Log Sawing Practices and Lumber Recovery of Small Hardwood Sawmills in West Virginia

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Abstract

A total of 230 logs from two species, red oak (*Quercus rubra*) and yellow poplar (*Liriodendron tulipifera*), were measured in five typical hardwood sawmills across West Virginia to evaluate log sawing practices and lumber recovery. Log characteristics such as length, diameter, sweep, taper, and ellipticality were measured in sawmills, while log scale and grade were determined by using the US Department of Agriculture Forest Service grading rules. The characteristics of sawing equipment, such as headrig type, headrig kerf width, and sawing thickness variation, were recorded during the measurement process. A general linear model was used to statistically analyze the relationship between lumber recovery and characteristics of logs and sawing practices. Results indicated that factors such as log grade, log diameter, species, log sweep, log length, and some two-factor interactions significantly affected lumber value and volume recovery.

The hardwood industry is an important component of West Virginia's economy, contributing approximately US$4 billion annually (Childs 2005). More than 500 primary and secondary processors are located in the state, and they employ approximately 29,000 workers. The scale and production capability of hardwood sawmills in the state vary from less than 100,000 board feet to more than 50 million board feet (MMBF) per year (Luppold 1995, Luppold et al. 2000). About 69 percent of the hardwood lumber sawmills produce less than 4 MMBF of green hardwood lumber per year (West Virginia Division of Forestry 2004). Luppold et al. (2000) also reported that one-third of the eastern hardwood lumber production is provided by mills that produce less than 3 MMBF annually. Those small sawmills are key contributors to the industry because they represent a significant share of the market.

Currently, hardwood sawmills are facing many challenges, including decrease in log size and log quality, limited resource availability, reduced profit margin between log costs and lumber prices, and pressures from foreign competition (Milauskas et al. 2005). In addition, the weak global economy and the housing market slowdown have impacted the hardwood products industry. All of these factors are pressuring hardwood sawmills to adopt more efficient processing methods that can increase the value or volume of lumber produced from logs. Many large-scale sawmills have adopted the latest sawing and optimization technologies to increase the value and yield of lumber. However, small-scale sawmills are less able to use advanced technologies because of high initial costs, long payback periods, and modifications to current operations (Occeña et al. 2001). Therefore, traditional sawing practices are still being used in small sawmills in the Appalachian region. These traditional sawing practices result in lower conversion efficiency, making it more difficult for small sawmills to survive in the highly competitive marketplace.

Maximizing the volume and value recovery of lumber from logs is one of the most common ways of improving the conversion efficiency and competitiveness in lumber production (Rappold et al. 2007). Over the past two decades, several studies have been conducted to analyze the relationships between lumber volume or value recovery

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and log characteristics or log sawing practices (Steele 1984, Shi et al. 1990, Harless et al. 1991, Wade et al. 1992, Steele et al. 1994, Maness and Lin 1995, Christensen et al. 2002, Young et al. 2007). For example, Steele (1984) reported that factors influencing lumber recovery during the sawmilling process include log diameter, length, taper and quality, kerf width, sawing variation, rough green-lumber size, size of dry-dressed lumber, product mix, decision making, condition and maintenance of mill equipment, and sawing method. Wade et al. (1992) used sawing equipment characteristics and log resource information to develop a multiple-linear regression model to estimate the lumber recovery factor (LRF) for hardwood sawmills. The data were obtained from the Sawmill Improvement Program studies of 35 hardwood sawmills that were located in 15 states and had an LRF between 5.0 and 7.5. Their results indicated that variables such as headrig kerf, log diameter, and log length significantly influenced LRF.

Given the current turbulent economic conditions, a complete analysis of sawing practices and lumber recovery would be beneficial for small-scale hardwood sawmills in West Virginia. Specifically, it was necessary to conduct a study that analyzed the impacts of sawing practices, log characteristics, and sawing equipment on lumber volume and value recovery for small-scale hardwood sawmills. The objectives of this study were to (1) investigate the current status of log sawing practices for small hardwood sawmills in West Virginia, (2) analyze lumber recovery produced from current sawing practices, and (3) identify the factors that significantly affect lumber volume/value recovery.

Materials and Methods

Five small hardwood sawmills in north central West Virginia were investigated for log sawing practices between October 2009 and August 2010. These mills were typical small-scale hardwood sawmills, with an annual production less than 4 MMBF (Table 1). All of the mills used the grade sawing method to produce lumber.

Sample selection

The sample logs of two hardwood species, red oak (*Quercus rubra*) and yellow poplar (*Liriodendron tulipifera*), were selected from log decks of the five sawmills with a total sample size of 230 logs. A total of 180 sawlogs were measured from No. 3 (30 red oak and 30 yellow poplar), No. 4 (30, 30), and No. 5 (40, 20) sawmills, while another 50 red oak logs were sampled from No. 1 (20) and No. 2 (30) sawmills. All the sample logs were selected to represent the range of size and quality for each species in West Virginia. The small-end diameters (inside bark) of the sample logs varied from 10 to 15 inches, and log length was between 8 and 16 feet (Table 2).

Table 1.—Summary of basic information for the selected sawmills.

