

Biased estimation of forest log characteristics using intersect diameters

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ABSTRACT

Logs are an important structural feature of forest ecosystems, and their abundance affects many resources and forest processes, including fire regimes, soil productivity, silviculture, carbon cycling, and wildlife habitat. Consequently, logs are often sampled to estimate their frequency, percent cover, volume, and weight. The line-intersect method (LIM) is one of the most widely used methods to obtain these estimates and has been shown to produce unbiased estimates of log characteristics. With the traditional LIM the diameters of each log at the point of its intersection with the sampling transect are used to estimate log characteristics. Based on a simulation study and a large set of empirical data, we found that use of intersect log diameters to define size classes provided biased estimates of log characteristics. The bias varied by diameter class. Results from the simulation study showed that log frequency and volume were overestimated in small-diameter log classes and underestimated in large-diameter classes. Similarly, results from our empirical analysis showed a 40% overestimate of log volume in the smallest diameter class (15–25 cm), and a 31% underestimate of volume in the largest diameter class (>50 cm). Just as size classes of snags and trees are best defined by their diameter-at-breast height (DBH), size classes of logs should be defined by their large-end diameters (LEOs). When large-end diameters of logs were used instead of diameters measured at the point of transect intersection, bias was substantially reduced or eliminated. These results indicate that line-intersect sampling could be substantially improved by including measurements of LEOs to estimate log characteristics. Our results have far-reaching implications for estimates of log characteristics, such as estimates of fuel loading and subsequent wildfire risk, carbon source and sink dynamics, silviculture, nutrient cycling, and habitat for wildlife. Without our suggested correction to line-intersect sampling, many forest resources associated with log characteristics will not be estimated accurately, affecting a plethora of log-based management and research programs.

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1. Introduction

Logs are an essential component of functioning forest ecosystems (Maser et al., 1979; Franklin et al., 1981; Maser and Trappe, 1984; Bull et al., 1997; Lofroth, 1998; Mellen et al., 2006). Two primary sampling methods – fixed-area sampling and line-intersect sampling – have been widely used to estimate log characteristics to understand forest processes in relation to fire risk, carbon cycling, soil productivity, silviculture, wildlife habitat, and many other resource issues. Sampling with fixed-area plots has been commonly used in ecological studies to estimate log characteristics for wildlife and soils (Graham and Cronnack, 1982; Means et al., 1992; Carey and Johnson, 1995; Harmon and Sexton,

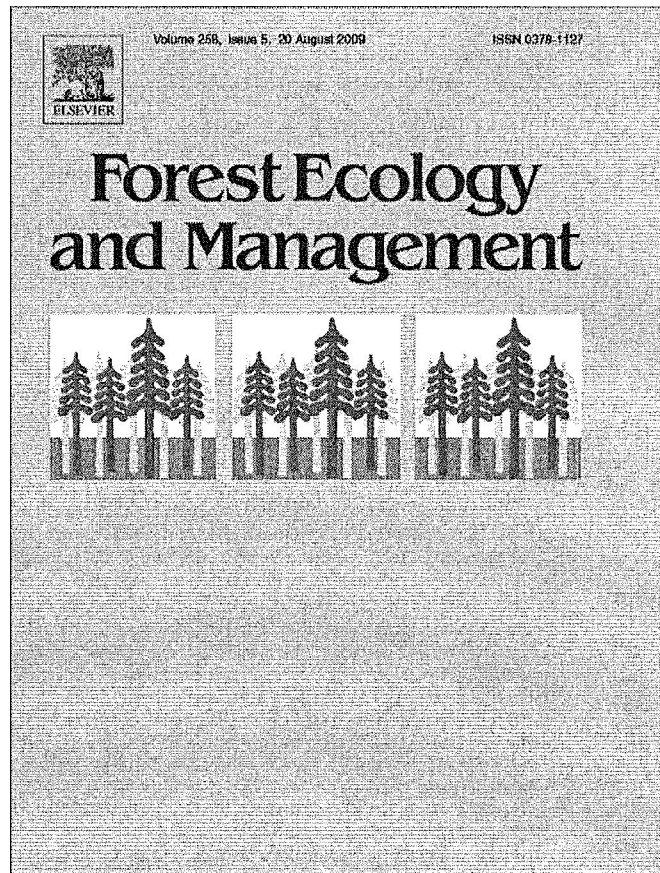
1996), but the line-intersect method has emerged as the most commonly used technique for sampling logs as part of silviculture and fuel management inventories (Warren and Olsen, 1964; Brown, 1974) and has been shown to provide unbiased estimates of total log volume (De Vries, 1973; Pickford and Hazard, 1978; Kaiser, 1983).

