dried under the Mod-1 schedule had higher odds of forming twists and cups. The Mod-2 schedule had significantly increased odds of surface checks, twists, cups, and crooks (Tables 2 and 3). However, the ORs for the improvement of the board bowing for both the Mod-1 and Mod-2 drying protocols were statistically significant (Table 3). The modified kiln schedules straightened out the sugar maple boards that had bowing before the drying process.

For the red oak, the cup occurrence post-drying had significantly higher odds under the modified schedule, while the occurrence of crooks had significantly lower odds compared with the quality results measured for the boards dried under the conventional BI red oak schedule (Table 3). The post-drying occurrence of end checks, surface checks, and shakes were not significantly affected by the dry kiln treatment for the red oak (Table 2).

Changes in the Lumber Grade Post-kiln Drying

For all three species, the percentage of boards that decreased in grade after kiln drying was higher for the batches that were processed using the conventional kiln schedules than for those dried using the modified kiln schedules (Fig. 4).

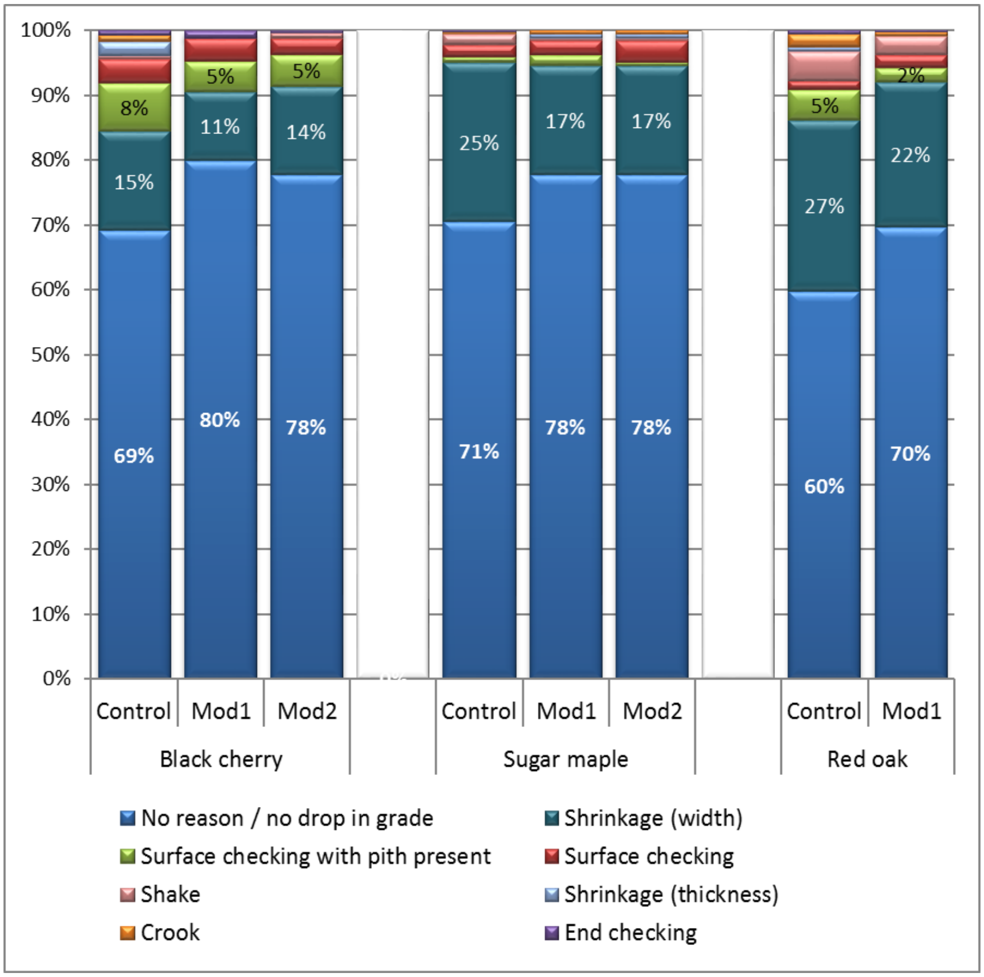

Fig. 4. Proportion of the boards sawn from small-diameter logs that decreased in grade after kiln drying