Site	Annual production (MMBF)	Log debarking	Sawing type	Sawyer's experience (y)	Grader's experience (y)
1	3	Ring debarker	Circular headrig	20	18
2	4	Ring debarker	Circular headrig	15	12
3	3	Ring debarker	Band headrig	18	10
4	2	Ring debarker	Band headrig	10	5
5	1	—	Band headrig	3	1

Log measurements

In order to document sawing pattern from a log, both ends of each of the sample logs were divided into four quadrants and labeled using consecutive numbers. These four quadrants were determined based on the major and minor axes at both log ends. The zero degree orientation of a log was predetermined along the log length. Log taper was calculated as the difference between large-end diameter and small-end diameter divided by log length. Log sweep was measured as the maximum deviation from straightness divided by log length. Log ellipticality was calculated based on both lengths of major and minor axes at the small end of a log (Steward 1999). Defects were measured along the entire log length and included defect type, location, and size. Defect types recorded included adventitious knot (AK), sound knot (SK), unsound knot (UK), overgrown knot (OK), light distortion (LD), medium distortion (MD), and heavy distortion (HD). Defect location was determined by measuring its distance from the small end of the log. The defect angle (0° to 360°) was measured and recorded relative to the zero degree orientation. Defect size was measured by length (along the log's length) and width (perpendicular to the long axis).

Log scaling, grading, and sawing

Currently, three major log scaling rules are used in the eastern United States: Doyle log rule, Scribner rule, and International ¼-inch rule (Cassens 2001). Most sawmills in West Virginia still use the Doyle scale, even though it is less accurate than the others (West Virginia Forestry Association 2001). The use of the Doyle scale may be attributed to the its long history as the standard hardwood logs scaling rule that attributes log volume to value (Bond 2006). However, when log shape and size change dramatically, the Doyle scaling rules do not correctly estimate log volume. A cubic log rule, which is based on the actual geometric volume, can be used to reduce the effects of log profile. In this study, the Smalians formula was adopted as the cubic scale rule to calculate the log volume (Fonseca 2005).

Table 2.—Distribution of the sample logs.

Species	Diameter class (in.)	Log length (ft)				
		8	10	12	14	16
Red oak	10	18	3	2	0	0
	11	9	4	1	2	0
	12	9	16	5	0	0
	13	13	7	6	0	0
	14	9	12	3	1	2
	15	10	8	6	3	1
Subtotal	—	68	50	23	6	3
Yellow poplar	10	3	1	2	1	0
	11	2	4	3	0	0
	12	9	5	2	3	1
	13	6	6	1	4	1
	14	3	5	3	1	0
	15	4	2	1	1	6
Subtotal	—	27	23	12	10	8
Total	—	95	73	35	16	11

The US Department of Agriculture Forest Service developed standard hardwood sawlog grading rules based on log shape and external log defects indicators (Rast et al. 1973). In this study, these log grading rules were adopted to predict high-grade lumber from a log. Log value was determined based on the prices at the time of the assessment, which were gathered from mills across the state by log grade, species, and dimension.

The sawing process for each sample log was videotaped to observe how sawyers cut logs using current grade sawing procedures. We recorded the first cutting line location relative to the major and minor axes, the time required for determining the opening face and sawing pattern, and the number of log turnings. The time for locating the opening face of a log started when the log was loaded on the carriage and ended before the sawblade began its first cut. Log sawing time started from the sawblade cutting the log until a square cant or the last piece of lumber was ejected from the headrig, and the carriage returned and stopped in front of the log deck in preparation for the next log.

Log products measurements

A series of consecutive numbers were marked on each sawn board to track its source. For example, ''1-1'' indicates that this is the first piece of lumber produced from log 1. After edging and trimming, the length, width, and thickness of each board were measured and its volume was computed in both board feet (bd ft) and cubic feet (cu ft). Both edges of each board were measured 4 to 5 times along its length, and mean thickness was calculated (rounded to $\frac{1}{32}$ in.). The lumber grade and surface measure were determined by a National Hardwood Lumber Association (NHLA) certified grader, and the lumber value was accordingly calculated based on lumber price matrix (Table 3). If a cant was produced, its length, width, and thickness were measured; the volume and value were determined based on species and size. Sawdust volume was computed by multiplying one-half the saw kerf by the surface area of the board (Ernst and Pong 1985). Chip volume was determined by subtracting the total lumber, cant, and sawdust volumes from the gross cubic log volume.

Lumber recovery analysis

Lumber volume, value, and grade yield for the two species of sawlogs, red oak and yellow poplar, was analyzed. Lumber volume recovery was analyzed using overrun, LRF, and cubic recovery percentage (CRP). Overrun refers to the difference between the actual volume of lumber produced by a mill and the log scale volume. LRF is expressed as nominal lumber volume in board feet divided by log volume in cubic feet (Wade et al. 1992). CRP is the cubic volume of rough green lumber expressed as a percentage of cubic log scale volume. CRP is a more accurate measure of lumber volume recovery than either overrun or LRF (Ernst and Pong 1985). The production of more lumber volume does not always lead to more lumber value. Value is based on quality or grade of lumber. Therefore, most mill managers are interested in lumber value recovery rather than lumber volume recovery. In this study, lumber value recovery was expressed as dollars per thousand board feet of lumber tally ($/MBF), dollars per hundred cubic feet of log volume ($/CCF), and dollars per thousand board feet of net Doyle log scale ($/MBFLS; Willits and Fahey 1988). The $/MBF represents the average value of the lumber produced from the log, while the $/CCF and $/MBFLS represent the value of the log, which are determined by lumber value and LRF (Parry et al. 1996). A value ratio, which is expressed as lumber value divided by log and sawing costs, was used to evaluate log processing profitability. If a value ratio is less than 1.00, it indicates that the resulting lumber value cannot cover the log and operational costs. Lumber grade yield is also an important indicator that can provide information that relates log grade to the grade of lumber produced. Lumber grade yield can be expressed as board feet volume yield or percentage of board feet volume of lumber grade recovered in each log grade. Log grades used were F1, F2, and F3 (Rast et al. 1973), and lumber grades included FAS, FAS 1 Face, No. 1 Common, No. 2 Common, and No. 3 Common (NHLA 2007).

