Effects of bark thickness estimates on optimal log merchandising

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Abstract

Bark plays a critical role in the life of a tree when it is standing. Once the tree is felled, however, bark has minimal value and may be a net financial loss to the forest industry. Because of bark's limited worth, logs are often bought and sold based on under bark measurements. Removing bark in the forest is generally very difficult, so over bark measurements are often made and converted to under bark using a bark thickness model. This study investigated the effect of six bark thickness models on the predicted volume and value recovery obtained during the log bucking process. The results indicate that the type of bark thickness model used is of lesser importance than obtaining the correct model coefficients. This study investigated the effect of using a bark thickness model developed for a different species or using data from the same species but a different site. Using the wrong species coefficients for the chosen model can result in 34 percent of the logs being out-of-specification, volume estimates being incorrect, and a loss of value to the forest owner of up to 11 percent. The results show that, for the stands in this study, 2 to 5 percent value gains could be achieved simply by using stand-specific bark thickness coefficients.

Other than serving as a source of energy, tannins, and landscape mulch, bark has little economic value in most species, hence most mills buy logs in terms of their wood-fiber volume beneath the bark and specify diameter limits in terms of under bark measurements (Ellis and Elliott 2001). In many of the forest product manufacturing processes, the inclusion of bark is a serious problem.

Bark thickness is estimated using equations or tables that use variables such as diameter over bark, height up the tree, or total tree height. Many of the models (Gordon 1983, Cao and Pepper 1986, Johnson and Wood 1987) were developed for measuring the standing volume of a tree and used independent variables such as inside bark diameter at breast height to increase their predictive power. The operational constraints of the merchandizing process of mechanical harvesters/processors means that the measurement requirements of many of these models cannot be met during this process. On most modern harvesters/processors, different bark thickness coefficients can be entered for a set of standard bark thickness equations.

The variations in bark thickness between species, sites, trees, and along a tree (e.g., Spurr 1952, Philip 1994, Wilhelmsson et al. 2002) mean that selecting the correct bark thickness equation and coefficients can have a significant impact on the estimated volume, value recovery, and number of logs produced that do not meet the desired specifications from a mechanical log merchandizing operation.

The objective of this study was to determine the importance of accurate bark thickness estimates on the volume and value recovery from optimal log merchandizing. This paper discusses the effects of different methods of estimating bark thickness from the perspectives of both mill and forest owners.

Methodology

Definitions

The following variables and regression coefficients are common to all models used in this paper. The equations are shown in **Table 1** and their definitions are:

b_i (i = 0, 1, 2, 3), model coefficients
h = height up the stem from the ground (m)

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dib = diameter inside the bark

dob = diameter over the bark

DBT = double bark thickness (dob − dib)

BTR = bark thickness ratio (dob/dib)

dbh_indicator = an indicator variable (1 if the diameter measurement is at breast height, 0 if it is above breast height)

Different thickness models

The following is a list of equations that appear to be the most applicable for estimating bark thickness at the time of harvest when the stem is being measured with a mechanical harvester/processor. The model coefficients (b_i) in these models are determined using bark thickness data sets measured carefully to minimize measurement errors (Gordon 1983, Gordon and Penman 1987).

Developing the models

Data collection. — Accurate bark thickness data were collected for three species: *Pinus radiata* D.Don (radiata pine), *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir), and *Pinus ponderosa* Lawson & C.Lawson (ponderosa pine). The radiata pine data were collected from two stands in the Central North Island of New Zealand. The Douglas-fir data sets were collected from the Mount St. Helens tree farm and Capitol Forest in Washington. The ponderosa pine data were collected from a stand in eastern Oregon. Details of these stands are given in **Table 2**. The measurements were made on trees that were felled mechanically and left on the ground. It is suggested that measurements from at least 20 trees are required to construct a new bark equation (Gordon and Penman 1987). In all but one of the datasets, at least 20 trees were measured (**Table 3**). On each tree, the under and over bark diameters were measured at the butt end and at 3-m intervals up the stem. In some cases, breast height measurements were made. The outside bark diameter measurements were made using a set of calipers. The bark was removed, in the Douglas-fir and ponderosa pine stands, using an axe. The inside bark diameters were then measured with calipers. In the radiata pine stands, a bark thickness gauge was used to determine bark thickness and under bark diameter. On trees that were out-of-round, two outside and inside diameters were measured then averaged. In some cases, diameter could not be measured at certain heights; these were estimated using the taper calculated from surrounding diameter measurements. **Table 3** gives summary statistics of the bark thickness datasets.

