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Estimating hardwood sawmill conversion efficiency based on sawing machine and log characteristics

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Abstract

Increased problems of hardwood timber availability have caused many sawmiller, industry analysts, and planners to recognize the importance of sawmill conversion efficiency. Conversion efficiency not only affects sawmill profits, but is also important on a much broader level. Timber supply issues have caused resource planners and policy makers to consider the effects of conversion efficiency on the utilization and depletion of the timber resource. Improvements in sawmill conversion efficiency would favorably impact sawmill profits, and would be equivalent in effect to extending existing supplies of standing timber. An equation was developed to estimate lumber recovery factor for hardwood sawmills based on the characteristics of sawing machines and log resources. Variables included in the model were headrig type, headrig kerf, average log diameter and length, and the influence of total sawing variation. The estimated coefficients significantly influenced lumber recovery factor. The model should be helpful in assessing conversion efficiency trends and potential benefits from gains in sawmill efficiency.

The efficiency with which hardwood sawmills convert logs to lumber has become increasingly important. Sawmillers are experiencing problems in the availability of hardwood logs and standing timber (3,9-11). Competition for hardwood timber has increased due to export and domestic demand growth and increased use of hardwoods for pulp and reconstituted panels. Competition has also increased due to reduced timber availability from growing pressures on forests for non-timber uses (3,9-11).

On a broader level, hardwood availability and conversion efficiency is of interest to those concerned with the utilization and supply of the nation's timber resources. Because of increasing concerns over timber resources, federal and state organizations have prepared assessments of the nation's future hardwood timber supply, as initiated by the Forest and Rangeland Renewable Resources Planning Act (16). Projections estimate an annual yield increase of 0.2 percent for timber industries as a result of technological change. Actually, the current level of technology in the hardwood sawmilling industry is unknown. The level of technology in hardwood sawmills may be best determined by the conversion efficiency of raw material to lumber. Better information on current hardwood sawmill conversion efficiency and the factors that influence it should aid in developing more accurate estimates of future improvements in technology and the influence of this technology on the timber resource.

Lumber recovery factor (LRF) is a measure of the conversion efficiency of sawmills. LRF is calculated as the nominal board feet (BF) of lumber recovered per cubic foot volume of log input to a sawmill. LRF has been used as a measure of conversion efficiency past research on sawmill efficiency (1,13-15).

The objective of this study was to quantify the relationship between LRF and hardwood sawmill and log characteristics. Results would thus allow expected and potential changes in hardwood sawmill and log characteristics to be evaluated with respect to their influence on conversion efficiency. Steele and Wagner

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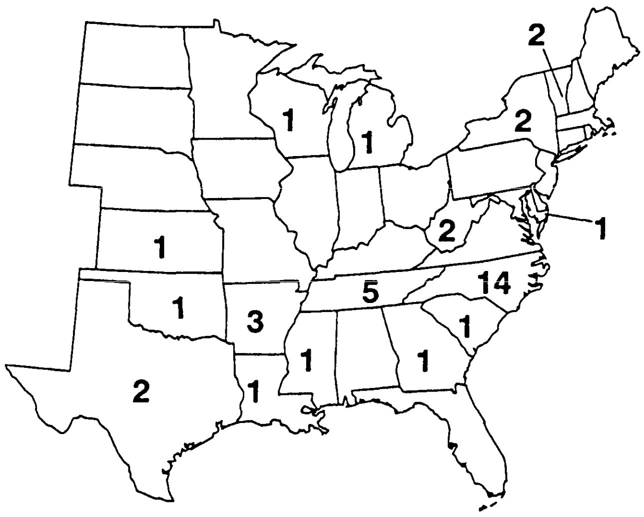

Figure 1.—Locations of SIP studies used in the analysis.

(14) developed a similar model that estimates LRF for softwood sawmills by region.

The data

Data were obtained from Sawmill Improvement Program (SIP) studies of 35 hardwood sawmills. The SIP was a cooperative effort of the USDA Forest Service, State and Private Forestry, and state forestry organizations. SIP studies of hardwood sawmills began in 1977 and continued until 1988. The objective of these studies was to determine the LRF of individual sawmills, and to identify potential changes that would increase LRF for each mill. Follow-up studies were made on many sawmills to check their progress. To avoid double counting of mills, only initial SIP studies were used in this analysis.

The 35 SIP sawmill studies used in this analysis were located in 15 states (Fig. 1). This study included only those sawmills that cut lumber grades that meet standards of the National Hardwood Lumber Association (NHLA) (12). All of the SIP studies used in the analysis had LRF values between 5.0 and 7.5 BF.

