Field Results for Line Intersect Distance Sampling of Coarse Woody Debris

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***Abstract**: A growing recognition of the importance of downed woody materials in forest ecosystem processes and global carbon budgets has sharpened the need for efficient sampling strategies that target this resource. Often the aggregate volume, biomass, or carbon content of the downed wood is of primary interest, making recently developed probability proportional-to-volume designs such as line intersect distance sampling (LIDS) of interest. This research presents field results from LIDS and conventional line intersect sampling (LIS) inventories of coarse woody debris (CWD) in three stands in northwestern Montana, USA. Field crews quickly adapted to the distance-limited selection protocol of LIDS, though its variable-length transect design increased data collection times relative to LIS in all three stands. Yet aggregate CWD volumes were estimated more precisely with LIDS, more than offsetting the time differential and rendering LIDS more efficient than LIS for volume estimation given a fixed sampling time or budget. Conversely, LIS generally performed more efficiently than LIDS with regards to the estimation of CWD abundance and aggregate length. Its transect design means that LIDS could be readily integrated into Forest Inventory and Analysis based programs to assess and monitor CWD stocks. However, the utility of LIDS, or of any other sampling strategy, must be determined by the relative importances of the estimable CWD attributes of interest.*

Keywords: downed woody materials; size-biased sampling; Lubrecht Experimental Forest.

Introduction

Coarse woody debris (CWD) is an important component of many forest ecosystems. Partially decayed wood on or in the forest floor provides habitat for diverse plant and animal species; regulates soil moisture and nutrient flux; and can modify wildfire behavior and severity (Brown *et al.* 2003; Harmon *et al.* 1986; Jonsson and Kruys 2001). Downed wood also represents a carbon reservoir (*e.g.*, Canadian Council of Forest Ministers 2006) and a potential source of biomass energy. Recognition of these functions has prompted the identification of CWD as an indicator of forest health and sustainability. This, in turn, has sharpened the need for efficient sampling strategies that specifically target the downed wood resource.

Line intersect sampling (LIS; Kaiser 1983) is one of the most commonly used survey methods for downed wood, and is currently implemented in the USDA Forest Inventory and Analysis (FIA) program (see Bechtold and Patterson 2005). Applying LIS, logs or fragments of CWD that are crossed by a fixed-length transect

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are selected into a sample. The search procedure of LIS is straightforward and the likelihood of detection errors small. However, in stand- and forest-level applications, LIS can require an inordinate sampling intensity to achieve estimates of acceptable accuracy, particularly when the aggregate volume or biomass of CWD is of interest (cf. Pickford and Hazard 1978; Woldendorp *et al.* 2004). Line intersect distance sampling (LIDS; Affleck 2008) is a novel CWD survey method that incorporates many elements of the search protocol of LIS, but also utilizes a probability proportional-to-volume selection design. As such, LIDS offers the potential for more rapid and accurate assessments of the aggregate volume of CWD resources, as well as its biomass and carbon content.

This report presents preliminary field research on the relative performance of LIDS and LIS based on downed wood sampling conducted in 2008 in northwestern Montana, USA. The next section provides an overview of the LIDS methodology and estimators and the following section describes the field sampling program. The closing section discusses the field results and comments on the perceived advantages and limitations of LIDS.

Line Intersect Distance Sampling

LIDS is a transect-based sampling method similar to LIS. However, like the perpendicular distance sampling strategy of Williams and Gove (2003), LIDS also incorporates a distance-limited selection criterion that allows for probability proportional-to-volume sampling of CWD.

Sampling is conducted from a point s located uniformly at random inside the tract of interest.[1] A line transect initiated at s is then oriented in the direction θ, also selected uniformly at random. These two design elements supply the basis for inference and obviate the need for any conditions concerning the spatial distribution or orientation of CWD particles on the tract of interest. In practice, the point s will be one of a collection of sample points $\{s_1, s_2, \ldots, s_T\}$ located independently or on a randomly positioned systematic grid. Similarly, radial transects (see Affleck *et al.* 2005) consisting of $M > 1$ segments can be employed in LIDS, in which case the first segment is oriented in the direction $\theta_1 = \theta$ and the orientations of the other segments follow at prescribed intervals (*e.g.*, in a Y-shaped transect $\theta_2 = \theta + 120°$ and $\theta_3 = \theta + 240°$). Where the LIDS strategy departs from LIS is in the fact that the transect as a whole, as well as any individual transect segments, have no fixed length. Instead, a critical distance constant k (m^{-1}) determines the sampling intensity; the role of this constant is analogous to that of Grosenbaugh's (1958) point-sampling constant k.