Table 1. — Bark thickness equations evaluated in this paper.

Eq.	Equation	Reference/Comment
[1]	$dib = b_1 dob$ where $b_1 = \frac{\Sigma dib}{\Sigma dob}$	Meyer (1946)
[2]	$DBT = b_1 dob + b_2$	(Loetsch et al. 1973); is used in StandForD
[3]	$dib = b_0 + b_1 dob + b_2 dob^2 + b_3 dob^3$	Gordon (1983)
[4]	$BTR = (b_o + b_1 h + b_2 dib_{(butt)})$	Used in OSU Buck (Sessions et al. 1993)
[5]	$\begin{array}{cc} \textit{Diameter (cm)} & \textit{DBT (cm)} \\ \hline 0 \text{ to } 20 & b_0 \\ \hline 21 \text{ to } 40 & b_1 \end{array}$	Used in StandForD
[6]	$DBT = b_o + b_1 dob + b_2 \ln(dob) + b_3(dbh\_indicator)$	Wilhelmsson et al. (2002)

Fitting models and data analysis. — The ratio used in Equation [**1**] (**Table 1**) was calculated by dividing the sum of the under bark diameters by the over bark diameters. The linear models (Eqs. [**2**], [**3**], [**4**], [**6**]) were fitted using the linear regression package in Microsoft Excel™. Equation [**5**], which is a lookup table, was developed by dividing the double bark thickness for each data set into four categories based on their corresponding over bark diameters. The categories represented 20 cm over bark diameter classes (i.e., 0 to 19 cm, 20 to 39 cm); in each of the four categories, the average double bark thickness was determined and assigned to that category.

Comparison of bark thickness equations. — The ability to compare performance of the different bark thickness equations was limited by the small data sets and the use of different dependent variables in the model. The small size of the data sets meant that data could not be split into two sets, one for fitting the model and one for validating the model, as suggested by many researchers. Therefore, fit statistics were used to evaluate the equations developed.

Measurements taken at several positions along the same tree are not independent (Muhairwe 2000). This causes the error terms to be correlated, resulting in invalid and misleading statistical inferences based on the t and F distribution tests. The following two statistics were used to judge the fit; modeling efficiency (EF) analogous to r^2, calculated as $(1-(\sum \hat{e}/\sum (y_i - \hat{y})^2))$ where $\hat{e}$ is the residual (observed − predicted value), and mean bias (Bias). As the goal of this paper was not to create and validate these bark thickness equations but rather to investigate the effect of different bark thickness estimates on volume and value recovery, only limited fit and test statistics are presented.

Effects of different models on volume and value recovery

Description of the stem databases. — The stem databases were collected by accurately measuring felled trees. Over bark diameters at approximately 3-m intervals up the stem, the location of changes in knot size, and the severity of other defects were collected for each tree (Marshall 2005). The stem form was also recorded; changes in stem curvature (sweep) were recorded by measuring the start and end location of the swept section and the severity relative to the diameter at the top of the swept section. A summary of the three stem databases is given in **Table 4**.

Table 2. — Stand details for bark thickness data.

Stand	Species	Latitude	Elevation	Age	Stocking	Average DBH	Average tree size
			(m)	(yr)	(trees/ha)	(cm)	(m^3)
RP_1	Radiata pine	38.2 S	500	31	372	na	2.34
RP_2	Radiata pine	38.2 S	250	28	300	na	2.34
DF_1	Douglas-fir	45.9 N	580	54	273	46	2.35
DF_2	Douglas-fir	46.9 N	490	49	306	46	1.86
PP	Ponderosa pine	44.9 N	975	Mixed age	415	27	0.39

Table 3. — Summary statistics of felled sample trees.