Sawing machine characteristics recorded in the SIP studies included sawkerf (headrig and resaw), sawing variation (within-board, between-board, and total), oversizing/undersizing, and rough green size. Sawkerf was estimated as the average width of 10 randomly selected saw teeth from each blade. The largest headrig kerf for sawmills in the analysis was .34 inch. Sawing variation, oversizing/undersizing, and rough green size were obtained by measuring maximum and minimum thicknesses from each of the study boards.

The hardwood SIP studies also measured a 50-log sample sawn during each study. Measurements of log diameter and average log length were taken.

Description of independent variables

Variables assumed to influence LRF were sawkerf, total sawing variation, rough green size, oversizing/undersizing, log diameter, log length, and product class. In the study of LRF of softwood sawmills, Steele and Wagner (14) included all of these variables with the exception of product class.

Kerf is an important factor influencing LRF (2,4,7,13). If other factors are held constant, a reduced kerf should increase a mill's LRF since less fiber is lost in the form of sawdust. An inverse relationship is therefore expected between kerf and LRF. Because the data included both headrig and resaw kerfs, it was decided that these two variables should remain separate (to test the significance of resaw kerf in explaining the variability in LRF).

Total sawing variation, the deviation of a sawblade from its intended line of cut, is a measure of the overall sawing accuracy of a machine during the sawing process. Total sawing variation is not directly measured, but is calculated from direct measurements of within-board and between-board sawing variation (5). The NHLA allows a maximum of 1/4 inch within-board variation for 4/4- to 7/4-inch nominal lumber thicknesses, and 3/8 inch within-board variation for 8/4- to 14/4-inch nominal lumber thicknesses (12). Thus, as much as 1/4 to 3/ 8 inch of wood fiber could be lost as planer shavings resulting from sawing variation. Theoretically, as total sawing variation increases, LRF should decrease, and an inverse relationship between sawing variation and LRF is therefore expected. Steele and Wagner (14) provide a more detailed explanation of total sawing variation.

Rough green size is the dimension of green lumber that includes allowances for the finished size of the dry-dressed lumber, planing allowance, shrinkage, and sawing variation (13). The relationship between rough green size and LRF should be negative (14, 15).

Oversizing/undersizing should also influence LRF (14,15). Oversizing is an additional allowance in rough green size above that required to manufacture a piece of lumber (14). Degree of oversizing is a management decision that usually results in additional wood lost as planer shavings. Undersizing, on the other hand, results in scant lumber that, when planed, produces lumber with planer skips that is sometimes unacceptable in the marketplace. Oversizing/undersizing should have a negative impact on LRF.

Log diameter has also been shown to influence lumber recovery (2,8, 13). As diameter increases, less fiber is lost as a percentage of log volume due to slabbing and edging. The relationship between log diameter and LRF is therefore expected to be positive.

Log length is also expected to influence LRF (8,13). Longer logs generally have greater amounts of wood lost as slabs due to taper. The relationship between log length and LRF is therefore expected to be negative.

Steele (13) explained that products of different dimensions should substantially influence LRF, because product dimension reflects the number of sawlines required to obtain lumber from a given log. Products requiring more sawlines to manufacture should result in a lower LRF. With all other factors equal, therefore, a mill that produces large dimension products should have a higher LRF than one that produces smaller products and the relationship between product size class and LRF should therefore be positive. Ayer-Sachet and Fahey (2) determined this relationship in their study of lumber recovery from ponderosa pine.

Analysis procedure

A multiple-linear regression model was specified to predict LRF for the 35 SIP sawmills based on headrig kerf, resaw kerf, average log diameter and length, total sawing variation, rough green size, oversizing/undersizing, and product size classes:

Model 1

$$LRF = b_0 + b_1(HK) + b_2(RK) + b_3(DIB) + b_4(LENGTH) + b_5(TSV) + b_6(RGS) + b_7(OS) + b_8(PC)$$

where:

LRF = lumber recovery factor
b_0 = intercept
b_1 - b_8 = regression coefficients to be estimated
HK = headrig kerf (in.)
RK = resaw kerf (in.)
DIB = average log diameter (in.)
$LENGTH$ = average log length (ft.)
TSV = weighted average total sawing variation
RGS = weighted average rough green size
OS = weighted average oversizing/undersizing
PC = product size classes

The variable *TSV* is the average total sawing variation weighted by the percentage of total lumber mix for each thickness. 0nly lumber of 4/4, 5/4, 6/4, and 8/4 nominal thicknesses was used because very few studies included other thicknesses. Calculation of *TSV* was computed by averaging by thickness the total sawing variation for both headrig and resaw. The average total sawing variation per nominal thickness was multiplied by its respective percentage production on headrig or resaw and added to the others to determine a single value per headrig and resaw for each sawmill.

