ESTIMATING BARK THICKNESSES OF COMMON APPALACHIAN HARDWOODS

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Abstract.—Knowing the thickness of bark along the stem of a tree is critical to accurately estimate residue and, more importantly, estimate the volume of solid wood available. Determining the volume or weight of bark for a log is important because bark and wood mass are typically separated while processing logs, and accurate determination of volume is problematic. Bark thickness is known to vary with species, tree diameter, and location along the stem. This paper examines the bark thicknesses of four Appalachian hardwoods: red oak (*Quercus rubra*), white oak (*Quercus alba*), yellow-poplar (*Liriodendron tulipifera*), and sugar maple (*Acer saccharum*). Using bark thickness measurements from multiple sites, average bark thickness by stem diameter and sample height location were determined. In addition, models were developed that predict bark thickness based on measured diameter outside the bark.

INTRODUCTION

Tree bark is a valuable residue resulting from the manufacture of wood products such as lumber, veneer, or pulp. Bark is used for a wide variety of products including mulch, charcoal filters, as a source of tannins for leather and textile processing, or as boiler fuel. Knowing the thickness of bark along the stem is critical in order to accurately estimate bark residue and, more importantly, estimate the volume of the solid wood contained in a log. Bark thickness also can serve as an indicator of tree quality. Because bark is not typically mixed with wood for most products, determining the volume or weight of bark for a log is important (Stayton and Hoffman 1970). Complicating matters is the fact that tree bark thickness is known to vary with species, tree diameter, and with location along the stem (e.g., the height above ground) (Forbes 1955). Measuring the volume of bark once it has been removed from the log can also present difficulties for at least two reasons: (1) using bark weight is problematic as the moisture content will vary depending on log yard conditions, season, and species; and (2) the volume of bark is difficult to determine due to variations in bark particle size and compaction. In addition, physically measuring bark on trees or logs is economically prohibitive due to the amount of time and effort it would require. While bark gauges exist that allow seasoned users to obtain an approximation of bark thickness at a specific location along the log, they only give results for those specific locations from which the stem thickness for an entire section is then extrapolated. Also, employing bark gauges properly requires experience and a feel for the instrument (Brack 2012) as even experienced users occasionally penetrate into the cambium layer. Furthermore, the pressure applied to take the measurement varies from species to species and is not necessarily consistent within a species.

Over the past 40 years, several studies have been conducted that have sought to predict bark thickness and volume of available hardwood. Stayton and Hoffman (1970) developed a model for sugar maple (*Acer saccharum*) to predict average bark thickness for a whole tree based on the average tree diameter. Stayton and Hoffman (1970) based their model on diameter measurements at

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1-, 8-, and 16-foot points up the stem. Their resulting model had an R^2 of 0.51 using the following equation:

$$AverageBarkThickness = 0.1986 + 0.0206 * AverageTreeDiameter$$

Their study was based on a sample of 90 trees. The average bark volume within the sample was 7.38 cubic feet, or approximately 13 percent of the merchantable stem volume. Stayton and Hoffman (1970) also found that bark thickness generally decreases with increased height. However, they were unable to develop equations capable of accurately predicting bark thickness at specific stem heights. Indeed, their research was complicated by sugar maple having four distinct bark types (platy, shell, compound, and ropy), making bark thickness prediction difficult (Sajdak 1968).

Other researchers examined multiple species. For example, Koch (1971) sought to develop models capable of predicting bark volume and thickness for yellow-poplar (*Liriodendron tulipifera*), red oak (*Quercus rubra*), black oak (*Quercus velutina*), and scarlet oak (*Quercus coccinea*), as well as red maple (*Acer rubrum*) in West Virginia. Samples for red oak and yellow-poplar came from two sites in West Virginia while the other species came from a single site in West Virginia. Koch collected approximately 60 sample trees for each species from each site. Using these samples he determined bark factors or ratios between diameter inside bark (DIB) and diameter outside bark (DOB). DOB is the measurement of the diameter to the outside edge of the bark while DIB is the measurement of the diameter to the inside of the bark. Given that logs are not perfect circles, diameter tape measures or calipers are used to measure DOB. Using the ratios allows an average bark thickness and volume to be calculated for the merchantable portion of a tree.