	RP$_1$	RP$_2$	DF$_1$	DF$_2$	PP
No. of trees	51	16	20	25	25
No. of observations	368	112	124	228	103
			(cm)		
Diameter inside bark					
Minimum	8.0	9.4	5.1	0.8	2.8
Maximum	59.0	58.0	72.1	81.4	57.2
Mean	29.7	29.4	34.4	25.6	19.1
Diameter outside bark					
Minimum	9.0	10.0	5.7	1.0	3.0
Maximum	68.0	67.0	82.2	89.2	61.7
Mean	32.0	31.2	37.7	27.6	22.3

The ponderosa pine stem descriptions and bark thickness measurements were collected from the same stand. The Douglas-fir stem descriptions were collected from the Mount St. Helens tree farm in Washington. The radiata pine stem descriptions were collected from a stand in the Central North Island of New Zealand.

Description of the log grade specifications. — Log grade specifications describe the minimum log characteristics required for a log to be sold as a particular grade at a given price. The specifications in this paper were obtained from the forest owners of the stands from which the stem data were collected. The specifications included characteristics such as range of log lengths and diameters (small and large end), minimum acceptable quality features (e.g., maximum branch size), and maximum allowable sweep. **Table 5** summarizes the log grade specifications used.

The price ranges given in **Table 5** are relative prices, not the market prices. Relative price takes into account not only the market price, but also the market demand. It does this by representing the importance of each log type relative to other log types (Murphy et al. 2004).

Description of the optimal bucking/bark thickness simulation model. — To compare the effect of the different bark thickness equations, the bark was first removed from the stems using the six bark thickness equations. Each set of unbarked stems was optimally bucked using the "BUCKIT" algorithm (Marshall 2005). BUCKIT uses a dynamic programming algorithm to determine the optimal cutting pattern given a stem description and set of log specifications. The volumes and values provided by the model were compared to those calculated using the other bark thickness equations.

Although studies have shown that measurement accuracy of mechanical harvester/processors is reasonably poor (Makkonen 2001, Andersson and Dyson 2002, Sondell et al. 2002), for purposes of simplification it has been assumed that all other stem measurements, including over bark diameter measurements, are accurate. Furthermore, it is assumed that all bark was intact on the stem during stem measurement and bucking.

A number of steps was required to determine the value loss and number of out-of-specification logs. Incorrect regression coefficients were generated from the bark thickness data from the other species and sites. A solution was first produced from the stem using the incorrect regression coefficients. This solution was then checked to see whether it was actually feasible, that is, could it be cut from the stem given the correct bark thickness estimates?

Table 4. — Summaries of stem databases.

Stem database	Stand	Average stem length	Average stem size	Number of trees
		(m)	(m^3)	
RP$_{SD}$	RP$_1$	29.0	2.34	107
DF$_{SD}$	DF$_1$	21.1	2.35	100
PP$_{SD}$	PP	13.3	0.39	100

Table 5. — A brief description of the log specifications used with each stem database.

Log specification	Stem database	Number of log grades	Length range	Price range
			(m)	(\$/m^3)
RP$_{LS}$	RP$_{SD}$	20	1.0 to 12.1	31 to 153
DF$_{LS}$	DF$_{SD}$	11	3.6 to 12.2	22 to 157
PP$_{LS}$	PP$_{SD}$	7	2.4 to 6.7	4 to 62

The BUCKIT algorithm assesses this by taking the stem, which has been optimally bucked based on incorrect bark thickness estimates, and dividing it into "sub stems" using the log length measurements from the optimal solution. If the original solution for that sub stem was found to be infeasible, i.e., the log cut from it would not meet diameter specifications, BUCKIT rebucked the sub stem. The value of logs from the solution produced once the stem was rebucked was the feasible optimal solution given the accurate bark thickness estimates. The number of logs from the original solution that had to be rebucked during this process was equal to the number of logs that would have been out-of-specification.

The percentage value loss was calculated as the percentage difference between the optimal dollar value and the actual dollar value. The optimal dollar value was equal to the total value of the stems when they were bucked using the correct bark thickness estimates. The actual dollar value was the value of the feasible logs produced when using the incorrect bark thickness estimates.