Table 3.—Lumber prices based on grades.[a]

Species	Thickness (in.)	Lumber grades[b]				
		FAS	F1F	1C	2C	3C
Red oak	4/4	705	695	500	375	300
	5/4	850	840	530	420	355
	6/4	905	895	630	435	375
	8/4	920	910	700	445	385
Yellow poplar	4/4	600	590	360	290	235
	5/4	600	590	385	305	250
	6/4	615	605	400	310	260
	8/4	615	605	420	325	260

[a] *Hardwood Market Report* for Appalachian Hardwoods 2009.
[b] Values are in dollars per thousand board feet of lumber tally ($/MBF). F1F = FAS 1 Face; 1C, 2C, and 3C = No. 1, No. 2, and No. 3 Common, respectively.

Lumber recovery can be affected by many factors, including raw material, equipment, machining, and processing (Steele 1984). A general linear model (GLM) was used to analyze the relationships among lumber recovery, characteristics of logs, and sawing equipment for small hardwood sawmills. It is often of interest to examine the effect of two or more factors on a response variable. However, interactions between more than two factors are difficult to interpret, and the associated degree of freedom from such effects may be more effectively used to more precisely estimate the error (Reese 2008); therefore only two-factor interactions were considered in this study. The GLM for analyzing lumber volume or value recovery can be expressed as

$$\begin{aligned} LR_{ijklmnopq} = {} & \mu + SP_i + LG_j + LEN_k + DIA_l + LT_m + LE_n \\ & + LS_o + SM_p + SP_i \times LG_j + SP_i \times LEN_k \\ & + SP_i \times DIA_l + LEN_k \times LT_m + \varepsilon_{ijklmnopq} \end{aligned} \tag{1}$$

where $i = 1, 2$; $j = 1, 2$; $k = 1, 2, \ldots, 5$; $l = 1, 2, \ldots, 6$; $m = 1, 2, \ldots, 4$; $n = 1, 2, \ldots, 5$; $o = 1, 2, \ldots, 5$; $p = 1, 2, \ldots, 5$; $q = 1, 2, \ldots, n$; $LR_{ijklmnopq}$ = the qth observation of lumber volume recovery (LRF) or lumber value recovery ($/MBF); μ = the mean of each response variable; SP_i = the effect of the ith species, 1 = red oak, 2 = yellow poplar; LG_j = the effect of the jth log grade, 1 = F2, 2 = F3; LEN_k = the effect of the kth log length; DIA_l = the effect of the lth log small-end diameter; LT_m = the effect of the mth log taper; LE_n = the effect of the nth log ellipticality; LS_o = the effect of the oth log sweep; SM_p = the effect of the pth mill requirements including sawyer's experience and grader experience in respect to each mill; $\varepsilon_{ijklmnopq}$ = an error component that represents uncontrolled variability; and q = the number of observations within each treatment.

Some variables that were measured quantitatively were categorized into different classes based on the following criteria (ranges for each class are in parentheses): log length (in feet) 8 (8 to 10), 10 (10 to 12), 12 (12 to 14), 14 (14 to 16), 16 (16 to 18); log diameter (in inches) 10 (10 to 11), 11 (11 to 12), 12 (12 to 13), 13 (13 to 14), 14 (14 to 15), 15 (15 to 16); log taper (inches per foot) 0 (0), 0.2 (0 to 0.2), 0.4 (0.2 to 0.4), 0.6 (0.4 to 0.6); log ellipticality 0 (0), 0.2 (0 to 0.2), 0.4 (0.2 to 0.4), 0.6 (0.4 to 0.6), 0.8 (0.6 to 0.8); log sweep (inches) 0 (0), 0.2 (0 to 0.2), 0.4 (0.2 to 0.4), 0.6 (0.4 to 0.6), 0.8 (0.6 to 0.8).

Results and Discussion

Statistics of sampled logs and sawn lumber

The average small-end diameter of the sampled logs was 12.9 inches (Table 4). The log length averaged 10.5 feet. Sweep ranged from 0 to 0.625 inch with an average of 0.03 inch, while log taper varied from 0.01 to 0.55 in./ft with an average of 0.16 in./ft. Fifty-four percent of the sampled logs exceeded 0.50 inch for the difference between the major and minor axes. The average ellipticality of the measured sawlogs was 0.29. The total number of defects per log was between 0 and 18, with an average of 5. The most frequently occurred defects were AK (8.6%), UK (10.6%), OK (29.6%), SK (26.6%), LD (5.6%), MD (14.8%), and HD (10.3%). Defect size varied greatly, with an average length of 5.2 inches and width of 4.3 inches. The average log volume was 54.8 bd ft (Doyle scale) or 11.05 cu ft. A total of 230 logs were sawn, and they yielded 2,160 boards and 147 cants of two sizes (3.5 by 6 in. and 3 by 8 in.). The total lumber and cant tally were 13,745 and 2,628 bd ft, respectively. The average number of pieces of lumber produced from each log was nine, with the average lumber length, width, and thickness of 9.5 feet, 6.4 inches, and 1.1 inches, respectively (Table 4).