RGS and *OS*, which represent the weighted average rough green size and oversizing/ undersizing, were calculated in the same manner as *TSV*.

The variable PC represents nine product classes that were identified as a function of dimension size. Product class influences were included in the model as dummy (indicator) variables and were defined as follows:

PCl = grade lumber
PC2 = pallet stock
PC3 = grade lumber, dimension, and construction
PC4 = grade lumber, timbers, ties, and squares
PC5 = dimension and construction
PC6 = grade lumber and pallet stock
PC7 = dimension, pallet stock, and construction
PC8 = construction, ties, dimension, and squares
PC9 = pallet stock and ties

Since our data were limited to SIP studies of 35 sawmills, our analysis procedure did not include formal validation of the estimated model. The data were therefore used to improve our model rather than to test it. Improvement in the predictive ability of the estimated model and in the adherence of coefficients to a priori expectations on algebraic sign and relative magnitude were important criteria in model selection.

Results

Model 1 coefficients were estimated using ordinary least squares, and the coefficients for headrig kerf, log diameter, and log length were significantly different from zero (at the 0.05 level), and had the expected signs. On the other hand, resaw kerf, weighted average total sawing variation, weighted average rough green size, weighted average oversizing/undersizing, and product class were not significant variables. Although Steele et al. (15) found resaw kerf, total sawing variation, rough green size, and oversizing/undersizing to be significant in softwood sawmills, their effect on LRF was minimal for the hardwood sawmills in our data set. As previously stated, smaller-dimension products require more sawlines to manufacture, and should therefore reduce LRF. A correlation matrix, however, showed that larger, more efficient sawmills use band headrigs and cut smaller dimension products. Thus, this relationship apparently offset the expected relationship of product class and *LRF*, causing PC to be insignificant. Because the above variables did not significantly influence *LRF* in our data set, they were not included in subsequent models.

To better express the influence of sawing variation on LRF, a modification of rough green size was used in subsequent analyses of the data. Rough green size, as previously mentioned, is the desired minimum nominal green thickness plus an allowance for sawing variation.

The minimum nominal rough green thickness, as set by the NHLA (12), was subtracted from each mill's rough green size. This result reflects the absolute fiber amount lost as planer shavings from sawing variation or cutting lumber thicker than necessary, and when divided by the mill's rough green size, represents the relative wood loss as a percentage of lumber dimension. The resultant value was weighed, as previously, by percentage production of each thickness for the headrig and resaw. The result was a single value that expressed the weighted average percentage fiber loss per piece of lumber. The rough green size variable was related to the actual volume fiber loss incurred by multiplying the percentage loss per piece of lumber by the estimated average number of pieces sawn per log for each mill (weighted by thickness between headrig and resaw, and considering the mill's average log diameter). This new sawing variation variable was denoted as *LOSS*, and is the number of pieces of the weighted average dimension that was lost per log from total sawing variation or cutting lumber thicker than necessary.

Further analysis was also required to accurately represent headrig kerf. The data were distinctly clustered in two groups: band headrigs and circular head-

TABLE 1. – *Estimated coefficients and regression criteria for Model 3.*

Parameter	Estimated value and standard error[a]
b_0	1.8892*[b] (.089)
b_1	.0961* (.096)
b_2	-.1340* (.022)
b_3	.0259* (.005)
b_4	-.0130**[c] (.007)
Regression criteria	
F = 30.26	R-squared[d] = 0.80 $S_{y.x}$[e] = .050 (In scale)

[a]Coefficient standard errors are in parentheses.
[b]* indicates significantly different from zero (α= .001).
[c]** indicates significantly different from zero (α= .10).
[d]R-squared is the coefficient of determination.
[e]$S_{y.x}$ is the standard error of the estimate.

rigs. When plotted with *LRF,* band headrigs had significantly higher *LRF* values than circular headrigs (and significantly lower kerf), which is similar to the results of Burry's study of 10 hardwood sawmills (6). In Model 1, the effect of headrig kerf as a continuous variable was to connect these two groups with a single, downward-sloping regression line, a spurious relationship between distinctly separate groups of data. To accurately reflect the influence of headrig kerf, a dummy variable, or intercept shifter, accounted for higher *LRFs* and lower kerf values of band mills.

