An assessment of the impact of FIA's default assumptions on the estimates of coarse woody debris volume and biomass

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Abstract: *Currently, Forest Inventory and Analysis estimation procedures use Smalian's formula to compute coarse woody debris (CWD) volume and assume that logs lie horizontally on the ground. In this paper, the impact of those assumptions on volume and biomass estimates is assessed using 7 years of Oregon's Phase 2 data. Estimates of log volume computed using Smalian's formula are known to be biased, overestimating volume. On the other hand, volumes estimated from the diameter at the point of intersection between the log and the transect are approximately unbiased, regardless of log shape, but may be more variable. In Oregon, Smalian's formula overestimated CWD volume and biomass by 3.6 and 4.2 percent, respectively, compared with the intersection diameter method, or 1.7 and 2.0 times the standard error of the estimates. The impact on the variance of the estimates was negligible. The assumption that logs lie horizontally would result in an underestimation of the total CWD volume. The sensitivity to this assumption was examined under several scenarios, suggesting that the bias may be between 4.1 and 8.1 percent of the volume estimates.*

Keywords: Down woody debris, line intersect sampling, Smalian's formula, intersect diameter, log inclination, Oregon.

Introduction

Coarse woody debris (CWD), defined as large pieces (logs) of down and dead wood in different stages of decay, plays a key role in ecosystem structure and function (Harmon et al. 1986). CWD may also account for a relatively large proportion of the total biomass and carbon pools in many forests ecosystems. In Oregon, for example, CWD volume and biomass are estimated to be 44% and 18% the net volume and biomass in live trees, respectively (Donnegan et al. 2008).

The Forest Inventory and Analysis (FIA) program uses line intersect sampling (LIS) to estimate the volume and biomass in down logs. Details of the measurement and sampling design, and estimation procedures, can be found in Woodall and Monleon (2008). In essence, a log is tallied if its centerline is intersected by the transect. Then, a LIS estimator for the total volume of down logs from the *i*-th plot, $\hat{\tau}_i$, is:

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$$\hat{\tau}_i = K \sum_{j=1}^{n_i} \frac{v_{ij}}{l_{ij} \cos\left(\theta_{ij}\right)} \qquad [1]$$

where v_{ij} is the measured volume from the j-th log; $l_{ij} \cos\left(\theta_{ij}\right)$ is the length of the horizontal projection of the j-th log's centerline (l_{ij} is the length of the centerline and θ_{ij} its inclination); K is a constant term that depends on transect length; and n_i is the number of down logs tallied in the plot. To estimate total biomass, the volume v_{ij} is multiplied by the log's bulk density and by a reduction factor to account for loss of mass due to decay (Harmon et al. 2008). Once an estimate for each plot is available, population estimates are obtained following standard FIA procedures (Scott el at. 2005).

Equation 1 requires that the individual log's volume be known, but volume is almost always estimated, not measured. FIA currently uses Smalian's formula to estimate volume for logs attributed as decay class 1, 2 3 or 4 logs (Waddell 2002, Woodall and Monleon 2008):

$$v_{ij} = \frac{1}{2} \left[\pi \left(\frac{DL_{ij}}{2} \right)^2 l_{ij} + \pi \left(\frac{DS_{ij}}{2} \right)^2 l_{ij} \right] \qquad [2]$$

where DL_{ij}, DS_{ij}, and l_{ij} are the large- and small-end diameters and length of the log, respectively. This equation is the average of the volume of two cylinders, one with cross-section equal to that of the large end of the log, and another with cross section equal to that of the small-end. It gives the volume of a frustum of a paraboloid and, therefore, if the log's shape is different, bias would result. Husch et al. (1972: 120) indicate that Smalian's formula tends to overestimate the volume of logs, reporting biases as large as 12%. They suggest that "Unless one is willing to accept a rather large error, Smalian's formula should not be used unless it is possible to measure the sections of the tree in 4-foot lengths."