For each species, the significance of the drying schedule in affecting the lumber grade (in terms of diminishment) during the kiln drying process was examined using a GLMM with a negative binomial distribution. For the black cherry and red oak, the lumber grade changes after the kiln drying process were significantly related to the dry kiln schedule (Table 4). For both species, the conventional schedule outcomes were significantly different (worse) than the modified kiln schedules, based on the summary data shown in Fig. 4. For the sugar maple, the grade changes were not significantly influenced by the dry kiln schedule.

Table 4. Results of the General Linear Mixed Modeling of the Change in the Lumber Grade After Kiln Drying

Species		Type III Pf > F	Mean	T-K Group[1]
Black Cherry	All Grades	< 0.0001	Convn: 0.3767	A
			Mod-1: 0.2129	B
			Mod-2: 0.2212	B
	No. 2AC and Better Grades Only	0.0111	Convn: 0.9093	A
			Mod-1: 0.5567	B
			Mod-2: 0.5719	B
Sugar Maple	All Grades	0.3919	Convn: 0.3056	A
			Mod-1: 0.2512	A
			Mod-2: 0.2745	A
	No. 2AC and Better Grades Only	0.7623	Convn: 0.5957	A
			Mod-1: 0.5536	A
			Mod-2: 0.6557	A
Red Oak	All Grades	0.0140	Convn: 0.6719	A
			Mod-1: 0.5035	B
	No. 2AC and Better Grades Only	0.1360	Convn: 0.9814	A
			Mod-1: 0.7847	A

[1] - T-K group is the Tukey-Kramer grouping for the least square means given an α = 0.05; For all of the factors, the means and associated results of the Tukey-Kramer grouping are reported.

Lumber dropping in grade as a result of defects that were initiated or exacerbated by dying-related stresses and a loss of value when the piece of lumber initially had a high quality/high grade board are larger concerns. As noted by Wiedenbeck *et al.* (2017), the percentage of boards that qualified for the three highest grade categories (collectively "Sel. & Btr.") was low before kiln drying, less than 5% for the black cherry and sugar maple and less than 8% for the red oak. The No. 1C fraction of the recovered lumber was only slightly higher. Most industrial drying operations will kiln dry all of their No. 1C and higher-grade lumber. The more valuable No. 2AC species are kiln dried if the kiln capacity is sufficient. Therefore, the changes in the grade results for the better grades of lumber are the most relevant to current practices. For both the black cherry and red oak, the number of lumber grade reductions induced by kiln drying appeared to be lower for the lumber dried under the modified treatments when compared with the conventional dry kiln treatment (Fig. 5). This was especially obvious for the highest-grade group (Sel. & Btr.) for the black cherry wood. However, the different schedule-based changes in the lumber grades from the higher grades of lumber were only statistically significant for the black cherry wood (p = 0.0111), as is shown in Table 4.