Fowler et al. (1997) examined multiple oak species in Michigan and developed a series of bark factors. Their measurements and analyses were based on 53 red oak, 23 black oak, and 28 white oak (*Quercus alba*) trees. Unlike Koch (1971), Fowler et al. (1997) used linear regression methods to determine a factor for each species from which bark thickness can be calculated. Red oak yielded the best coefficient of determination (R^2 = 0.418) for all models. White oak resulted in the weakest correlation (R^2 = 0.014), while black oak bark had an R^2 = 0.270. Thus, overall, the bark factors developed by Fowler et al. (1997) explained only a relatively small portion of the bark thickness variance observed within the samples.

One of the most comprehensive examinations of bark thickness was accomplished by Hilt et al. (1983) in which the authors studied 10 hardwood species. Their study sampled approximately 200 trees per species. The data used by the authors was originally collected in the 1960s for the development of log and tree grades for hardwoods (Hanks et al. 1980). As such, the authors note that "mostly larger trees were analyzed in the study." The trees were bucked in 8- and 16-foot long logs and the DIB measured at the small end of each log. The number of measurements per tree depended on tree size, however, all trees had at least two DIB and bark thickness measurements, but no tree had more than seven measurements. A linear regression analysis was conducted for each species. The resulting bark factor equations had the form of:

$$DIB / DOB = \beta_0 + \beta_1 * DOB / DBHOB$$

where DBHOB is the diameter at breast high measured outside the bark. Although no coefficient of determination was reported for their analyses, the authors did test to see if the β_1 term was

Table 1.—Location of log sample sites and number of samples selected

Species	Location	Elevation (feet)	Number of trees	Number of samples
Yellow-poplar	WVU Experimental Forest, WV	2300	33	505
Yellow-poplar	Camp Creek State Forest, WV	2600	33	482
	Total		66	987
Red oak	WVU Experimental Forest, WV	2300	33	355
Red oak	MeadWestvaco Forest, Rupert, WV	3200	33	423
	Total		66	778
White oak	Fernow Experimental Forest, WV	2936	32	497
White oak	Fayette County, Site 1, WV	2451	15	145
White oak	Fayette County, Site 2, WV	2425	16	276
	Total		63	918
Sugar maple	Fernow Experimental Forest, WV	2438	34	449
Sugar maple	MeadWestvaco Forest, Rupert, WV	3451	31	466
	Total		65	915
All species	Total		260	3598

significantly different from zero. In all species except black cherry (*Prunus serotina*), southern red oak (*Quercus falcata*), and American beech (*Fagus gradifolia*), the β_1 term was found to be significantly different from zero (a = 0.05).

The findings presented in these past studies were typically based on four bark thickness measurements per tree. In addition, for some studies the number of trees sampled was small. The research presented in this manuscript used a greater number of bark thickness measurements per tree. The findings of bark thicknesses measurements and modeling of four common hardwood species (yellow-poplar, red oak, white oak, and sugar maple) from the central Appalachian region are presented in this manuscript.

METHODS

Recently, a series of yellow-poplar, red oak, white oak, and sugar maple log defects were collected and studied to determine the relationships among external log defect indicators and internal defect manifestations (Thomas 2008, Thomas 2009b, Thomas 2012, Thomas[2]). Log defects are imperfections that appear on the surface of the log and indicate the presence of an interior defect. Such defects decrease the grade and value of the log as well as the grade and value of the lumber and products that can be obtained from the log. A total of 66 yellow-poplar, 66 red oak, 63 white oak, and 65 sugar maple trees were randomly selected from sites in West Virginia. On these sites, the total number of trees available for harvest was determined. Depending on the number of trees available, a selection factor was determined which dictated which trees would be selected (i.e., every third tree). In some instances, the forester in charge of the harvest chose to leave one of the selected trees and would pick a substitute tree. From the 260 trees sampled in this study, a total of 3598 bark measurements were recorded (Table 1).