Alternatively, volume may be estimated from the diameter at the point of intersection between the log's centerline and the transect (van Wagner 1968):

$$v_{ij} = \pi \left(\frac{DI_{ij}}{2} \right)^2 l_{ij} \qquad [3]$$

where DI_{ij} and l_{ij} are the intersection diameter and length of the log, respectively. This method gives an unbiased estimate of volume, without any assumptions about the shape of the logs. It can be motivated as a crude Monte Carlo approach to volume estimation. The volume of a log of arbitrary shape may be estimated by taking a random sample of points along the log's centerline, measuring the area of the cross-section at each point, multiplying by the log's length, and averaging. Because the point of intersection is a random point, multiplying the area of the cross-section at the intersection by the log length is basically a Monte Carlo

approximation to the volume based on a single sample. It follows that the estimator is unbiased, but it may be highly variable. Therefore, using intersection diameter instead of Smalian's formula may result in greater variance.

Equation 1 also requires knowledge of the inclination of the log, to calculate the length of the horizontal projection of the log's centerline. Currently, FIA does not measure log inclination, implicitly assuming that it is 0 or that it can be ignored. Logs may not lie horizontally because the terrain is not flat, they are supported but other trees or structures, or they are snags leaning more that 45 degrees from vertical (which are logs by FIA definition). Ignoring log inclination underestimates the total volume, with the bias being proportional to the reciprocal of the cosine of the inclination. So, if the inclination is 10%, actual volume is only 0.5% greater than the reported volume. However, this figure rises to 41% when the inclination is 100% (45 degrees).

The objective of this study is to evaluate the impact of the current assumptions regarding individual log volume estimation and log inclination on the estimates of total CWD volume and biomass in Oregon.

Materials and methods

Data

CWD data were collected in all FIA Phase 2 plots in Oregon, between 2001 and 2007 (7 panels). Two, 58.9 foot-long transects were measured in each subplot, for a total of 8 transects and 471.2 ft per plot. If the centerline of a log was intersected by the transect, the length, decay class and diameter at the intersection point were recorded. If the decay class was 1 through 4, the large- and small-end diameters were also recorded. Only logs in forestland were tallied. Details of the field procedures can be found at USDA Forest Service (2007). In total, the dataset includes 7,115 plots (51% forested) and 58,241 logs.

Individual log volume estimation

To assess the effect of the method used to estimate individual log volume, total volume and biomass and their variances were estimated after computing the volume of each individual log using either Smalian's formula (eq. 2) or the intersection diameter formula (eq.3). Only decay class 1-4 logs were included in the analysis because, lacking end diameter measurements, Smalian's formula can not be computed for decay class 5 logs. Log inclination was set to 0 (FIA default assumption). Estimates were obtained as described in Woodall and Monleon (2008).

Log inclination

Log inclination was not recorded in the field, but the slope (inclination) of the subplot was recorded. To estimate the impact of inclination, four scenarios based on the slope of the subplot were considered. We assumed that logs were lying on

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the ground, so that their inclination depended only on the slope of the terrain and orientation of the log with respect to the slope. Therefore, the impact on the estimates of logs that did not lie on the ground because they are supported was not considered. The four scenarios were (Fig. 1):

A. Default: logs lie horizontally (θ_{ij} in eq. 1 equals 0). This is equivalent to assuming that all logs are oriented perpendicular to the slope.

B. Log orientation is uniform, independent of the slope. Logs may be facing downslope or across the slope, or in any other orientation, with equal probability