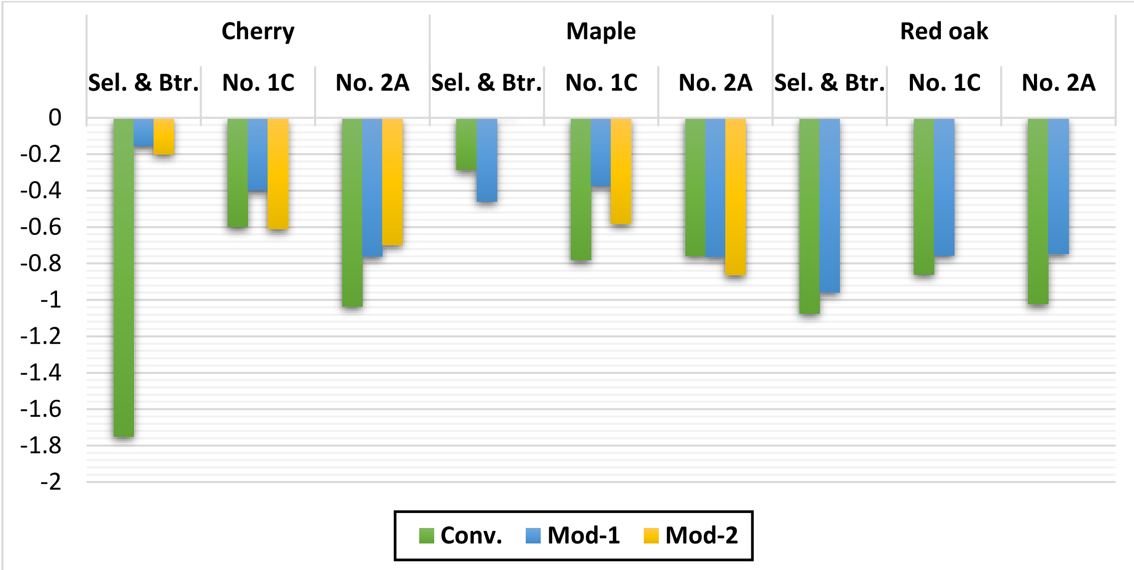

Fig. 5. Lumber grade change for grades No. 2AC and better after kiln drying

Drying defects associated with lumber grade diminishment

For the boards that changed grade during the kiln drying process, the drying defect/outcome that had the greatest negative impact on the dry board grade and value of the lumber was the width shrinkage. In the red oak and sugar maple, between 17% and 27% of the boards decreased in lumber grade because of the width shrinkage, which caused the clear areas on the board to not meet the minimum width requirements (Fig. 4). Width shrinkage was the most prevalent grade lowering agent for the black cherry as well, but only 11% to 15% of the boards were affected.

Width shrinkage is of particular relevance when drying lumber sawn from small-diameter logs because a substantial proportion of the lumber recovered will be narrow and correspondingly, a substantial portion of the clear areas within the boards will be narrow. The NHLA standard grade rules specify minimum widths for lumber and clear area (cutting) for boards by grade. For the highest grades (FAS and FAS-1F), these minimum widths are 6 in for boards and 3 in to 4 in for clear cuttings. For the Selects grade, the minimum widths are 4 in for boards and 3 in to 4 in for clear cuttings. For lumber grades No. 1C through No. 3B, the minimum widths are 3 in for boards and 3 in for clear cuttings. The kiln-dried grading rules compensate for shrinkage by specifying that minimum board widths may be 0.25 in scant (*i.e.*, undersized). However, the minimum clear area cutting widths within the boards must remain unchanged (NHLA 2014).

Surface checking, either with or without the presence of pith in the board (checks are more common closer to the pith), was the second most prevalent type of defect that lead to reductions in the lumber grade. The only form of warping that contributed to degradation was crooking; however, warping resulted in a decrease in the lumber grade in less than 1% of the black cherry and sugar maple boards and just over 1% of the red oak boards.

The ORs were calculated to evaluate the three defects that were most important in grade (and therefore value) reduction (Table 2). For the black cherry and red oak, the odds of surface checks and width shrinkage causing reductions in the lumber grade after drying were not significantly different among the dry kiln treatments. For the sugar maple, the most important grade lowering defect, width shrinkage, had significantly lower odds of occurring under the modified schedules when compared with the conventional schedule (Table 2). Interestingly, the defect that most often had a negative impact on the lumber grade after kiln drying appeared to be less of a problem when using the modified kiln drying protocols (modified schedules) for the sugar maple. However, the sugar maple was the species for which the modified drying schedules did not have a significant influence on the grade reduction. For the sugar maple dried using the conventional drying schedule, 86% of the grade reductions were caused by width shrinkage (Fig. 4). For the other two species, the importance of this defect compared with the other defects was lower, with 48% of the grade reductions caused by shrinkage for the black cherry dried with the conventional schedule and 68% for the red oak. Thus, for these two species, reducing the occurrence of other types of drying defects also played a role in the overall improvement in the drying quality with the modified dry kiln schedules.