A particle of CWD crossed by a LIDS transect segment is selected into the sample provided that two conditions are met. First, the central axis of the particle, not simply a branch or lobe, must be intersected by the transect segment. The central axis of a particle is the longest line segment connecting two points on the particle's boundary. Denote the length of the i^{th} particle's central axis by l_i (m). The

[1] See Appendix A for a summary of the notation.

central axis of a freshly fallen log can often be taken as the pith of the main stem and its length will then coincide with the log's length. An odd-shaped particle of CWD can have a central axis that is only partially within the core of wood, however (see *e.g.*, Affleck 2008).

The second condition for particle selection stipulates that the distance from the sample point to the particle is less than a critical distance determined, in part, by k. Specifically, if the m^{th} transect segment crosses the central axis of the i^{th} particle at the point $x_{m,i}$, then the distance (in m) from s to $x_{m,i}$ must not exceed the critical distance ($D_{\mathsf{crit},i}$):

$$D_{\mathsf{crit},i} = \frac{k\,a(x_{m,i})}{M} ,$$

where $a(x_{m,i})$ is the cross-sectional area (m^2) of particle i contained within the intersection plane. This intersection plane is the vertical plane lying perpendicular to the particle's central axis and containing the point $x_{m,i}$. For the idealized needle-shaped particle lying on flat ground, this cross-sectional area will be a circular face of wood; if this particle is tilted from the horizontal, then $a(x_{m,i})$ measures an elliptical surface. More generally, $a(x_{m,i})$ measures the area of an approximately elliptical section of particle i or the sum of the areas of several such sections if multiple branches of particle i are cut by the intersection plane.

It follows from these conditions that the probability of selecting the i^{th} particle on a given segment of a LIDS transect is directly proportional to its cubic volume (Affleck 2008). This result, in turn, implies that a design-unbiased estimator of the volume of CWD per unit area is given by

$$\widehat{V}_s = F\,n_s , \tag{1}$$

where n_s is the total number of particle selections made on the transect located at s and $F = \frac{10000\pi}{2k}$ is a constant volume factor (m^3·ha^{-1}). Estimating aggregate CWD volume per unit area following LIDS is thus similar to estimating aggregate tree basal area per unit tract area following horizontal point sampling: a count of the number of selected particles (or trees) is simply blown-up by a volume (or basal area) factor.

Other CWD population parameters can be estimated if measurements such as l_i and $a(x_{m,i})$ are taken on the selected particles (see Affleck 2008). For example, a design-unbiased estimator of the number of particles per unit area based on a single transect located at s is

$$\widehat{N}_s = F \sum_{m=1}^{M} \sum_{i\in\mathscr{C}_{s,m}} \frac{1}{l_i \cos(\phi_i)\, a(x_{m,i})} , \tag{2}$$

where ϕ_i is the tilt (°) of the central axis of particle i with respect to the horizontal plane and the second summation extends over the collection $\mathscr{C}_{s,m}$ of particles selected by the m^{th} segment of the transect located at s. A corresponding design-unbiased estimator of the aggregate length of the central axes of CWD particles per unit tract area is

$$\widehat{L}_s = F \sum_{m=1}^{M} \sum_{i \in \mathscr{C}_{s,m}} \frac{1}{\cos(\phi_i)\, a(x_{m,i})} \ . \tag{3}$$

For comparison, design-unbiased estimators of the aggregate volume, abundance, and length of CWD following LIS are given in Appendix B.