The above methodology has been used to investigate the impact on volume estimates, value loss and number of the logs produced that were out-of-specification when:

1. different bark thickness function forms were used
2. bark thickness coefficients from the incorrect species were used, and
3. bark thickness coefficients from the correct species, but generated from stem data collected from another geographical location, were used.

The last two of these situations were investigated using just one of the bark thickness equations (Eq. [**2**]) and up to five species. Many of the harvester/processors built around the world follow the StandForD standards (Skogforsk 2004). The standards specify four bark thickness equations. Probably the most flexible StandForD equation has the functional form used in Equation [**2**].

Results and discussion

Developing the bark thickness models

The Bias for each equation is presented in **Table 6**. Although the goal was not to determine the best function to describe bark thickness of these tree species, the results in **Table 6** indicate the most appropriate function in terms of statistical fit.

All models obtained a modeling efficiency (EF) of at least 0.98, so it could not be used as the selection criteria. An EF value of 1 indicates a “perfect” fit, 0 reveals that the model is no better than a simple average, with a negative score indicating a poor model (Vanclay and Skovsgaard 1997).

With the exception of the sample of Douglas-fir stems from Stand DF_2, Equation [**4**] gave the best statistical fit as indicated by the bias. The bias on all of the models was low, with the exception of Equation [**6**]. It was originally developed for Norway spruce, which has near-constant bark thickness along its stem.

Table 6. — Fitted and test statistics comparing the fit of the different equations on the different datasets.

	Radiata pine		Douglas-fir		Ponderosa pine
Equation	RP_1	RP_2	DF_1	DF_2	PP
[**1**]	0.00	0.00	0.00	0.00	0.00
[**2**]	0.00	0.00	0.00	−0.02	0.00
[**3**]	0.00	0.00	0.00	−0.02	0.00
[**4**]	−0.01	−0.02	−0.03	−0.05	−0.04
[**5**]	−0.01	0.02	−0.05	0.00	−0.04
[**6**]	−0.21	−0.14	−0.56	−0.17	−0.15

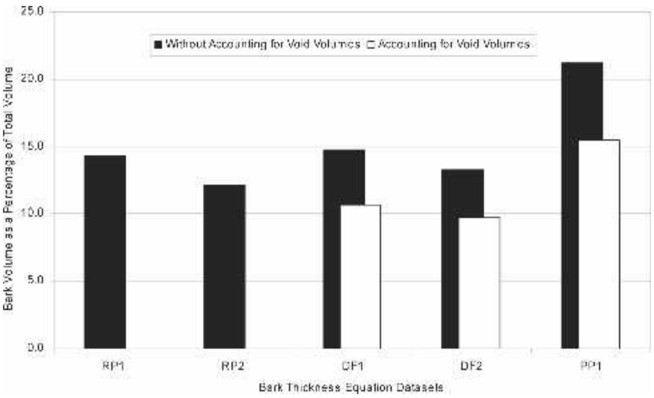

Figure 1. — Bark thickness impacts on log merchandising.

Figure 1 shows the interspecies and site differences graphically; the bark volume is expressed in terms of the percentage of the total volume of the stem (wood plus bark). The bark thickness for all stems was calculated using Equation [**2**]. For Douglas-fir and ponderosa pine, the volume was reduced by the percentages of void space in bark given in Krier and River (1968) as referenced by Bowyer et al. (2003). The results are in the same range as those published by Meyer (1946).

Effect of different bark thickness equations on volume and value estimates

The effects of the six bark thickness equations on the volume and value estimates for the sample stems are given in **Table 7**. No results were available for Equation [**4**] using dataset RP_{SD}, because the under bark diameter at the stump was not recorded for these trees.

The results in **Table 7** show that volume and value will be inflated substantially if bark thickness is not taken into consideration. The results for the six equations are similar, with a few exceptions. The volume and value produced for the Douglas-fir stems (DF_{SD}) is considerably greater when using Equation [**6**] than when using the other equations. This relates to the poor fit obtained for Equation [**6**]. Equation [**6**] has a large bias (**Table 5**) causing the under bark diameters and the volumes (**Table 6**) to be over-estimated. The poor estimate of volume from using Equation [**6**] on the Douglas-fir stands indicates that the appropriateness of a functional form for a particular species should be checked before implementing it on a harvester/processor. Significant value would be lost for the forest owner if the log buyers were accurately scaling the logs upon arrival to their log yard; many of the logs would be unlikely to meet the buyer’s specifications.