Log products distribution

The distribution of lumber and cant, chips, and sawdust by sawmill are shown in Figure 1a. More lumber and cants were produced from the band sawmills (No. 3 to 5) compared with the circular sawmills (No. 1 and 2). The circular sawmills converted about 51.2 percent of logs into lumber and cants with about 4.7 percent yield loss compared with the band mills. The distribution of log products changed slightly as the log diameter increased (Fig. 1b). The lumber and cant volume increased 5.8 percent and the chip volume decreased 9.4 percent when the diameter increased from 11 to 15 inches. The proportion of lumber and cant for 10-inch logs was somewhat higher than other diameter classes except for 15-inch logs. It should be noted that all 10-inch logs were sawn at one sawmill (No. 5) that used a band saw, where the sawyer was more concerned about the improvement of lumber recovery than productivity.

Log processing

Primary breakdown is the focus of log processing in this study. All the sample logs were cut from large end to small end in all sawmills. The location of the slabbing or opening face is the key to maximizing lumber recovery. After a log is loaded onto a carriage, the sawyer will determine the appropriate log opening face by rotating the log. In order to

Table 4.—Statistics of the sawlogs measured and sawn lumber.[a]

	Red oak			Yellow poplar		
	Mean (SD)	Minimum	Maximum	Mean (SD)	Minimum	Maximum
Log						
SED (in.)	13.2 (1.8)	9.6	15.8	13.0 (1.7)	10.0	15.5
LED (in.)	14.5 (2.5)	10.0	19.8	14.2 (2.0)	10.1	19.6
Length (ft)	10.2 (1.9)	8	16	11.0 (2.4)	8	16.1
Sweep (in.)	0.04 (0.12)	0	0.63	0.02 (0.07)	0	0.62
Taper (in./ft)	0.18 (0.14)	0.01	0.61	0.13 (0.08)	0	0.51
Ellipticality	0.27 (0.13)	0	0.59	0.31 (0.13)	0	0.58
Log defects						
No. of defects	6 (2.5)	0	18	4 (2.2)	0	16
Defect length (in.)	5.4 (2.1)	1.65	16	4.9 (2.0)	1.25	15
Defect width (in.)	4.5 (2.5)	1.65	17	4.2 (2.4)	1.25	15
Log volume						
Doyle log rule (bd ft)	54.3 (25.5)	15.6	137.8	55.4 (26.7)	18.0	138.4
Scribner rule (bd ft)	68.1 (27.9)	24.5	160.2	70.2 (30.5)	27.2	160.9
International ¼-in. rule (bd ft)	60.0 (26.4)	19.0	145.4	60.6 (28.2)	21.5	146.1
Cubic log rule (cu ft)	10.9 (4.5)	4.3	25.9	11.2 (4.9)	4.7	26.2
Lumber						
Length (ft)	9.2 (3.06)	8	16	9.9 (2.98)	8	16
Width (in.)	6.4 (1.32)	3	10.6	6.3 (1.38)	3	10.5
Thickness (in.)	1.13 (0.03)	0.94	1.25	1.13 (0.05)	1.0	1.38
Lumber tally (bd ft)	5.5 (1.6)	1.9	15.8	5.9 (2.2)	2.0	17.7
Cant						
Cant tally (bd ft)	21.6 (8.76)	14	37.3	24.9 (6.65)	14	37.3

[a] SD = standard deviation; SED = small-end diameter (inside bark); LED = large-end diameter (inside bark); bd ft = board feet; cu ft = cubic feet.