For some disciplines all log sizes are important. For wildlife, however, it is the larger pieces that are most important as habitat, as are the larger trees and snags (standing dead trees). When sampling trees or snags, it has been standard procedure to measure the diameter-at-breast-height (OBH) to define individual size classes. OBH in the United States is defined as 1.4 m up from the forest floor on the uphill side of the tree (Husch et al., 1972). This standardization has allowed for both temporal and spatial comparisons within and among disciplines for multiple size classes of both trees and snags. For logs, however, no similar standard presently exists.

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For example, in silvicultural and fire disciplines, log size is defined by its diameter at the point of intersection along line transects. This type of line-intersect sampling for forestry applications was first proposed by Warren and Olsen (1964) for quantifying logging residue. Howard (1981) used the method to assess residue in different harvest settings, and Safranyik and Linton (1987) used it to characterize bark beetle-susceptible logging residue. The method was described for sampling forest fuels to assess fire hazard and predict fire behavior by Van Wagner (1968) and Brown (1971,1974).

Line-intersect sampling now is widely used in North America as an integral part of photo series work to quantify forest residues (Maxwell and Ward, 1976, 1980; Fischer, 1981a,b,c,d; Blonski and Schramel, 1981). As described by Van Wagner (1968), Brown (1971,1974), and by Marshall et al. (2000), line-intersect sampling involves measuring the diameter of logs at the point that each piece is intersected by a transect. Data on transect length and the intersect diameters of logs encountered by the transects are then used in equations developed by Van Wagner (1968) and De Vries (1973) to estimate parameters of different log characteristics. These equations allow the user to estimate the mean and variance of the number of pieces or logs per unit area, combined length of pieces, percent cover, mid-sectional area and diameter, and many other characteristics; but the most common estimates are those for log volume and weight.

In line-intersect sampling the minimum log diameter of interest is first specified in relation to the sampling goals. For example, the focus of Brown's (1974) log inventory handbooks addressed both fine material having intersect diameters <7.62 cm, and pieces >7.62 cm: these diameter categories corresponded to moisture time-lag classes of woody fuels for predicting fire behavior (Fosberg, 1970). For quantifying logging residue, Howard (1981a,b) set the lower diameter limit at 7.65 cm. For any specific parameter such as volume or weight, logs were divided into five classes based on the intersect diameters (0.6–50.8 cm), and other variants as in Maxwell and Ward (1976, 1980), Koski and Fischer (1979), Fischer (1981a,b,c,d) and Blonski and Schramel (1981).

Although most common, intersect diameters are just one way that log sizes have been measured. Logs have also been defined by their small-end diameters. For example, in eastern Washington and Oregon, the National Forest Plan Amendment (U.S. Department of Agriculture Forest Service, 1995) stipulated that 37–49 logs/ha (>1.8 m long) and 30.5 cm or greater in diameter at their small-end diameter be retained in mixed-conifer stands. Other approaches include ocular estimates to describe percent cover of logs for small mammal habitat (Carey and Johnson, 1995). Finally in some studies, results of diameter measurements are provided, but it is unclear at what point along the bole of a log (large-, mid-, or small-section) the measurements were made (Bowman et al., 2000).

Given the small budgets typically available for disciplines concerned with logs, use of log sampling methods that can provide information to all disciplines is essential. Standardizing how log size classes are defined thus would allow for more uniform interpretation and understanding of what sizes of logs are important across various disciplines in forest ecology.