[2] Thomas, R.E. [N.d.]. Predicting internal sugar maple (Acer saccharum) log defect features using surface defect indicator measurements. Manuscript in preparation. On file with author.

Table 2.—Comparison of sample measurements by species and sampling location

Species	Site	Mean bark thickness	Mean DOB[a]	Mean ring count
		--------*Inches*--------		
Yellow-poplar	WVU Experimental Forest	0.54	11.21	51.4
	Camp Creek State Forest	0.55	9.75	58.5
	Overall	0.54	10.49	54.9
	Difference significant	Yes	Yes	Yes
Red oak	WVU Experimental Forest	0.33	11.04	58.7
	MeadWestvaco, Rupert, WV	0.32	13.73	77.6
	Overall	0.33	12.27	67.3
	Difference significant	Yes	Yes	Yes
White oak	Fernow Experimental Forest, WV	0.34	12.96	82.0
	Fayette County, Site 1, WV	0.36	13.67	127.7
	Fayette County, Site 2, WV	0.31	11.01	64.0
	Overall	0.33	12.49	83.9
	Difference significant	Yes	Yes	Yes
Sugar maple	Fernow Experimental Forest, WV	0.28	11.63	64.2
	MeadWestvaco, Rupert, WV	0.28	11.90	65.6
	Overall	0.28	11.77	64.9
	Difference significant	No	Yes	Yes

[a]DOB=diameter outside bark.

The trees were originally harvested for defect studies where a random set of defects was selected from each log. The goal of this selection was to obtain as many as four defects of each type from each log. The height of the defect up the stem as well as the diameter of the defect on a given log sample were not used as decision criteria in the defect selection process. Once the defects were selected, the log diameter inside the bark and the bark thickness were measured to the nearest 1/16 (0.0625) of an inch. Log diameter and bark thickness were measured along the minor and major axes (minimum and maximum diameter) of the sample and were averaged. The defect areas were bucked from the logs at a minimum of 8 inches above the defect indicator. Although the measurements were taken near defects, they were taken well beyond the defective area. In addition, the growth rings were counted for every defect sample used. All defect samples missing bark were excluded from this study.

Statistical Methods

Using R (R Foundation for Statistical Computing, Vienna, Austria), a number of statistical tests were used to determine if there were any significant differences for bark thickness among sample sites, DOB, or ring count measurements for each species. First, Anderson-Darling normality tests (Anderson and Darling 1952) were performed to determine if the data were normally distributed ($\alpha = 0.05$). The test revealed that none of the measurements for bark thickness or diameter outside bark from any of the sites or species were normally distributed. Due to the non-normal distributive nature of the data, Wilcoxon rank sum tests (Wilcoxon 1945) were used to determine if there were significant differences ($\alpha = 0.05$) in the measurements of the red oak, sugar maple, and yellow-poplar data due to collection site. Since the white oak samples were collected from three sites, a Kruskal-Wallis rank sum test (Corder and Foreman 2009) was used to test for significant differences ($\alpha = 0.05$) in measurements among these three sites. Table 2 lists the mean bark thicknesses, mean DOB, and mean ring count by species and site and indicates if the difference between or among the sites was significant. The comparisons for each species involved three statistical tests, thus the significance level was adjusted for each individual test using the Bonferonni correction (Adbi 2007).

A series of general linear regression analyses were performed on the bark thickness data using the R statistical software. Two models were examined, one that used DOB as a single independent variable, and a second that used sample height, (i.e., the height at which bark thickness was being estimated) and DOB as the independent variables. Bark thickness was the dependent variable for both models. The coefficient of determination and the mean absolute error (MAE) were determined for each species using both models.