Synopsis of the Sawmill Recovery of Value Products from Small-diameter Hardwood Logs

As was first reported by Wiedenbeck *et al.* (2017), approximately 25% of the boards recovered from small-diameter hardwood logs decreased to a lower grade value after kiln drying. This loss in grade after the lumber was dried intensified the pre-existing situation in which only a small fraction of the lumber sawn from these logs was classified in higher grade categories (FAS, FAS-1F, Selects, and No. 1C) before being selected for lumber drying (between 9% and 22% depending on the species) (Wiedenbeck *et al.* 2017). Lumber recovered from logs that were of intermediate quality (Forest Service log grades F2 and F3) comprised approximately 80% of the small-diameter logs sawn and were found to yield significantly higher value lumber products on average than the logs that were graded as cull logs because of excessive amounts of sweep, crook, or unsound regions (Wiedenbeck *et al.* 2017). Almost 60% of the lumber recovered from the Forest Service Grade F2 logs in this study (approximately 4% of all of the study logs) was graded as No. 2C or better.

Given that the width shrinkage and surface checking in the boards that contained pith were identified as the two lumber drying defects that caused the greatest decrease in the lumber grade, recovering lumber from the inner portion of the log should not be attempted when sawing logs that are 12 in or smaller in diameter (this lumber was recovered in this study). Boards sawn from the outer portions of the log will not only contain higher quality wood, but these boards should be wider and not be affected by the variable stresses that are present in wood near the pith.

Scholl (2006) produced original insight into basic lumber recovery from small-diameter logs post-drying and developed new knowledge on the effects of different dry kiln temperatures and relative humidity schedules on the lumber quality outcomes for each species (Wiedenbeck *et al.* 2017). It was determined that for the black cherry and red oak, the dry kiln schedules that lowered the final dry- and wet-bulb temperatures reduced the occurrence of some types of warp (bow and crook) and generally reduced the proportion of boards that dropped in grade during drying. For the sugar maple, the modified dry kiln schedules were not effective at accomplishing either of these objectives.

CONCLUSIONS

1. The major grade-lowering defect that arose during the kiln drying of lumber recovered from small-diameter (≤ 12 in) logs was excessive width shrinkage that caused clear cutting areas to be of insufficient size to meet the requirements of the NHLA grade.
2. Surface checking during drying, which is more problematic when wood that contains or is proximal to the pith is found in the board, was a problem encountered in drying lumber from small-diameter logs.
3. The dry kiln schedules developed to reduce the development of warp during drying were somewhat effective for the black cherry and red oak, but ineffective for the sugar maple. However, the degree of warp that developed during drying generally did not have a large enough magnitude to cause the lumber to drop in grade.
4. The modified dry kiln schedules reduced the proportion of black cherry and red oak boards that decreased in grade during drying.
5. While all of the lumber recovered from the small-diameter logs was kiln-dried in this study, typically, only the higher grades of lumber are kiln-dried. Reductions in the lumber grade for the lumber graded No. 2AC and better were minimized by using the modified kiln schedules for the black cherry. For the red oak and sugar maple, the modified schedule did not improve the drying outcomes (grade change).
6. The red oak results were complicated by the presence of bacterially infected (BI) wood in many boards. This condition is commonly encountered when sawing red oak.
7. Given the width shrinkage and surface checking in the boards that contained pith were identified as the two lumber drying defects that caused the greatest decrease in the lumber grade, recovering lumber from the inner portion of the log should not be attempted when sawing logs that are 12 in or smaller in diameter.

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