With multiple LIDS transects located on the tract, transect-specific estimates can be combined and standard errors estimated. For example, transect-based estimates of aggregate CWD volume per hectare can be averaged together:

$$\widehat{V} = \frac{1}{T} \sum_{t=1}^{T} \widehat{V}_{s_t} \ ,$$

where $\widehat{V}_{s_t}$ is the estimate obtained from the transect located at sample point s_t ($t = 1, 2, \ldots, T$). Also, if sample points are located independently, then normal-theory confidence intervals can be constructed from the estimated standard error

$$s(\widehat{V}) = \sqrt{\frac{\sum_{t=1}^{T} \left(\widehat{V}_{s_t} - \widehat{V}\right)^2}{T(T-1)}} \ ,$$

or from a bootstrapping procedure (Efron and Tibshirani 1994).

Field Data Collection

To assess quantitative and qualitative differences in the practical application of LIS and LIDS, a collection of stands in the Lubrecht Experimental Forest in northwestern Montana were identified for field survey. Stands were selected to cover a range of (overstory) forest types and a variety of downed wood assemblages. All were second-growth, managed stands and ranged in age from approximately 40 years to over 150 years. Field results from three of these stands (Table 1), all sampled in the summer of 2008, are discussed below.

Table 1: Characteristics of selected stands, sampling intensities, LIS transect lengths (L), and LIDS volume factors (F).

Stand	Leading species	Basal area ($m^2 \cdot ha^{-1}$)	Sample points	L (m)	F ($m^3 \cdot ha^{-1}$)
A	*Pseudotsuga menziesii v. glauca*	30.1	60	48	10
B	*Pinus contorta*	22.7	28	9	15
C	*Larix occidentalis*	44.8	30	42	8

Sample points were distributed uniformly and independently at random within each stand. Each sample point served to locate a Y-shaped LIS transect of total length L (m) as well as a Y-shaped LIDS unit with volume factor F. The two sampling units were superimposed and their orientations were selected uniformly and independently at random. Each segment of a transect was initiated at a 2 m distance from the sampling point. Pilot sampling was conducted in each stand to determine the LIS transect lengths and LIDS volume factors that would result in the selection of 6-9 particles per sample point. As a result, distinct transect lengths and volume factors were used within each stand (Table 1).

Following the definition of Valentine *et al.* (2008), a log or segment of downed wood was considered a particle of CWD if it exceeded 7.5 cm in diameter at any point along its central axis. That is, a connected fragment of downed wood was deemed either a single particle of CWD or an element of fine woody debris – logs were not partitioned into multiple coarse and fine woody segments. Dead wood within live trees, woody material suspended more than 2 m above the forest floor, and downed wood buried beneath the litter layer in the forest floor were not considered. Partially rooted snags or stumps were considered CWD particles only if they leaned more than 45° from the vertical.

The length of the central axis and its tilt from the horizontal were measured on every selected particle. Cross-sectional diameters were obtained for every lobe (*e.g.*, branch or stem fork) within the intersection plane. Generally, two diameters were measured on each lobe, with one diameter being made in the horizontal plane and the other taken at right angles (but still in the vertical intersection plane). The cross-sectional area of the selected particle was then obtained from the sum, over all lobes, of the products of paired diameters. Additionally, the species of the particle was determined, at least to the level of softwood, hardwood, or unknown, and decay class was assessed on the five point scale of Meidinger (1998).

Both LIS and LIDS were implemented at each sampling location, with the order of implementation determined randomly and in advance of sampling. Only the first method applied at a given point was timed. Two person crews were used throughout and separate data collection times were obtained for each of the three segments of the Y-shaped units. The elapsed times included all elements of segment orientation and layout; particle selection and measurement; and travel back to the sample point. All distances were measured using tapes and were corrected for slope. Particle species and decay information was collected primarily to render the collection times consistent with those of standard CWD sampling programs.