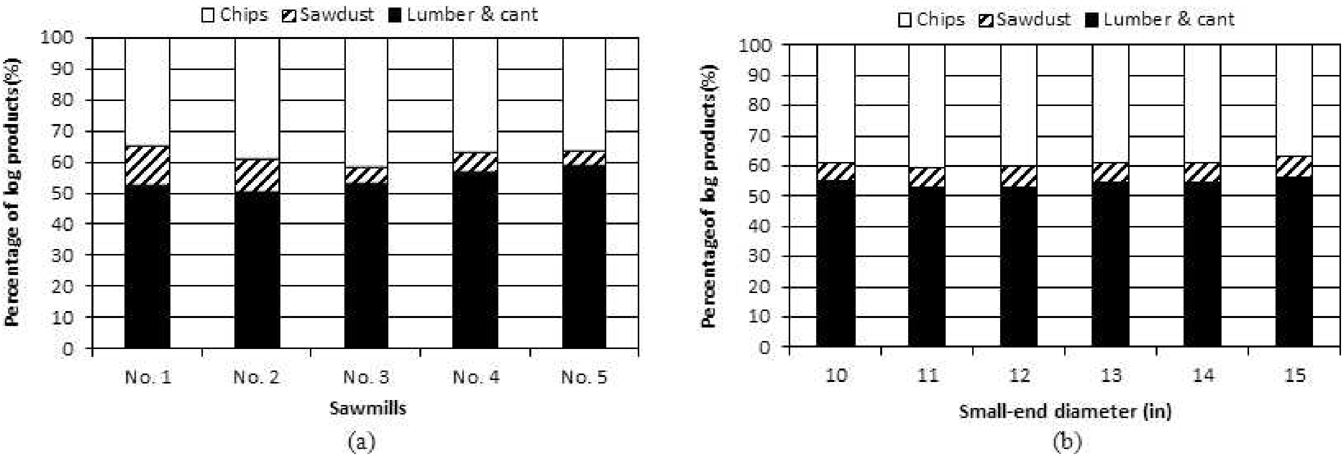

Figure 1.—Distribution of processed log products by sawmill and diameter class. (a) Distribution of log products by sawmills (No. 1 to 2 are circular sawmills and No. 3 through 5 are band sawmills). (b) Distribution of log products by diameters.

achieve more lumber value, the log should be positioned so that the defects are located on the edges of potential sawing faces so that they can be easily removed during the edging process. However, we found that many defects were not positioned at the edges of the sawing faces. Because all sawmills used no taper sawing, the poor log face should be the first opening face in order to obtain more lumber recovery (Malcolm 1961, 1965). The poor log sawing face can be determined by identifying the external defects. However, we observed in these sawmills that the first opening face was not always the poor log face. In our study, only 35 percent of first opening faces were observed on poor faces. There were two major reasons why the sawyers could not select the first opening face correctly: debarked logs and short decision time. It is difficult to identify all the defects on the debarked logs. In addition, there is very limited time for the sawyers to consider how to saw a log at the headrig.

The average width of the first board was 5.6 inches, slightly less than the commonly used 6 inches. The widths of lumber were divided into four classes: 4, 6, 8, and 10 inches. The distribution of the average width by log diameter class is shown in Figure 2. The proportions of wider lumber (8 and 10 in.) increased as the log diameter increased. It was noted that owing to the size of logs selected, a majority of the lumber produced was 6 inches wide. As expected, a small percentage of 8-inch-wide boards was produced from 12-inch-diameter logs or smaller. The lumber width from 10-inch logs was less than 8 inches.

During log processing, lumber is intentionally oversized to allow for sawing variation, shrinkage from drying, and final surfacing. In this study, 4/4 thickness was the normal thickness of the finished lumber for four sawmills, while one sawmill used 5/4 thickness. The targeted green thickness for 4/4 and 5/4 lumber were 1⅛ and 1⅜ inches, respectively. Therefore, there was ⅛-inch oversizing, which can result in an average of 9.3 percent yield loss (from shrinkage and surfacing) depending on log diameter (Steele 1984). The average lumber thickness variation was 0.055 inch with a range of 0 to 0.125 inch. If the variation was more than 0.03 inch, it could be associated with machine alignment, maintenance, or operation (Kilborn 2002). The sawing variation for two sawmills was greater than 0.03 inch; therefore, machine adjustment is recommended to minimize the variation of lumber thickness in these two sawmills.

The sawing efficiency was analyzed by computing the average log sawing time and the number of times that the log was turned during the sawing process. The average sawing time per log was 130 seconds, and the average sawing time per thousand board feet (MBF) was 565 seconds. The logs with more sweep and greater ellipticity increased processing time over straight and round logs due to additional log turning and elapsed time at the headrig. The time needed to determine the opening face averaged 6.5 seconds, while the average number of times that the log turned was 4.1. All the sawyers rotated logs by 180 degrees after the opening cut except for poor form logs (such as those with heavy sweep, crooked, or twist). The reason for the 180 degree rotation was that the logs could be easily rotated to produce boards that were wider and required less edging. We noted that at most, one or two flitches were produced from the opening face before rotating when logs had small-end diameters less than 13 inches. Two or three pieces of lumber were cut from the first opening face on larger logs.

Lumber recovery

The volume recovery differed by log diameter and log scaling rules (Table 5). When the Doyle log scale was used, an average overrun for red oak and yellow poplar was 40.7 and 47.3 percent, respectively. If the Scribner log scale was

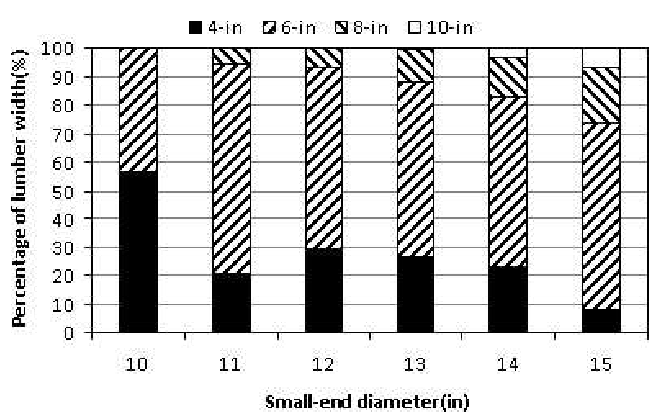

Figure 2.—Distribution of lumber width by log diameter class.