The main reason for two models was because of the potential for autocorrelation issues with the DOB only model. Very strong autocorrelation can result in apparent trends when there is no real trend underlying the series. Using a series of Durbin-Watson tests (Hogg and Ledolter 1987), it was determined that the autocorrelation present in the DOB only model was significant ($\alpha = 0.05$), but no significant autocorrelation existed in the DOB and height model. The Durbin-Watson test returns a test statistic valued between 0 and 2. The closer the test value is to 0, the stronger the auto correlation. The closer it is to 2, the weaker the autocorrelation. With our models, the lowest Durbin-Watson value observed with the DOB only model was 1.64, indicating relatively weak autocorrelation.

Using these regression results, Cook's distance (Cook and Weisberg 1982) was used to determine if any individual observation had an influence on the accuracy of the regression results. The number of observations identified as having a significant influence by species was: 11 for yellow-poplar, 16 for red oak, 11 for white oak, and 12 for sugar maple. Most of these observations were taken on thicker bark samples collected near the base of the tree.

Bark thickness data were randomly grouped into model development (66.67 percent) and model testing (33.33 percent) sets for each species. In the regression analyses, diameter outside bark was used as the independent variable and bark thickness as the dependent variable. Using these results, prediction equations were developed and tested using the development data set, and the correlation coefficient and the coefficient of determination were determined.

RESULTS AND DISCUSSION

Significant correlations between DOB and bark thickness were found for all species, indicating that bark thickness can be predicted based on DOB. Also, the overall coefficient of determination between bark thickness and DOB as well as the MAE for each species was determined. In addition, significant correlations were found to exist between DOB, height on stem, and bark thickness for all species. These results are listed in Table 3.

Yellow-Poplar

The yellow-poplar bark thickness prediction model was developed using 987 bark thickness measurements collected from 66 trees harvested from two sites (Table 1). Mean bark thicknesses from the two sites were 0.54 and 0.55 inches, and this difference of 0.01 inch was found to be statistically significant ($\alpha = 0.05$). The differences between the mean DOB and the mean ring counts

Table 3.—Bark thickness correlation results for model development, testing, and overall by species and model

Species	Model	Development		Testing		Overall	
		R^2	MAE	R	MAE	R^2	MAE
Yellow-poplar	DOB (Eq. 1)	0.211	0.075	0.495	0.078	0.223	0.076
	DOB + Height (Eq. 2)	0.264	0.072	0.531	0.077	0.270	0.074
Red oak	DOB (Eq. 3)	0.033	0.059	0.145	0.064	0.028	0.060
	DOB + Height (Eq. 4)	0.039	0.059	0.175	0.064	0.036	0.060
White oak	DOB (Eq. 5)	0.110	0.066	0.346	0.067	0.110	0.066
	DOB + Height (Eq. 6)	0.131	0.065	0.383	0.065	0.137	0.065
Sugar maple	DOB (Eq. 7)	0.045	0.055	0.217	0.057	0.045	0.057
	DOB + Height (Eq. 8)	0.065	0.055	0.242	0.077	0.058	0.056

Table 4.—Average observed yellow-poplar bark thickness and bark thickness calculated using different methods.

Diameter	Average by diameter class	Calculated using Thomas and Bennett (Eq. 1)	Calculated using Thomas and Bennett (Eq. 2)[a]	Calculated using Haygreen and Bowyer equation	Calculated using Hilt et al. equation[b]
			Inches		
20 >	--	0.77	0.82	0.92	0.73
18 - 20	0.75	0.73	0.76	0.83	0.73
16 - 18	0.74	0.68	0.70	0.75	0.73
14 - 16	0.65	0.63	0.64	0.67	0.71
12 - 14	0.61	0.58	0.58	0.59	0.67
10 - 12	0.55	0.53	0.52	0.50	0.62
8 - 10	0.51	0.48	0.46	0.42	0.54

[a]Assuming height of 16 feet.
[b]Assuming the diameter at breast height measured outside the bark is 20 inches.