Another variable transformation was to take the natural logarithm of the dependent variable, *LRF.* The purpose of this was to improve the predictive ability of the model by reducing the absolute scale of variation, and to ensure that all values predicted for *LRF* would be non-negative. Model 2 therefore contains significant variables from Model 1, with the transformations just described:

Model 2

$$\ln LRF = b_0 + b_1(BAND) + b_2(HK) + b_3(DIB) + b_4(LENGTH) + b_5(LOSS)$$

where:

- $\ln LRF$ = natural logarithm of lumber recovery factor
- b_0 = intercept term for mills with circular headrigs
- b_1 = intercept difference for mills with band headrigs
- b_2 - b_5 = regression coefficients to be estimated
- *BAND* = dummy variable for mills with band headrigs (*BAND* =1 for band headrig mills, 0 otherwise)
- *HK, DIB,* and *LENGTH* = same as Model 1
- *LOSS* = number of pieces of weighted average dimension lost per log due to sawing variation

In Model 2, the intercept reflects mills with circular headrigs, and the dummy variable for band headrig allows the model to reflect higher *LRF* values for band mills. Both the intercept and the intercept shifter for band mills were significant at the 0.05 level. The continuous variables for average log diameter and average log length were also significant. Headrig kerf and the number of pieces of weighted average dimension lost per log *(LOSS)* were not significant, however, and the estimated coefficient for headrig kerf was positive.

The positive coefficient for headrig kerf indicated the potential presence of multicollinearity, and a correlation matrix showed headrig kerf to be negatively correlated with log length. In the data set, hardwood sawmills with larger headrig kerfs were processing shorter logs, and because larger kerf and shorter logs have opposing influences on *LRF,* the separate influences of the variables were not reflected by the coefficient estimates. To address this problem, headrig kerf and log length were first standardized to remove the influence of absolute scale, and the variables were then combined to reflect interaction. Headrig kerf was divided by the mean headrig kerf of the 35 studies (.224 in.), while log length was divided by the mean log length of the 35 studies (12.97 ft.). Because headrig kerf and log length are not equally important in predicting *LRF,* various weights were tested for each term. The best fit was obtained by using a weight of 2.75 for log length. Thus, the standardized log length term was multiplied by the constant 2.75 and then added to the standardized kerf term. The result was a unitless variable that allowed the equation to reflect the influence of both headrig kerf and log length on LRF.

A plot of the number of pieces of weighted average dimension lost per log with the natural logarithm of *LRF* indicated that the *LOSS* variable should be squared to produce a better fit.

Model 3

$$\ln LRF = b_0 + b_1(BAND) + b_2(KERF\text{-}LENGTH) + b_3(DIB) + b_4(LOSS^2)$$

where:

- $\ln LRF$ = natural logarithm of lumber recovery factor
- b_0 = intercept term for mills with circular headrigs
- b_1 = intercept difference for mills with band headrigs
- b_2 - b_4 = regression coefficients to be estimated
- *BAND* = dummy variable for mills with band headrigs (*BAND* -1 for band headrig mills, 0 otherwise)
- *KERF - LENGTH* = variable for combined effects of headrig kerf and average log length
- *DIB* = average log diameter
- $LOSS^2$ = number of pieces of weighted average dimension lost per log due to sawing variation, squared

All variables in Model 3 were significant at the 0.001 level except for $LOSS^2$, which was significant at the 0.10 level. Also, the signs of the estimated coefficients were theoretically correct. The coefficients and associated standard errors are given in Table 1. Figures 2, 3, 4, and 5 show the relationship of *LRF* with each independent variable, while holding the other variables constant at their means.