Table 5.—Statistics of lumber volume recovery.[a]

Species	SED (in.)	No. of logs	Overrun (%) Doyle	Scribner	International ¼ in.	LRF	Cubic recovery (%)
Red oak	10	22	80.4	11.6	45.8	6.5	55.3
	11	16	47.0	4.3	17.6	6.2	51.5
	12	30	46.2	5.5	17.0	6.3	52.5
	13	26	28.9	2.7	6.7	6.4	53.1
	14	27	23.9	3.7	10.0	6.4	53.6
	15	29	17.9	−0.1	4.5	6.5	52.8
Yellow poplar	10	7	76.0	15.6	49.8	7.0	59.2
	11	9	60.6	6.6	31.6	6.6	55.1
	12	20	46.6	6.7	23.8	6.8	56.7
	13	18	41.9	6.7	20.8	6.8	57.1
	14	12	30.0	3.7	24.5	6.9	57.6
	15	14	29.0	3.4	15.5	7.1	59.4

[a] SED = small-end diameter (inside bark); LRF = lumber recovery factor.

used, an average overrun for red oak and yellow poplar was 4.6 and 7.1 percent, respectively. When using the International ¼-inch log scale, an average overrun for red oak and yellow poplar was 16.9 and 27.7 percent, respectively. The average LRF for red oak and yellow poplar was 6.37 and 6.87, respectively, while the average CRP (green-lumber basis) for red oak was 53.2 percent and for yellow poplar was 57.5 percent. The results indicated that more volume could be recovered from yellow poplar than red oak. This is because there were fewer surface defects in the sampled yellow poplar logs than in red oak logs, and all yellow poplar logs were sawn by band sawmill. We also found that logs of lower grade presented lower lumber volume recovery because defects must be edged or trimmed from boards to improve the grade (Fig. 3).

Saw kerf had a significant impact on lumber volume recovery. The average saw kerf for circular sawmill and band sawmill was 0.305 and 0.125 inch, respectively. Therefore, more wood would be required to produce a board using a circular headrig compared with a band headrig. The average LRF and CRP for circular sawmills were 6.1 and 51.2 percent, respectively. The average LRF and CRP for band sawmills were 6.6 and 55.5 percent, respectively. Although a thin kerf increases lumber volume recovery and reduces waste, it does not mean that band sawmills would always be more profitable than circular sawmills because of the costs associated with operation, equipment, and labor. In addition, some sawmills use circular headrigs only to process low-value logs or make relatively few headrig cutting lines on each log.

The lumber value recovery was $449/MBF for red oak and $327/MBF for yellow poplar. The average $/CCF was $289/CCF for red oak and $227/CCF for yellow poplar. The average $/MBFLS was $632/MBFLS for red oak and $462/MBFLS for yellow poplar (Table 6). There were significant differences in lumber value recovery between the two species due to the difference in lumber price and log quality. Similar to our findings for lumber volume recovery, we noted that more lumber value recovery can be achieved from high-quality sawlogs. For example, the average lumber value recovery was $496/MBF for F2 red oak logs, while it was $403/MBF for F3 red oak logs. For yellow poplar, the average lumber value recovery was $366/MBF for F2 logs and $289/MBF for F3 logs.

Profit is a major incentive for mill managers to continue improving productivity and is directly related to production costs. Assuming that the prices paid for F2 and F3 yellow poplar logs were $150/MBF and $140/MBF in Doyle log scale, the purchase prices for red oak logs were $300/MBF for F2 grade and $280/MBF for F3 grade, and the average operating cost ranged from $160/MBF for circular sawmills to $200/MBF for band sawmills, a value ratio was computed

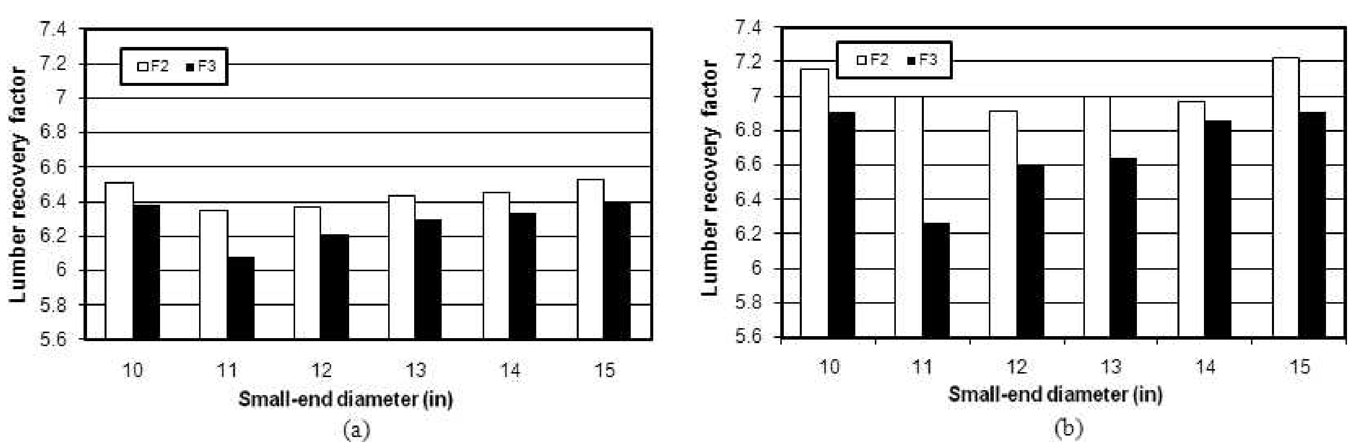

Figure 3.—Lumber recovery factors (LRFs) by diameter class and log grade. (a) LRFs for red oak. (b) LRFs for yellow poplar.