In the course of earlier studies (Bate et al., 2002, 2004), we first became aware that log size class distributions based on intersect diameters were different from those based on LEOs. The intersect diameter might fall anywhere along a log's length, whereas the LED has a consistent and definable location on a log. One may think of LED as approximating the DBH of a tree or snag. For logs with rootwads intact, the LED is indeed equivalent to the DBH if the tree had remained standing (Bate et al., 2008). For logs with no rootwad attached, the LED is the diameter at the largest end of the log that is complete. An analogy for using intersect diameters versus LEDs to

characterize logs would be the measurement of snag or tree diameters at random heights along the bole of the snag or tree, and then using these measurements to assign snags or trees to diameter size classes.

Based on these observations we hypothesized that diameter classes based on intersect diameters would misrepresent the size distribution of logs and potentially bias the estimates of log characteristics that use intersect diameters. Accordingly, the purpose of our study was to document the degree of bias, if any, in estimates of log characteristics when using intersect diameters.

2. Methods

We examined potential biases in estimating log characteristics when diameter classes were based on intersect diameters versus large-end diameters. Possible biases were examined in two ways. In one approach, we simulated sampling logs in a small stand (simulation study) to evaluate potential differences in log frequencies and volume in four diameter classes, when these classes were based on intersect diameters versus large-end diameters. In the second approach (empirical study), we used data from previous studies of logs (Bate et al., 2002, 2004) to compare estimates of log volume based on intersect diameters versus large-end diameters, and comparisons of these estimates with true values (log census) of log volume obtained from field work.

2.1. Simulation study

We randomly selected 100 logs from a data set collected in an old-growth stand on the Flathead National Forest in northwestern Montana (see Bate et al., 2004 for details). The majority (~93%) of logs encountered at this site were unaltered by human activities such that log lengths followed a normal distribution. The stand was 2.2 ha in size and contained 467 logs 2:15 cm in large-end diameter and 2:1 m in length. From this data set we randomly selected 100 logs to create our population of logs, using their diameter and length characteristics to create "logs" for our simulation study. Logs selected ranged from 1 to 25.3 m in length, from 15 to 74 cm LED, and from 2 to 47 cm small-end diameter.

We made a model of each log from a small-diameter (3 mm) dowel. Actual lengths of logs made in meters in the field were converted to centimeters, and actual diameters measured in centimeters in the field were converted to millimeters on the log models. Each log model was given a numeric identifier and labeled at both ends as to its large and small-end diameters.

We then made a 100 by 100 cm wooden frame to represent the boundaries of 100 by 100 m "stand." Within this framed area all 100 logs were randomly tossed each time we sampled. After each toss we randomly selected a starting point within the frame. From each starting point we then established a 100 cm long transect (100 m equivalent). We simulated sampling for estimates of volume (m³/ha) using the line-intersect method (De Vries, 1973; Brown, 1974). We used the bounceback method whenever the transect hit the edge to ensure that all edges of the "stand" were also sampled (Bate et al., 2008). We performed this sampling simulation 30 times.

For each log model intersected we measured the distance from the small end of the log and applied a taper equation created for each individual log to determine what the diameter would be at the point of intersection. To calculate the log's diameter at intersection (D_i), we assumed constant taper for the log along its bole by using the following equation:

$$D_i = \frac{l_i - s_i}{L_i} \quad (1)$$

where l_i = large-end diameter (cm) of log; s_i = small-end diameter (cm) of log; L_i = length (cm) of log.

By using the equation above, then multiplying it by the distance measured from the small-end diameter, we obtained the intersected diameter for each log model. Using the 30 transects as our sample unit, we calculated the volume of logs in each of the four diameter classes: (1) <15 cm; (2) 15–25 cm; (3) 26–50 cm; and (4) >50 cm. Diameter classes were defined using either the intersect diameter or the LED of each log model. For each diameter class, we tallied the number of logs and summed total volume.