Model 3 parameter estimates maybe used to assess the expected influence of changes in sawmill characteristics, log length, or diameter. Changing from a circular headrig type to a band headrig, for example, would increase *LRF* by an estimated 15 percent (given the following example mill and resource characteristics):

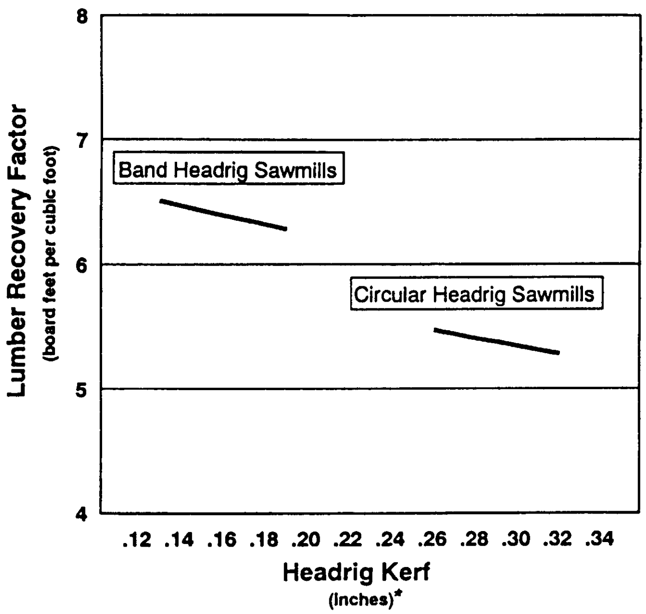

Figure 2.—Relationship between predicted *LRF* and headrig kerf for hardwood sawmills with circular and band headrigs. Variables held constant are: *LENGTH* = 12.97 feet; *LOSS*= 1.30 pieces; and *DIB* = 13.88 inches. (* Relationships are plotted only over the range of headrig kerf information represented by the data set for the 35 mills.)

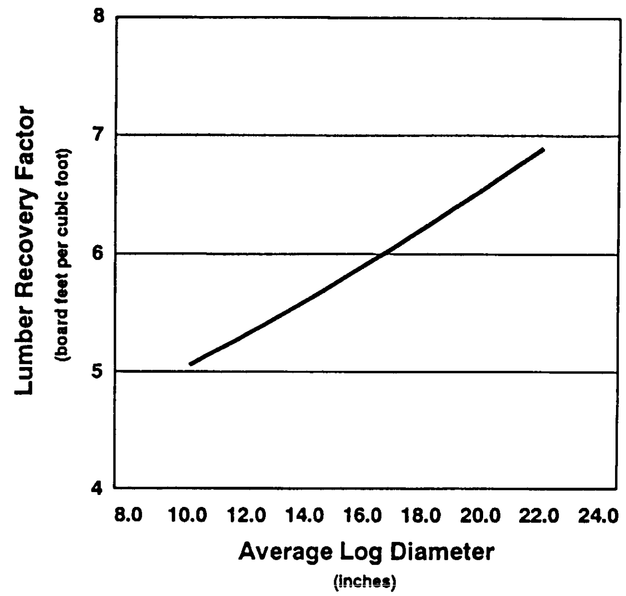

Figure 4.—Relationship between predicted LRF and average log diameter for hardwood sawmills with circular headrigs. Variables held constant are: *KERF* = .224 inch; *LOSS* = 1.30 pieces; and *LENGTH* = 12.97 feet.

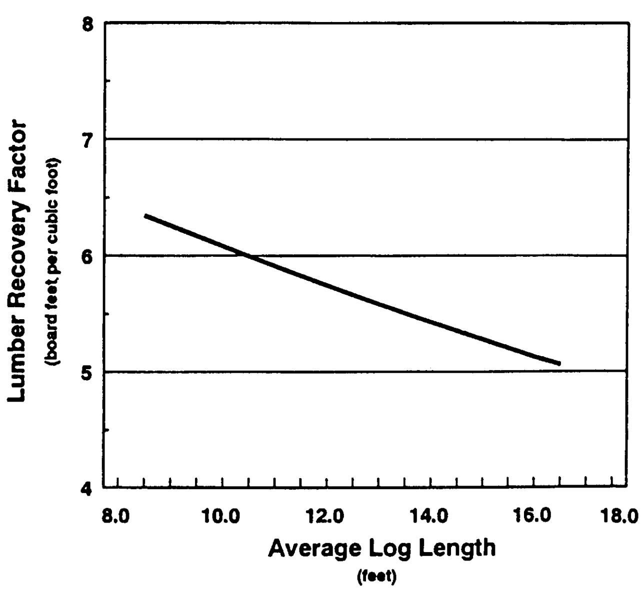

Figure 3.—Relationship between predicted LRF and average log length for hardwood sawmills with circular headrigs. Variables held constant are: *KERF* = .224 inch; *LOSS* = 1.30 pieces; and *DIB* = 13.88 inches.