of the two sites also were significantly different at α =0.05 (Table 2). Using the yellow-poplar model development data set, the correlations between DOB, height, and bark thickness were determined, and the following prediction models were developed:

$$BarkThickness = 0.295 + DOB * 0.024 \quad (1)$$

$$BarkThickness = 0.159 + DOB * 0.0302 + Height * 0.00015 \quad (2)$$

Overall, the coefficients of determination (R^2) and correlation coefficients (R) were stronger with the second model (Eq. 2) which used DOB and height. In addition, Equation 2 had a lower MAE than Equation 1 (Table 3). Table 4 lists by diameter class the average observed bark thickness, the estimated bark thickness using Thomas and Bennett's models developed in this study (Equations 1 and 2), as well as results based on equations from Haygreen and Bowyer (1996) and Hilt et al. (1983). Averages within diameter class were determined using the overall data set with 2-inch diameter intervals. It is interesting to note that the bark thicknesses calculated using Equation 2 fall between the values determined by the other equations in all but one instance. Values from Equation 1 were within the range of Haygreen and Bowyer's and Hilt et al.'s equations in all but two instances. In these cases, Thomas and Bennett's models predicted values that were slightly less than those calculated by the Haygreen and Bowyer and Hilt et al.

Red Oak

Red oak bark thickness prediction models were developed using 778 thickness measurements collected from 66 trees harvested from two sites (Table 1). Mean bark thicknesses from the two sites were 0.33 and 0.32 inch, and the difference of 0.01 inch between sites (Table 2) was found to be significantly different ($\alpha = 0.05$). In addition, differences between the mean DOB and ring count were significantly different ($\alpha = 0.05$) between the two sites. The difference in mean bark thickness could possibly be explained by the difference in age and measured sample diameter between the sites. Samples from the MeadWestvaco site were, on average, nearly 20 years older and 2 inches wider in diameter. Using the model development set, the correlations between DOB, height, and bark thickness measurements were determined and the following prediction models were developed:

$$BarkThickness = 0.267 + DOB * 0.005 \quad (3)$$

$$BarkThickness = 0.291 + DOB * 0.0042 - Height * 0.000046 \quad (4)$$

R^2 and R coefficients for both models were weak but statistically significant ($\alpha = 0.05$). Equation 3 had slightly stronger correlations and lower MAE values than were observed with Equation 4 (Table 3). Of the four species examined, red oak samples had the weakest correlations. Table 5 lists by diameter class the average observed bark thickness, the calculated bark thickness using Equations 3 and 4 by Thomas and Bennett, as well as equations from Haygreen and Bowyer (1996) and Hilt et al. (1983), and the bark factor equation from Fowler et al. (1997). Diameter class averages were determined using the overall data set with 2-inch diameter intervals. As seen in Table 5, the bark thicknesses calculated using the Hilt et al. equation are thickest of all the methods. In addition, the thicknesses calculated by Fowler's equation are less than those observed and those calculated using the Thomas and Bennett's models for DOBs of 16 inches and under. For diameters over 16 inches, bark thicknesses calculated using Thomas and Bennett models were less than bark thicknesses calculated using the other methods.

Table 5.—Average observed red oak bark thickness and bark thickness calculated using different methods

Diameter	Average by diameter class	Calculated using Thomas and Bennett (Eq. 3)	Calculated using Thomas and Bennett (Eq. 4)[a]	Calculated using Haygreen and Bowyer equation	Calculated using Hilt et al. equation[b]	Calculated using Fowler et al. bark factor equation
			Inches			
20 >	--	0.37	0.37	0.78	0.60	0.51
18 - 20	0.39	0.36	0.36	0.71	0.60	0.46
16 - 18	0.34	0.35	0.35	0.65	0.60	0.37
14 - 16	0.33	0.34	0.34	0.58	0.59	0.29
12 - 14	0.33	0.33	0.34	0.52	0.56	0.22
10 - 12	0.32	0.32	0.33	0.45	0.52	0.16
8 - 10	0.30	0.31	0.32	0.39	0.46	0.11

[a]Assuming height of 16 feet.
[b]Assuming the diameter at breast height measured outside the bark is 20 inches.