2.2. Empirical case

We used field data of log inventories from an earlier study (Bate et al., 2002, 2004). In that study we conducted complete inventories of all logs > 15 cm LED and > 1 m long in 17 stands; unharvested ($n = 9$) and harvested ($n = 8$) mixed-conifer sites (1.2–7.4 ha) in Oregon and Montana. We defined unharvested sites as those in which <10% of the logs had their lengths modified by having been sawn at one or both ends. Conversely, harvested sites (clearcut, seedtree, and shelterwood harvest units) had most of the log lengths modified by cutting or breakage during harvesting operations or by firewood cutters. For every qualifying log within each stand we measured its length, LED, and SED. Volume for each piece was calculated by Smalian's formula (Harmon and Sexton, 1996). This formula was appropriate because most logs were cone-shaped (Harmon and Sexton, 1996). The complete inventories yielded "true" numbers and volumes of logs in the study stands, and were the basis against which we compared the bias and precision of line-intersect and strip-plot log sampling techniques in Bate et al. (2002, 2004). True densities of logs in harvested stands ($n = 8$) ranged from 146 to 283 pieces/ha ($\bar{x} = 200.7$), whereas densities in unharvested stands ($n = 9$) ranged from 146 to 367 pieces/ha ($\bar{x} = 221$).

Line-intersect sampling, which was done following the Brown (1974) method, was conducted on 900 m of transect on each of the 17 study sites. In addition to the prescribed measurement of the intersect diameters, we also recorded LED, SED, and length of each intersected piece. The number of logs intersected in harvested sites ranged from 3.6 to 7.4 ($\bar{x} = 5.5$) per 100 m of transect. In unharvested sites, the number of logs intersected ranged from 5.3 to 30.2 ($\bar{x} = 12.9$) per 100 m of transect. We then used the true empirical data from the original complete inventories (Bate et al., 2002) to assess the potential bias in volume estimates of logs based on whether diameter classes were defined by the intersect diameter or LED of each log. For each size class we calculated the mean volume (m^3/ha) plus its 90% confidence interval.

To test for differences in volume, we first calculated the mean and the 90% confidence interval within each size class. Then we examined whether true mean values fell within the confidence

interval of the estimated mean (or by contrast, the estimated mean fell within the bounds of the true mean). If so, then the two values were not different. If the true mean was outside the values of the confidence interval for the estimated volume, however, this indicated that the true mean was either significantly higher (above the upper value of the confidence interval) or lower (below the lower value of the confidence interval) than the estimated mean volume.

We used ordinary least squares regression to evaluate the relation between the proportional representation of the largest size class of logs among all logs, and the amount of observed error (compared to the true values) when using LED or intersect to define diameter classes.

3. Results

3.1. Simulation study

In our simulation study, 210 log models were intersected along the 30 random transects that we sampled. Estimated volume of all logs intersected was $62.6 \text{ m}^3/\text{ha}$ ($n = 30$) using both intersect- and LED-defined approaches (Table 1). Actual volume was $56.9 \text{ m}^3/\text{ha}$. We observed differences in mean volume for three size classes. In the two smallest size classes, estimates of log volume and number of logs were higher when intersect diameters were used. For example, in the smallest size class (<15 cm) the estimated volume was $2.9 (\pm 0.9) \text{ m}^3/\text{ha}$ based on intersect diameters in contrast to no logs present in this size class based on LEOs. Estimated volume was $4.2 \text{ m}^3/\text{ha}$ higher using intersect diameters compared to estimates using LEDs for the 15 to <25 cm size class although both estimates excluded the true volume for this size class. Volume, however, was substantially lower (true volume did not fall within estimated confidence intervals) when estimated with intersect diameters ($10.6 \text{ m}^3/\text{ha}$) versus LEOs for the largest size class. In the second largest size class (25 to <50 cm) we observed no difference in log volume, although 43 more logs were counted using the LED approach compared to the intersect one (Table 1).

3.2. Empirical study

Our empirical study used results from a log census (complete inventory of all logs present) as the true values of log characteristics for evaluating potential bias in estimates based on line-intersected diameters. Total volume estimated for all logs, i.e. all diameter classes combined, in harvested or unharvested sites were 4–7% lower than true values, but not statistically different from true volume (Table 2).

Overall, estimated volumes based on LED-defined diameter classes varied less widely from true volumes (–40 to +17%) than did those in intersect-defined classes (–69 to +40%). In the special case of the smallest diameter class, the intersect-defined class in both harvested and unharvested sites indicated that volume was

Table 1

Comparison of number of logs and estimated volumes ($\text{m}^3/\text{ha} \pm 90\%$ confidence interval) to true volumes when intersect versus large-end diameters are used to define size classes in the simulation study.