The relative efficiency of LIS and LIDS were determined from the average implementation times and from the observed precision of stand parameter estimators. Relative efficiency was calculated as

$$\mathsf{RE} = \frac{\bar{\mathsf{t}}_{\mathsf{LIDS}} \times s^2(\widehat{Y}_{\mathsf{LIDS}})}{\bar{\mathsf{t}}_{\mathsf{LIS}} \times s^2(\widehat{Y}_{\mathsf{LIS}})} ,$$

where $\bar{\mathsf{t}}_{\mathsf{method}}$ is the average transect sampling time for a particular method and $s(\widehat{Y}_{\mathsf{method}})$ is the corresponding standard error of an attribute estimator. This measure of efficiency is both attribute- and stand-specific. RE can be interpreted as the time needed to achieve a given margin of error using LIDS relative to the time needed to achieve the same margin of error with LIS.

Results & Discussion

Across all three stands, LIS was implemented more rapidly than LIDS (Fig. 1) even though more particles tended to be selected and measured when LIS was applied (Fig. 2). Therefore, the time differential between the two methods can likely be attributed to the variable-length transect design of LIDS. Whereas only a fixed length of line needed to be followed for LIS, in LIDS the crew had to traverse a minimum of 30-50 m along each segment with the total distance traveled depending largely on sighting conditions (*i.e.*, on density of vegetation and variability in micro-topography). Due to the distance-dependent selection criterion of LIDS, determining whether particles were "in" or "out" of the sample was more involved than for LIS. However, with the aid of a simple look-up table (*e.g.*, Table 6 in Appendix B) the crew quickly became familiar with the size-distance relationships implied by a given volume factor. Distances and intersection diameters seldom needed to be measured to determine selection: sufficiently large particles near the sample point and overly small particles far from the sample point were easily identified. Moreover, particles encountered at distances approaching their critical distances were often marked as 'borderline' and evaluated for selection subsequent to the field work. In general, the length (l_i) measurements were the most time-consuming, save on particles having multiple lobes or branches crossing the intersection plane.

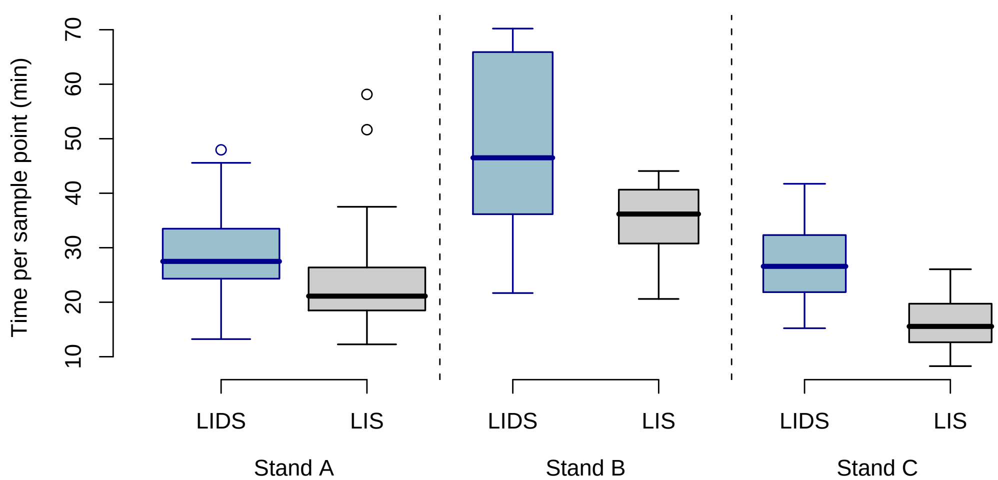

Figure 1: Distributions of transect data collection times by sampling method and stand.

With regards to CWD volume, the two methods produced similar estimates for stands A and C (Table 2). LIDS and LIS estimates differed by approximately 32% in stand B although their confidence intervals from 1000 bootstrap replications overlapped. Notably, in all three stands the time differential favoring LIS (Fig. 1) was more than offset by increased precision on the part of LIDS (Table 2). That is, LIDS permitted the collection of more information on aggregate volume per sample point and per unit time, resulting in favorable (≤ 1) relative efficiencies. In each stand, the difference in precision between the two methods was more pronounced than the differences in estimated tract volumes, markedly so in the case of stand B.