White Oak

The white oak bark thickness prediction model was developed using 918 thickness measurements collected from 63 trees harvested from three sites (Table 1). The mean bark thicknesses measured from the three sites were 0.34, 0.36, and 0.31 inches with a difference of $\pm$0.05 inch. The Kruskal-Wallis rank sum tests (α = 0.05) showed that all three site variables were significantly different (α = 0.05) among the sites (Table 2). This was not surprising, given a 2.6-inch difference in mean DOB and a range of 63 for mean ring count. It is interesting to note that the thinnest mean bark thickness was with the youngest and smallest DOB site, Fayette Site 2, while the thickest mean bark thickness was observed at Fayette Site 1 which had the largest mean DOB and was the oldest site. Using the white oak development data sample set, the correlations between DOB, height, and bark thickness measurements were determined and the following prediction equations were developed:

$$BarkThickness = 0.221 + DOB * 0.009 \quad (5)$$

$$BarkThickness = 0.169 + DOB * 0.0107 + Height * 0.0000675 \quad (6)$$

White oak correlations were the second strongest of all species examined (Table 3). In addition, all correlations were significant (α = 0.05). Table 6 lists the average observed bark thickness by diameter class, and bark thickness calculated using Thomas and Bennett's Equations 5 and 6 as shown above, as well as equations from Hilt et al. (1983) and Fowler et al. (1997). Diameter class averages were determined using the overall data set in 2-inch diameter intervals. The bark thicknesses calculated using Hilt et al.'s equation were thickest of all the methods. As with red oak, the thicknesses calculated by Fowler's equation were less than those observed and less than the ones calculated using the Thomas and Bennett equation for DOBs of 14 inches and under. For diameters over 16 inches, bark thicknesses calculated using the Thomas and Bennett models were less than the other methods but close to the average bark thickness measured.

Table 6.—Average observed white oak bark thickness and bark thickness calculated using different methods

Diameter	Average by diameter class	Calculated using Thomas and Bennett equation 5	Calculated using Thomas and Bennett equation 6[a]	Calculated using Hilt et al. equation[b]	Calculated using Fowler et al. bark factor equation
Inches					
20 >	0.38	0.41	0.41	0.68	0.51
18 - 20	0.38	0.39	0.39	0.67	0.45
16 - 18	0.38	0.37	0.36	0.64	0.40
14 - 16	0.37	0.36	0.34	0.61	0.35
12 - 14	0.34	0.34	0.32	0.56	0.30
10 - 12	0.30	0.32	0.30	0.50	0.25
8 - 10	0.30	0.30	0.28	0.43	0.20

[a]Assuming height of 16 feet.
[b]Assuming the diameter at breast height measured outside the bark is 20 inches.

Sugar maple

The sugar maple bark thickness prediction model was developed using 915 bark thickness measurements collected from 65 trees harvested from two sites (Table 1). Mean bark thickness was 0.28 inches at both sites (Table 2). Using Wilcoxon rank sum tests, it was determined that there was no significant (α = 0.05) difference in mean bark thickness between the two sites. However, mean DOB and ring count were significantly different (α = 0.05) between the two sites, although the differences were small. Using the sugar maple model development set, the correlations between DOB, height, and bark thickness measurements were determined and the following prediction equations were developed:

$$BarkThickness = 0.190 + DOB * 0.007 \quad (7)$$

$$BarkThickness = 0.129 + DOB * 0.0131 + Height * 0.0000828 \quad (8)$$

Sugar maple had the second weakest correlations of all species examined (Table 3), but all correlations were significant (α = 0.05). Table 7 lists by diameter class the average observed bark thickness and the calculated bark thickness using Equations 7 and 8 by Thomas and Bennett and equations from Haygreen and Bowyer (1996) and Hilt et al. (1983). Diameter class averages were determined using the overall data set with 2-inch diameter intervals. Bark thicknesses calculated using the Hilt et al. (1983) equation were the thickest of all the methods, and those calculated using the Haygreen and Bowyer (1996) equation were the thinnest. Bark thicknesses calculated using Thomas and Bennett models (Eqs. 7 and 8) were between the values determined by the other two methods.