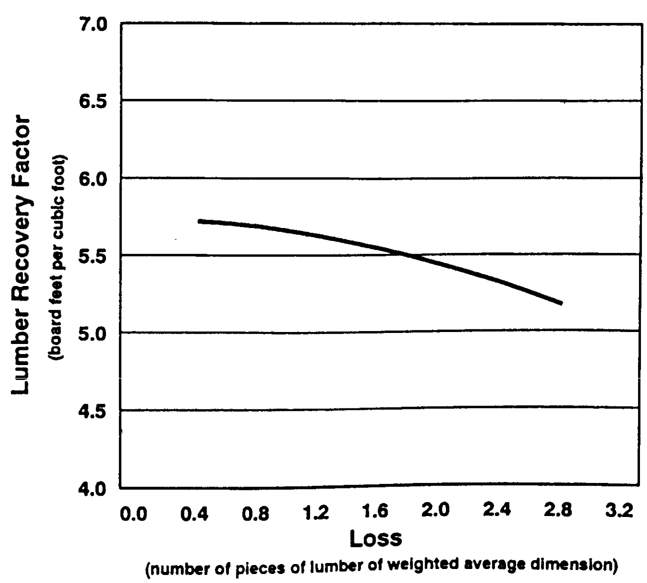

Figure 5.—Relationship between predicted *LRF* and the number of pieces of weighted average dimension lost per log from total sawing variation for hardwood sawmills with circular headrigs. Variables held constant are: *KERF* = .224 inch; *LENGTH* = 12.97 feet; and *DIB* = 13.88 inches.

TABLE 2.- *Absolute changes and elasticities reflected by the coefficient estimates of Model 3.* [a]

Variable	Estimated absolute change	Estimated arc elasticity[b]
Headrig kerf	LRF is increased by .026 for circular mills and .052 for band mills for each .01 inch reduction in headrig kerf	-.13
Log length	LRF is reduced by .157 for circular mills and .173 for band mills for each 1 foot increase in log length	-2.15
Log diameter	LRF is increased by .147 for circular mills and .162 for band mills for each 1 inch increase In log diameter	+.36
Loss	LRF is reduced by .020 for circular mills and .022 for band mills for each .10 Increase in the number of pieces lost per log from total sawing variation	-.05

[a]Absolute changes and elasticities were calculated for changes in each variable with all other variables held constant at their means.
[b]As an example, a 1 percent increase in headrig kerf results in an estimated .13 percent decrease in LRF.

	Before	After
Headrig type	Circular	Band
Headrig kerf	.248	.167
Average log diameter	14.6	Same
Average log length	10.8	Same
Average rough green size		
4/4	1.250	Same
6/4	1.623	Same
Percent of lumber mix		
4/4	70	Same
6/4	30	Same
Lumber recovery factor	5.90	6.80

Model coefficients may also be summarized as estimates of absolute change and as elasticities (Table 2). In terms of absolute change, for example, a reduction in circular headrig kerf of 0.010 inch increases *LRF* by an estimated 0.026 nominal BF per cubic foot of log input. Other estimates are: *LRF* increases by 0.147 for each 1 inch increase in log diameter, *LRF* decreases by 0.157 for each 1 foot increase in log length, and *LRF* decreases by 0.020 for each 1 piece increase in the number of pieces lost to total sawing variation (all other variables at their respective means). The relative importance of each variable in causing changes in *LRF* is best indicated by sensitivity analysis, however. Sensitivity (in the form of elasticities) was tested to determine the change in the dependent variable based on a 1 percent change in an independent variable (again, all others at their respective means). For model 3, the elasticities indicate that a 1 percent increase in headrig kerf results in a -0.13 percent decrease in *LRF*, a 1 percent increase in log length results in a -2.15 percent decrease in *LRF*, a 1 percent increase in log diameter results in a 0.36 percent increase in LRF, and a 1 percent increase in the number of pieces lost to sawing variation results in a 0.05 percent decrease in LRF.

Conclusion

Data from 35 hardwood sawmills having resaws were used to estimate LRF based on characteristics of hardwood sawing machines and log resource. Although our data were not extensive enough for formal validation of the estimated model, signs of the estimated coefficients were as expected, and all coefficients significantly influenced LRF.

For hardwood sawmiller, the resultant model is a useful tool to estimate changes in conversion efficiency from changing machinery or log characteristics, or management decisions that influence yield. For policy makers and planners, the model can be used to estimate the impact of expected technological changes on regional hardwood timber resources. A computer program is being developed that facilitates the calculations necessary to employ the model. This software will allow a sawmiller to simply input machine and log characteristics to determine expected changes in LRF.

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