Size classes (cm)	True volume	Based on intersect diameter		Based on LED ^a	
		No. of logs	Volume (m^3/ha) (CI)	No. of logs	Volume (m^3/ha) (CI)
<15	0	54	2.9 (0.9) ^{a,b}	0	0.0 (0)
15–25	5.14	74	12 (3.1) [*]	70	7.8 (2.1) [*]
26–50	33.4	75	37.1 (9.1)	118	37.4 (8.8)
>50	18.3	7	10.6 (6.2) [*]	22	17.4 (7.5)
Total	56.9	210	62.6 (12.4)	210	62.6 (12.4)

^a LED is large-end diameter.

^b Asterisks denote significant differences between log volumes within size classes because true volume does not fall within confidence interval bounds of estimate.

Table 2

Estimated versus true log volumes ($\text{m}^3/\text{ha} \pm 90\%$ confidence interval [CI]) in different size classes defined by intersect diameter or large-end (LED) diameters. Log resource data from harvested and unharvested mixed-conifer stands in Oregon and Montana, 1998–1999 (Bate et al., 2002).

Treatment	Log size classes (cm)	Mean volumes (m^3/ha)			Proportion of estimate to true	
		True (CI)	Intersect (CI)	LED (CI)	Intersect	LED
Harvested stands ($n = 8$)	<15	0.0	3.5 (1.3)*	0.0	–	–
	15–25	10.2 (2.2)	8.9 (2.6)	9.1 (2.6)	0.87	0.89
	26–50	15.9 (4.9)	18.7 (7.9)	18.1 (7.1)	1.18	1.14
	>50	15.6 (6.1)	9.1 (8.3)**	11.8 (7.9)	0.58	0.82
	All logs	41.7 (7.1)	36.6 (12.9)	40.1 (12.2)	0.88	0.96
Unharvested stands ($n = 9$)	<15	0.0	6.6 (2.1)*	0.0	–	–
	15–25	15.9 (4.8)	22.3 (6.6)**	18.6 (5.3)	1.40	1.17
	26–50	34.7 (11.7)	27.9 (13.9)	33.6 (15.8)	0.80	0.97
	>50	15.7 (6.3)	4.9 (2.9)*	9.4 (4.7)*	0.31	0.60
	All logs	66.3 (18.3)	55 (21.5)	61.6 (22.6)	0.83	0.93

Asterisks denote significant differences between log volumes within size classes because true volume does not fall within confidence interval bounds of estimate (*) or estimated volume does not fall within the bounds of the true volume (**).

present in that class (3.5 and 6.6 m^3/ha) when, in fact, there were no logs inventoried in that size class as defined by LED.

In harvested sites, we observed no significant differences between true and estimated volumes in any of the diameter classes when using LED-defined diameter classes. When intersect-defined classes were used, the volume in the smallest class (<15 cm) was significantly overestimated, and volume in the largest diameter class (>50 cm) was significantly underestimated compared to true volume.

In unharvested sites, we observed that the estimated volume in the smallest log class (<15 cm) was also significantly overestimated when the class was intersect-defined. The intersect-defined class showed volume in the smallest class even though there were no logs in that class (<15 cm). The next smallest class (15–25 cm) was also significantly overestimated when using intersect-defined diameter classes.

Logs in the largest diameter class (>50 cm) in unharvested sites had the greatest bias associated with how the diameter classes were defined. The true volume of large logs was significantly underestimated by both diameter-class-defining systems. The main difference, however, was the degree of bias. In particular, use of intersect-defined diameter classes for the largest size class significantly underestimated true volume, with the estimate only 30% of the true value volume (means 4.9 m^3/ha vs. 15.7 m^3/ha). Volume of large logs using LED-defined diameter classes also significantly underestimated volume, being only 60% of the true volume (means 9.4 m^3/ha vs. 15.7 m^3/ha) (Table 2).