Effect of species and sites on bark thickness variation

Prediction error can be minimized by using bark thickness coefficients derived from the correct species and sites. Regression coefficients were obtained for Douglas-fir, ponderosa pine, and radiata pine from data collected for this study and for lodgepole pine and Western hemlock from Smith and Kozak (1967).

Table 8 shows the percentage of logs out-of-specification, differences in volume and value from using the regression coefficients from an incorrect species, and differences in volume and value from using the correct species but generated from trees grown on another site. The percentages were based on having a zero tolerance for logs that have diameters that are out-of-specification. Mills normally have some level of tolerance for accepting logs with diameters that are smaller or larger than stated in the specifications. Therefore, the percentages given in **Table 8** represent maximums.

Table 7. — Volume and value estimates for the different bark thickness models from the forest owner’s perspective.

	Equation						
Stem database	0[a]	[1]	[2]	[3]	[4]	[5]	[6]
RP_{SD}							
Volume (m^3)	269.0	232.6	231.0	230.6	N.A.	232.7	234.0
Value ($)	21,512	17,692	17,440	17,392	N.A.	17,781	17,805
DF_{SD}							
Volume (m^3)	268.4	229.0	228.9	229.1	227.7	228.7	238.2
Value ($)	34,035	27,463	27,434	27,531	27,330	27,634	29,189
PP_{SD}							
Volume (m^3)	47.6	37.5	37.5	37.2	38.2	38.2	38.8
Value ($)	1,730	1,148	1,143	1,124	1,194	1,201	1,219

[a] No reduction in diameter due to bark thickness (i.e., it is assumed that diameter inside bark = diameter outside bark).

Table 8 shows that not taking into account thickness of bark results in the highest percentage of logs that were out-of-specification, and the largest volume and value differences. Using a bark thickness equation with the incorrect species regression coefficients, however, can

Table 8. — The percentage of logs out-of-specification and volume and value difference from using different bark thickness equation coefficients.

	Out-of-spec			Volume difference			Value difference		
	RP_{SD}	DF_{SD}	PP_{SD}	RP_{SD}	DF_{SD}	PP_{SD}	SD_{RP}	DF_{SD}	PP_{SD}
	(%)								
OBD[a]	21	33	34	16	17	27	2	4	11
Species									
Lodgepole pine	8	30	31	6	8	18	0	3	11
Radiata pine		28	32		2	17		3	9
Western hemlock	3	15	34	2	4	15	0	2	8
Douglas-fir	10		29	5		12	2		8
Ponderosa pine	14	14		−14	−10		5	3	
Site									
Another stand	4	23		2	2		0.5	2	
Smith and Kozak (1967) A[b]		12	14		7	3		3	3
Smith and Kozak (1967) B[c]		13			11			6	

[a] OBD = over bark diameter
[b] Coastal Douglas-fir
[c] Interior Douglas-fir

in some cases cause almost as many logs to be out-of-specification.

The results for species that grow in mixed stands such as Douglas-fir and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and lodgepole pine (*Pinus contorta* Dougl. Ex Loud.) and ponderosa pine are also interesting. A harvester operator must select the correct species for each tree. The results indicate that, if the operator mistakenly identifies a Douglas-fir as a western hemlock, the volume estimate could be off by approximately 4 percent. These results highlight the importance of entering the right species coefficients for the species being processed by a harvester/processor and also educating the operators on the importance of correctly identifying the tree species at the time of processing.