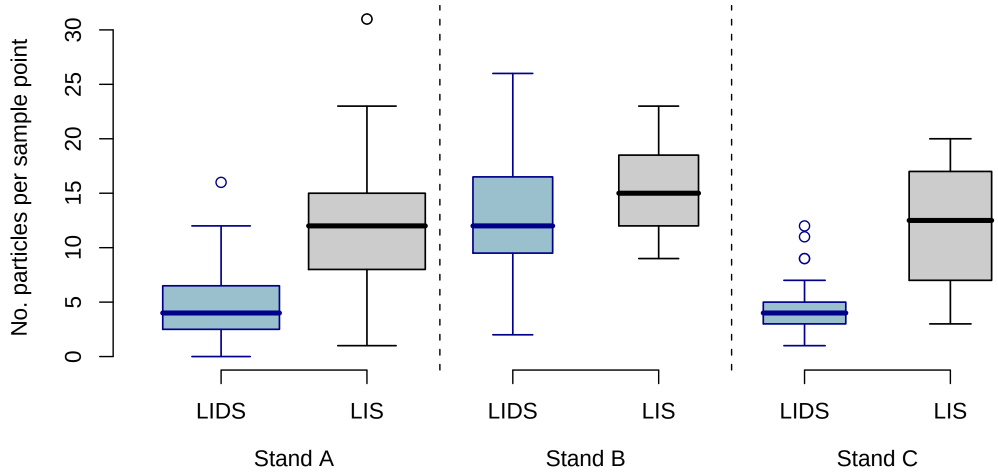

Figure 2: Distributions of transect particle counts by sampling method and stand.

Table 2: CWD volume estimates and corresponding standard errors with lower bounds (LB) and upper bounds (UB) of 90% confidence intervals from 1000 bootstrap replications.

		Volume ($m^3 \cdot ha^{-1}$)			Precision ($m^3 \cdot ha^{-1}$)			
Stand	**Strategy**	**LB**	$\widehat{V}$	**UB**	**LB**	$s(\widehat{V})$	**UB**	**RE**[a]
A	LIDS	41.33	47.50	55.00	3.78	4.38	5.25	0.74
	LIS	37.34	45.41	55.50	4.25	5.62	7.60	
B	LIDS	166.61	189.11	216.43	12.39	15.01	19.72	0.09
	LIS	199.64	260.87	426.90	17.99	57.48	104.94	
C	LIDS	30.67	37.33	43.92	3.16	4.08	5.18	0.66
	LIS	32.22	40.84	54.73	4.91	6.56	8.33	

[a] Relative efficiency of LIDS *vs.* LIS for volume estimation; values below 1 indicate that LIDS is more efficient.

Note also that in one sense the relative efficiencies reported in Table 2 understate the performance of LIDS: if aggregate CWD volume is of central interest, then length measurements and in many cases cross-sectional diameter measurements need not be taken, offering the potential for considerable time savings with LIDS.

Within-stand differences between LIDS and LIS estimates of the abundance or aggregate length of CWD were larger than those for volume (Tables 3 and 4). Excepting stand B, LIS offered improved precision in abundance estimates and thus was more efficient than LIDS. This result is consistent with previously reported simulation research (Affleck 2008) and presumably results from lower variation in particle lengths relative to variation in particle volumes. The probability proportional-to-length LIS design also explains why LIS estimated the aggregate length of CWD more precisely (Table 4) in all three stands. In addition, although aggregate CWD length is rarely of central interest, the relative efficiency estimates of Table 4 understate the performance of LIS in the sense that measurements of length are not required to estimate this attribute using LIS (cf. equation 6 in Appendix B).

The results for stand B are notable for the marked relative efficiency of LIDS in the estimation of aggregate volume (Table 2) as well as the relative inefficiency of

Table 3: CWD abundance estimates and corresponding standard errors with lower bounds (LB) and upper bounds (UB) of 90% confidence intervals from 1000 bootstrap replications.