We tested whether the true proportion of large logs among all logs in our sample stands might have some bearing on the amount of bias we observed in relation to how we defined diameter classes. Fig. 1 shows the difference between the true and estimated volumes based on each method of assigning diameter classes. As the percent composition of large-diameter logs increased, bias increased as well, for both methods used to assign diameter classes. When we regressed error on proportion of large logs among all logs, the slope (bias) for intersect-defined classes ($b = -2.12$; Fig. 1B) was twice as steep as the slope for LED-defined classes ($b = -1.02$; Fig. 1A).

4. Discussion and conclusions

The use of line-intersect sampling to estimate log characteristics has a long history, especially in silviculture and fire management. In practice, the size classes used for portraying log characteristics for fire management have been based on the intersect diameters of the material sampled (Maxwell and Ward, 1976, 1980; Blonski and Scharnel, 1981; Fischer, 1981a,b,c,d). We hypothesized that diameter classes defined by intersect diameters might bias the estimates of log volumes, or other log characteristics by size class. Indeed, our results showed that when intersect-defined diameter classes were used log characteristics in the smaller diameter classes were significantly overestimated, while those in the larger diameter classes were significantly underestimated. This was clearly shown in our simulated study, and was corroborated with our empirical data

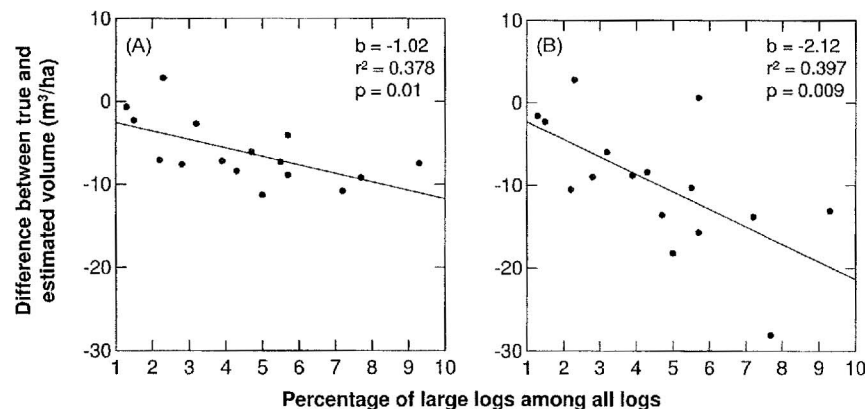


Fig. 1. Amount of error between estimated and true volume of logs (m^3/ha) regressed on percentage of large logs (≥ 50.8 cm LED) among all logs (≥ 15 cm LED), when diameter classes were defined by (A) large-end diameter, or (B) intersect diameter. Data are from the empirical study of Bate et al. (2002, 2004).

analysis. Bias was much smaller when diameter classes were defined by LEDs (Table 2).

We also found some bias in log characteristics for some LED-based measurements. Both the intersect- and LED-based measurements always provided estimates that varied from the true volume in the same direction. Overall, however, the size classes based on intersect-diameters consistently had a greater degree of bias (Fig. 1).

Our results demonstrate the risks of estimating log characteristics based on intersect diameters, as traditionally done with line-intersect sampling. Just as analyses of tree and snag diameters are consistently and accurately measured at breast height (DBH), we believe that there is parallel compelling logic for measuring logs at their large-end diameter (LED). This approach would minimize the bias associated with line-intersect sampling that conventionally measures the diameter of whatever portion of log that happens to intersect the transect. The use of LEDs necessitates that this measurement be taken as part of line-intersect sampling. If measuring the LED for every log in the field is cost prohibitive because of increased time requirements, visually categorizing logs into LED-defined size classes could provide a suitable alternative. Under this approach, trained field personnel could visually ascertain what size class in which the log fits without leaving the transect line. Only for borderline cases would the LED need to be actually measured.

Resource specialists from diverse disciplines, such as silviculture, fire, wildlife, and soils, need unbiased estimates of log characteristics to manage these structures effectively. In addition the added importance of estimating log volume accurately for estimating carbon sequestration in forests, adds particular emphasis for the need to use unbiased log sampling methods. By measuring both intersect and large-end diameters of logs during sampling protocols, the data collected become immensely more useable and accurate for multiple disciplines. Large-end diameters define a log population and allow for accurate temporal and spatial comparisons of logs among size classes.

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