C. Log orientation is predominantly downslope, according to the histogram in figure 1.

D. All logs are oriented downslope (θ_{ij} in eq. 1 equals the subplot slope)

Scenario D would provide an upper bound for the bias, while scenario B, in which the orientation of the pieces are not affected by the slope, would be a reasonable lower bound. Log volume was calculated from the intersect diameter, so that all decay classes could be included. For scenarios B and C, estimates are based on the average of 1000 simulations from the appropriate log orientation distribution.
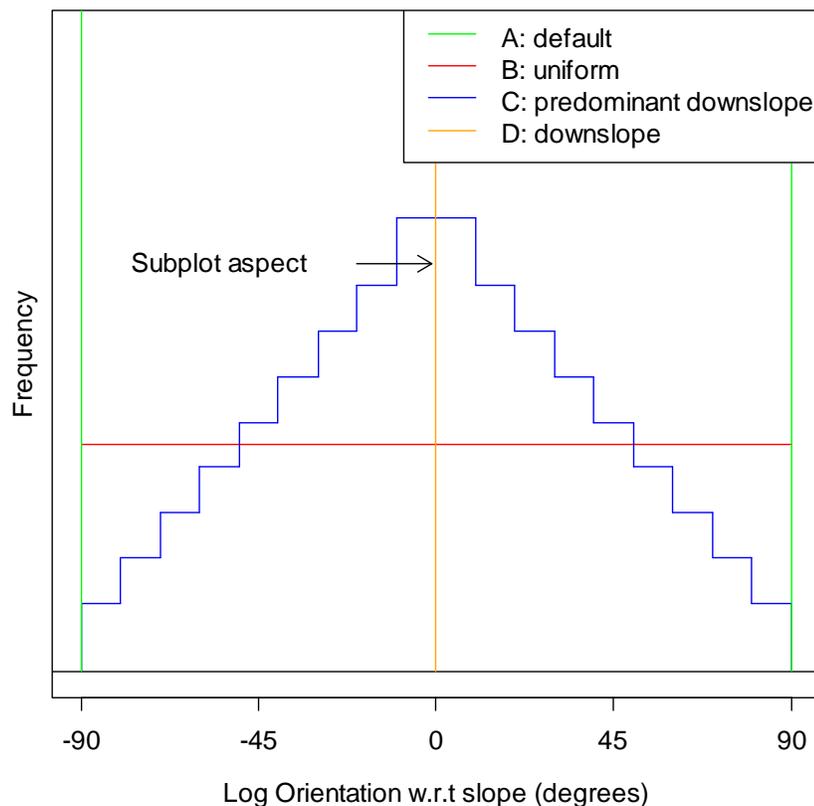

Figure 1: Distribution of the orientation of logs with respect to subplot slope for the four scenarios considered in this study. For scenarios A and D, all pieces are oriented perpendicular to the slope (-90 or 90 degrees) or downslope (0 degrees), represented here by vertical lines at those points.

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Results

Individual log volume estimation

Using intersect diameter to estimate log volume, instead of the default Smalian's formula, reduced the estimated total CWD volume on Oregon's forest lands by 1,378 million cubic feet (3.6%) and biomass by 11.2 million tons (4.2%) (Table 1). The practical significance of the difference between the two methods, rather than its statistical significance, is most relevant in this case. Nevertheless, the estimated differences were 10 times greater than their respective standard errors. Therefore, the difference between the parameters estimated by those two methods is highly statistically significant.

Because the estimator based in the intersection diameter is unbiased, a more relevant comparison may be between the bias, estimated by the difference between the two methods, and the sampling error. Estimated bias was 1.7 and 2.0 times the standard error of Smalian's volume and biomass estimates, respectively. Therefore, the bias, not the sampling error (SE), dominates the overall error.

Table 1: Estimated total CWD volume and biomass in decay class 1-4 down logs on Oregon forest land, by individual log volume equation.

Individual log volume equation	Volume		Biomass	
	Total	**SE**	**Total**	**SE**
	-- million cubic feet --		-- million tons --	
Smalian's formula	38,170	824	267.4	5.7
Intersection diameter	36,795	798	256.2	5.4
Difference	-1,378	138	-11.2	1.0

The estimate of log volume using Smalian's formula may be less variable than that from using the diameter at the intersection. The results from this analysis indicate that, at the scale of this study, any effect on the SE of the estimate is negligible. The SE of the intersection diameter method was 798 million ft^3, while that of Smalian's formula was 824 million ft^3. However, the estimated volume and biomass were also greater when using Smalian's formula. Relative to the estimates of the total, the SE was almost identical between both methods: 2.160% (Smalian) and 2.170% (intersection) for volume, and 2.118% (Smalian) and 2.126% (intersection) for biomass.

Log inclination

Accounting for the effect of plot slope increased the estimated CWD volume between 1.72 and 3.38 billion ft^3, or 4.1 to 8.1 %, compared with the current FIA default scenario (Table 2). The magnitude of the difference for scenarios B, C and D was 2.0, 2.7 and 3.9 times the SE of the default scenario, respectively.

Table 2: Estimated total CWD volume in down logs on Oregon forest land, by log inclination scenario. Volume was calculated from the intersection diameter, all decay classes included.