SUMMARY AND CONCLUSION

Most bark thickness studies conducted prior to this research have been based on a larger set of sample trees, but on fewer bark thickness measurements (typically 3 to 7) per stem. In contrast, this study was based on a fewer number of trees but more bark thickness measurements per stem (overall average of over 8 per stem), indicating the key difference between the studies. In addition, the trees used in this study were taken from active logging operations from forests that were slated for harvest.

Table 7.—Average observed sugar maple bark thickness and bark thickness calculated using different methods

Diameter	Average by diameter class	Calculated using Thomas and Bennett (Eq. 7)	Calculated using Thomas and Bennett (Eq. 8)[a]	Calculated using Haygreen and Bowyer equation	Calculated using Hilt et al. equation[b]
Inches					
20 >	--	0.34	0.42	0.328	0.72
18 - 20	--	0.32	0.39	0.294	0.71
16 - 18	0.30	0.31	0.37	0.260	0.69
14 - 16	0.31	0.30	0.34	0.226	0.65
12 - 14	0.29	0.28	0.32	0.192	0.60
10 - 12	0.27	0.27	0.29	0.158	0.53
8 - 10	0.26	0.25	0.26	0.124	0.46

[a]Assuming height of 16 feet.
[b]Assuming the diameter at breast height measured outside the bark is 20 inches.

Yellow-poplar had the strongest correlation between bark thickness and DOB with an R^2 of 0.223 and a MAE of 0.078 inch. The yellow-poplar bark thicknesses as calculated using the Thomas and Bennett equations (Eqs. 1 and 2) were similar to those calculated using equations derived by Haygreen and Bowyer's (1996) and Hilt et al. (1983). The weakest overall coefficients of determination between DOB and bark thickness were with sugar maple (R^2 = 0.045) and red oak (R^2 = 0.028). For these two species, DOB explained only a small percentage of the variance in bark thickness in our samples. However, the correlations were highly significant (α = 0.05).

Overall, the largest differences in sample characteristics among the sites occurred with white oak. Samples from the Fayette Site 1 had a mean ring count of approximately 126, which was 62 and 45 more than those from the other sites (Fayette Site 2 and Fernow Experimental Forest, respectively), resulting in significant differences (α = 0.05) among sites. Mean bark thickness and mean DOB also were significantly different among the three sites. Despite the differences among sites, white oak had the second highest coefficient of determination (R^2 = 0.137) of all the four species examined. Furthermore, the relationship between diameter and bark thickness was stronger in our samples than those encountered by Fowler et al. (1997). Sugar maple had the least differences in sample characteristics among the sample sites. Overall, the second weakest correlations were observed with sugar maple.

One of the main goals of this research was to develop a method of estimating bark thickness from stem measurements. Using an expensive laser scanner and the equations developed here would allow operators to estimate bark thickness and, therefore, bark volume and total solid log volume. Given the low correlations between DOB and bark thickness, more work is needed. However, the low mean absolute error is encouraging. In the future we plan to collect additional samples for each species from a larger geographic area in an effort to improve the models. This would also provide a means of validating the current bark thickness equations. As additional species data is collected for the hardwood log defect databank (Thomas 2009b), bark thickness prediction models will be developed.

ACKNOWLEDGMENTS

The authors would like to thank the West Virginia University Experimental Forest staff, West Virginia Division of Forestry, and MeadWestvaco, Inc. in Rupert, WV for their assistance in sample site identification and sample collection.

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