Table 6.—Statistics of lumber value recovery.[a]

Species	SED (in.)	No. of logs	Dollars per thousand bd ft of lumber tally ($/MBF)	Dollars per hundred cu ft of net log scale ($/CCF)	Dollars per thousand bd ft of net log scale ($/MBFLS)
Red oak	10	22	485	320	782
	11	16	422	264	639
	12	30	420	267	620
	13	26	446	286	584
	14	27	454	291	607
	15	29	469	304	557
Yellow poplar	10	7	341	240	518
	11	9	304	206	452
	12	20	301	205	442
	13	18	334	228	474
	14	12	326	225	421
	15	14	357	254	467

[a] SED = small-end diameter (inside bark); bd ft = board feet; cu ft = cubic feet.

based on species, diameter classes, and sawmills (Fig. 4). The average value ratios for red oak and yellow poplar were 1.13 and 1.10, respectively (Fig. 4a). The value ratio for logs with grades F2 and F3 was 1.21 and 0.98, respectively. It should be noted that processing lower grade logs did not always result in profits. Although sawmills purchased the low-grade logs at minimum price, the value of lumber recovered may not be sufficient to cover the purchasing and processing costs. Although the average lumber value ratio was greater than 1 (Fig. 4b), some processed logs were sawn at a loss.

Table 7 shows the percentage of lumber grade yield in terms of species, log grade, and diameter class. The percentage of higher grade lumber increased as the quality of logs increased (Table 7). Among the F2 grade sampled logs, approximately 57.1 and 58.5 percent of No. 1 Common or better lumber were produced from red oak and yellow poplar logs, respectively. Approximately 27.5 and 22.4 percent of the lumber were No. 2 Common or lower for red oak and yellow poplar, respectively. For the F3 grade logs, 24.1 and 15.7 percent of No. 1 Common or better lumber were produced from red oak and yellow poplar, respectively. About 57.6 and 64.2 percent was No. 2 Common or lower lumber for red oak and yellow poplar, respectively. Overall, a majority of lumber produced in the studied sawmills were No. 1 and No. 2 Common.

Factors affecting lumber recovery

The results showed that log grade ($F = 50.01$; df = 1,188; $P < 0.0001$), log diameter ($F = 8.27$; df = 5,188; $P < 0.0001$), log species ($F = 54.33$; df = 1,188; $P < 0.0001$), sawmills ($F = 126.73$; df = 4,188; $P < 0.0001$), log length ($F = 3.19$; df = 4,188; $P = 0.0146$), interaction between log species and grade ($F = 7.8$; df = 1,188; $P = 0.0058$), and interaction between log species and log length ($F = 3.32$; df = 4,188; $P = 0.0117$) had statistically significant effects on lumber volume recovery. Duncan's multiple range tests showed that all the sampled sawmills had a statistically significant difference (at the 5% significance level) in terms of lumber volume recovery (No. 1, 7.0; No. 2, 6.7; No. 3, 6.2; No. 4, 6.1; No. 5, 5.9). The average volume recovery for red oak (6.4) was significantly lower than that of yellow poplar (6.8). For lumber value recovery, log grade ($F = 86.31$; df = 1,188; $P < 0.0001$), log species ($F = 99.53$; df = 1,188; $P < 0.0001$), log taper ($F = 3.72$; df = 3,188; $P = 0.0125$), and different sawmills ($F = 14.21$; df = 4,188; $P < 0.0001$) were statistically significant variables. Duncan's multiple range tests indicated that sawmills No. 1 ($434/MBF) and No. 5 ($450/MBF), No. 1 ($434/MBF) and No. 3 ($411/MBF), No. 2 ($401/MBF) and No. 3 ($411/MBF) were not significantly different at the 5% significance level. The average lumber value recovery for red oak ($451/MBF) was significantly higher than that of yellow poplar ($329/

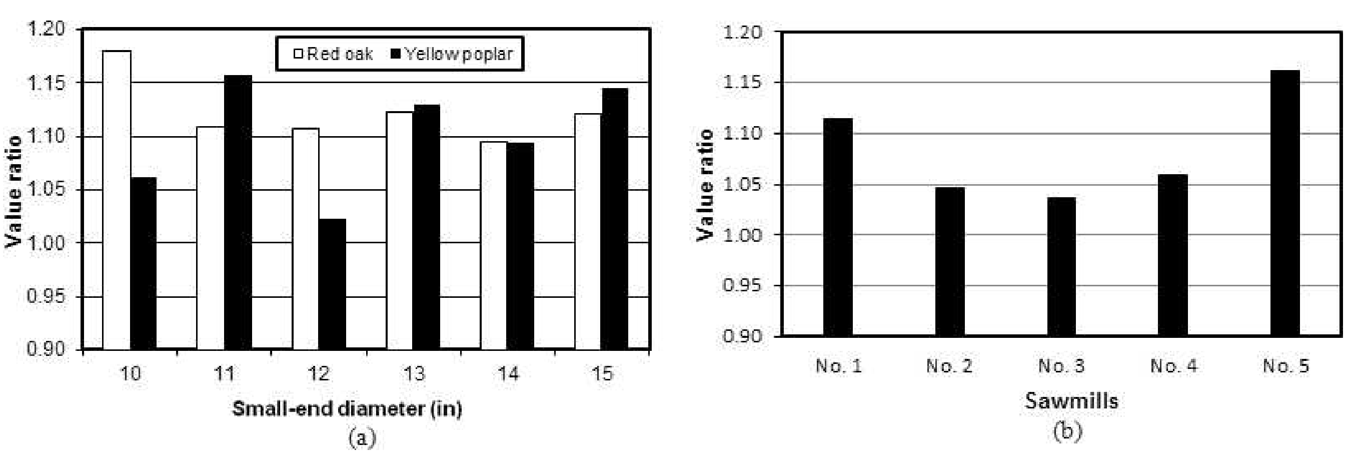

Figure 4.—Value ratio by diameter class and sawmills. (a) Value ratio by diameters. (b) Value ratio by sawmills.