Scenario	Volume (billion ft^3)		Difference with scenario A	
	Total	SE	Total	%
	-- billion cubic feet --		-- billion cubic feet --	
A: default	41.92	0.86		
B: uniform	43.64	0.90	1.72	4.1
C: predominantly downslope	44.21	0.92	2.29	5.5
D: downslope	45.30	0.94	3.38	8.1

Discussion

The assumptions evaluated in this study, regarding individual log volume estimation and piece inclination, had a very significant effect in the estimation of total CWD volume and biomass in Oregon. Standard sampling and estimation procedures implicitly assume that the measurement error and bias are negligible compared with the sampling error. In this study, however, the magnitude of the estimated bias was several times that of the estimated sampling error, a result that has important consequences for estimation. For example, confidence intervals constructed with biased totals and their standard errors would be unreliable, because the true coverage is much less than the nominal coverage.

The trade-off between sampling error and measurement bias depends on the sample size. While sampling error decreases as sample size increases, the bias does not. For regional studies that include a large number of plots, such as this study, the sampling error is very small and bias dominates. Nevertheless, the estimated magnitude of the biases (over 4% of the estimated value in most cases) seems significant enough to be of concern even for questions involving much smaller areas and sample sizes. Reducing the bias may involve changes in measurement techniques and protocols, which in some cases may result in higher costs. However, there is a balance between allocating resources to increase the sampling size or reduce the measurement error, and both aspects should be considered.

Regarding the method used to estimate individual piece volume, both theoretical and practical results support the use of diameter at the intersection point. Neither Smalian's nor the intersection point method requires the measurement of the length of individual pieces, because the length (l_{ij}) factors out of eqs. 2 and 3. However, the intersection diameter method only requires the measurement of a single diameter and avoids having to leave the transect path to measure the diameters at both ends of the piece. This method is unbiased and, at the scale of this study, the impact on the variance is negligible. Additional assessments using individual plots did not seem to indicate increased variance when using intersection diameter, compared with Smalian's formula. The diameter at the intersection method attempts to estimate the average cross section of all the pieces. Thus, the rate of convergence is driven by the number of

intersections between transects and logs, not by the number of plots. Therefore, as long as a moderate number of intersections are included, the unbiased intersection diameter method is likely to perform as well as or better than Smalian's formula.

Accounting for log inclination may require additional field measurements. However, ignoring this variable would have a very significant impact on the estimator, at least in mountainous areas such as Oregon. The assumption that the orientation of the logs is uniform with respect to the slope (scenario B) seems to be a realistic lower bound for the bias caused by ignoring log inclination. Even then, the estimated bias was 4.1% of the total volume and 2 times the estimated SE. The actual bias due to ignoring log inclination is likely to be greater than that reported in this study, because the scenarios ignored the effect of leaning snags or supported logs. Supported snags are likely to be more frequent after disturbances such as hurricanes, so ignoring log inclination may substantially underestimate the disturbance impact. This study suggests that measurements directed to reducing this bias may be a reasonable allocation of resources, even at the cost of reduced sample size or transect length.

Biases and differences between methods have been compared with the estimated totals and their standard errors. To put those figures in perspective, the estimated differences can be compared with statewide carbon emissions in the State (Table 3). Depending on the assumption considered, the difference in the estimated carbon pools in CWD ranged between 32 and 65% the total anthropogenic carbon emissions in the state in 2000, highlighting the importance of accurate measurements of pools such as CWD at the regional level.

Table 3: Comparison between current carbon estimates in CWD and 2000 Oregon emissions.

	CO_2 equivalents	Percent 2000 OR CO_2 emissions[a]
	- million metric tons -	--- percent ---
Current estimate	505.8	
Intersect diameter	-19.3	32.4
Inclination:		
B: uniform	+19.8	33.2
C: pred. down	+26.3	44.1
D: downslope	+38.8	65.0

[a]Emissions estimated at 59.54 million metric tons of CO_2 equivalents. Source: Oregon Department of Energy, http://oregon.gov/ENERGY/GBLWRM/Oregon_Gross_GhG_Inventory_1990-2005.htm, accessed on October 10, 2008.

Acknowledgements

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