It appears from the limited data sets available that the effect of site could be just as important as the species effect. The results show that, for a number of species, it is important that not only are the coefficients for the correct species applied but, in many cases, for the correct geographical location. The two radiata stands were geographically close, being less than 20 km apart, yet there was still 0.5 percent value loss from using the other stand's coefficients. It would be relevant to ask if the amount of value lost is sufficient to economically justify the development of a bark thickness equation for each individual stand. Using the value loss and the stocking rates of the radiata pine stand (RP_1), it was estimated that approximately US$ 0.82/m^3 (US$ 640/ha) could be spent obtaining bark thickness coefficients for that stand given that no bark thickness coefficients existed. If bark thickness coefficients existed only for the RP_2 stand, US$ 0.26/m^3 (US$200/ha) could be justified to develop new coefficients for the RP_1 stand.

A much larger number of bark thickness equations generated from trees from different locations for each species is required before the true effect of site can be determined. As noted in the introduction, Wilhelmsson et al. (2002) developed a bark thickness equation in which latitude is an independent variable; this approach could provide a cost-effective way to adjust bark thickness estimates for the different sites.

When the wrong bark thickness models' coefficients are used, the percentage of logs not meeting the diameter specifications of the mills increases. Mills specify minimum and maximum diameter ranges because mill designs are tailored to a specific diameter range. The average diameter of the log supply can have a large impact on lumber recovery and value-added for the sawmill over time. Williston (1981) showed that a drop in the average diameter of approximately 25 mm could reduce a mill's added value by 6 percent. A Swedish study, using a sawing simulator, showed that measurement error distributions with standard deviations (SD) for diameter and length of 6 mm and 4 cm, respectively, could produce between 18 percent and 37 percent of boards that were off-grade (Chiorescu and Gronlund 2001).

The forest owner's revenue would have decreased with the increase in the number of logs that would have been rejected for not meeting diameter specification. The accuracy of the under bark volume estimates is also affected by the accuracy of the bark thickness estimates. Harvester volume measurements are used increasingly as the basis for payment of stumpage sales in Scandinavian countries. In Finland, this type of system is used in 85 to 90 percent of all logging operations (Andersson et al. 2004). This type of volume determination has advantages for both the forest owners and log buyers. The forest owners receive payment for the harvested timber faster than other systems. The buyers also benefit, by more readily integrating timber transportation from different sites (Möller 1998).

Dealing with the effect of sites on bark thickness estimates can be more complex and expensive than with the effect of species. To reduce the cost of accounting for site variation, models with independent variables that account for spatial variation could be developed and used. For Scots pine, two bark thickness equations have been developed that have latitude as a dependent variable; one has been implemented on some of the modern harvester/processors (Skogforsk 2004). Ideally, the harvester operator would have a physiological model for bark thickness that gave highly accurate bark thickness estimates using only simple environmental inputs. For some high value species, however, it would be financially worthwhile to develop new bark thickness regression coefficients for each stand that the harvester enters.

Significant value for the forest owner can be lost when the rejected logs are downgraded to a product of a lesser value. Unfortunately, the inside bark diameters were not known for the bucking sample stems. Therefore, all value loss estimates are in relation to the value obtained from estimating bark thickness using the coefficients developed from trees from the same stand as the bucking stems.

Conclusion

Bark plays a critical role in the life of a tree when it is standing. The commercial uses of bark, however, are limited when compared to the wood fiber of the tree. For that reason, logs are bought and sold in terms of their under bark measurements. Bark, however, is difficult to remove in the forest, so it has to be estimated using a bark thickness model.

The major effects for mill owners of being supplied logs from a harvester using the wrong bark thickness model are 1) the number of logs supplied that are out-of-specification and 2) potential over- or under-payment to the logging contractors and forest owners if payment is based on the volume calculated from the harvester measurements. For the forest owners, the major effect is a potential loss in value from their resource.

This paper demonstrated that care must be taken in estimating the thickness of bark during the log bucking process. Given the bark thickness models used in this analysis, it appears that it is more important to obtain the model coefficients that correspond to the correct species and site, than to select the exact model's form. Having coefficients for the correct species appears to be extremely important, as in some case the results were as bad, if not worse than, not correcting for bark thickness. Using the wrong species coefficients resulted in up to 34 percent of the logs being out-of-specification, up to 11 percent of the forest owner's value being lost, and in incorrect estimates of the volume. The impact on site does not seem as important as having the correct species, yet value loss of 2 to 5 percent suggests that the effect of site should still be considered, particularly in the case of high value stands.

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