Table 7.—Statistics of lumber grade yield.[a]

Species	Log grade	SED (in.)	% of lumber grade volume					
			FAS	F1F	1C	2C	3C	P
Red oak	F2	10	4.7	9.4	45.0	39.0	1.9	0.0
		11	6.7	9.3	35.4	20.9	6.7	20.9
		12	9.7	12.5	26.1	25.4	5.7	20.7
		13	12.8	9.6	33.4	21.3	1.6	21.4
		14	11.5	10.7	32.2	22.8	5.7	17.1
		15	16.1	14.5	34.6	21.0	4.2	9.6
	F3	10	0.0	0.0	20.7	39.9	39.4	0.0
		11	1.1	1.1	28.3	41.1	12.0	16.4
		12	2.0	2.7	21.1	35.9	20.8	17.5
		13	2.3	0.8	16.6	40.1	18.7	21.5
		14	4.7	0.0	25.6	30.3	16.6	22.8
		15	3.0	0.6	16.8	31.6	25.0	23.1
Yellow poplar	F2	10	14.2	0.0	33.0	52.8	0.0	0.0
		11	8.5	17.5	50.8	15.5	0.0	7.8
		12	0.8	8.6	33.5	24.4	4.6	28.2
		13	7.5	11.5	31.0	25.1	3.0	21.9
		14	18.3	14.6	30.8	12.3	5.0	19.0
		15	6.0	20.4	38.6	17.4	1.4	16.2
	F3	10	0.0	0.0	9.3	25.9	64.8	0.0
		11	0.0	0.0	10.3	35.3	27.8	26.7
		12	0.0	0.9	12.3	25.8	37.0	24.0
		13	0.0	2.1	24.0	25.9	26.3	21.8
		14	0.0	0.0	9.4	38.2	23.5	28.9
		15	0.0	0.0	35.5	27.5	28.9	8.1

[a] SED = small-end diameter (inside bark); F1F = FAS 1 Face; 1C, 2C, and 3C = No. 1, No. 2, and No. 3 Common, respectively; P = Pallet.

MBF). The R^2 of the GLM was 0.85 for lumber volume and 0.73 for value recovery, which indicated that the goodness of fit for the lumber volume recovery model was better than lumber value recovery.

Logs with a lower grade resulted in lower lumber volume and value recovery because defects must be edged or trimmed from boards to improve the grade. When logs have 3 inches or greater sweep, the traditional straight sawing methods could result in a significant volume loss. Therefore, curve sawing may be appropriate for logs with 3 inches or greater sweep in order to improve lumber recovery (Hamner et al. 2006). For small-diameter logs, there is a higher percentage of chips or hog fuel produced during log processing. Usually, the greater the log diameter, the more volume recovery percentage can be achieved. However, exceptions may occur under some circumstances. For example, when processing some large-diameter (15 in. or more) and older logs, lower volume recovery could occur due to internal decay or holes (Steele 1984). Species had an impact on lumber volume and value recovery. The red oak sawlogs of this study had more sweep and contained more defects than yellow poplar sawlogs, which resulted in lower lumber volume recovery. However, since red oak lumber currently commands higher prices than yellow poplar, more lumber value could be recovered from the red oak. Lumber volume and value recovery were different among sawmills because of differences in mill equipment and operators' experience.

Conclusions

This study investigated the current status of log sawing practices at five typical small Appalachian hardwood sawmills in West Virginia. Our findings indicated that small sawmills' inefficiency in converting hardwood logs into lumber was mainly due to inappropriate selection of opening face, dimensional oversize, and sawing variations. Mill managers can improve these aspects to increase lumber recovery and business profitability. For example, it is recommended that log graders should mark the first opening face on the debarked logs before sawing in order to improve the lumber recovery and quality. Lumber volume/value recovery and grade yield were significantly different among sawmills. However, owing to the limited production data collected, it is difficult to consider how the specific differences of log characteristics, sawing equipment, and sawyer's skills affect the lumber recovery in each individual mill. Log grade, diameter, sweep, length, species, sawmill specifications, and the interactions between log species and grade and between log species and log length had statistically significant effects on the lumber volume recovery. Furthermore, log grade, species, and sawmill specifications had statistically significant effects on the lumber value recovery. Lumber value recovery was affected somewhat differently by those factors that affect lumber volume recovery.

Further assessments with a larger sample of logs and sawmills across West Virginia would be needed to produce more robust statistic results. Additional factors that influence lumber recovery, such as board edging and trimming, should be considered. In addition, an affordable, cost-effective log sawing optimization system should be developed and implemented to assist small sawmill operators in hardwood log processing in the region. By controlling the best opening face and log rotation, the optimal log sawing patterns can be determined.

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