		Abundance (#·ha^{-1})			Precision (#·ha^{-1})			
Stand	**Strategy**	**LB**	$\widehat{N}$	**UB**	**LB**	$s(\widehat{N})$	**UB**	**RE**[a]
A	LIDS	1319.7	1807.4	2645.3	266.8	366.7	520.6	14.45
	LIS	1210.2	1365.1	1553.6	90.2	106.3	129.1	
B	LIDS	3014.3	3496.5	4252.0	264.0	353.4	514.2	0.88
	LIS	3392.3	3914.4	5092.0	249.4	442.1	745.7	
C	LIDS	997.5	1455.1	2260.6	230.1	393.3	628.9	6.92
	LIS	1074.0	1354.4	1708.3	145.2	195.3	246.3	

[a] Relative efficiency of LIDS *vs.* LIS for abundance estimation; values below 1 indicate that LIDS is more efficient.

Table 4: CWD length estimates and corresponding standard errors with lower bounds (LB) and upper bounds (UB) of 90% confidence intervals from 1000 bootstrap replications.

		Length (m·ha^{-1})			Precision (m·ha^{-1})			
Stand	**Strategy**	**LB**	$\widehat{L}$	**UB**	**LB**	$s(\widehat{L})$	**UB**	**RE**[a]
A	LIDS	4176.3	5107.3	6698.3	536.1	729.3	1003.0	10.95
	LIS	3665.2	4025.2	4467.0	198.9	242.8	307.3	
B	LIDS	21231.6	23932.3	26859.1	1369.7	1704.7	2272.6	2.10
	LIS	24819.3	27052.6	29301.5	1200.5	1383.5	1658.4	
C	LIDS	4501.0	7038.1	11328.6	1019.3	1931.7	3150.1	41.88
	LIS	3690.1	4325.9	4908.5	342.4	389.9	454.8	

[a] Relative efficiency of LIDS *vs.* LIS for length estimation; values below 1 indicate that LIDS is more efficient.

LIS in abundance estimation (Table 3). This even-aged pine stand of approximately 90 years had recently undergone intense self-thinning, generating a considerable quantity of CWD in the process (Fig. 3). However, the downed wood exhibited little variation in decay class, shape, or size. It therefore was anticipated that the statistical advantages of LIDS with regards to volume estimation would be less pronounced in this stand: a probability proportional-to-volume design is less effective, in principle, if the particles' volumes are relatively uniform. Of course, part of the apparent efficiency of LIDS derives from the poor performance of LIS. The latter is presumably the result of using such a short transect ($L = 9$ m). However, there were few areas in this stand with exposed ground and any increase in the transect length would have greatly increased the average sampling times and particle counts.

In sum, these preliminary field results support previous theoretical and simulation research (Affleck 2008) indicating the potential efficiency of LIDS for CWD volume estimation. Moreover, it is clear that LIDS is a practical alternative to LIS in the field: crews can successfully apply the LIDS selection protocol with the aid of simple lookup tables (see Appendix C). Therefore, where the aggregate volume of CWD is of central interest, LIDS appears to be a viable and accurate sampling strategy. Since particle mass and carbon content tend to scale in proportion to particle volume, it also follows that LIDS could offer real advantages over LIS in estimating the aggregate biomass or carbon content of downed wood (cf. Valentine

Figure 3: Photograph taken in stand B; the downed logs in this even-aged *Pinus contorta* stand showed less variation in size relative to the other stands surveyed.

et al. 2008). Ultimately, however, the utility of LIDS or any other strategy, LIS included, will be dictated by the set of descriptive population parameters of interest and the relative importance attached to each. If the aggregate biomass, length, and abundance of CWD ($\#\cdot\text{ha}^{-1}$) are to be estimated with comparable precision, then a sampling strategy that provides reasonably accurate estimates of all three parameters must be sought. Strategies such as LIDS, LIS, and fixed-area plot sampling that tend to be more nearly optimal for one of these parameters may be relatively inefficient overall.

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Appendix A: Symbols Used

Table 5: Symbols and their units.

Symbol	Units	Definition
s_t	(m, m)	coordinate location of sample point t ($t = 1,2,\ldots,T$)
θ_m	$^\circ$	orientation of transect segment m ($m = 1,2,\ldots,M$)
T	–	number of sample points (*i.e.*, number of LIDS or LIS transects)
M	–	number of segments on a radial transect
k	m^{-1}	LIDS critical distance constant
F	$\text{m}^3\cdot\text{ha}^{-1}$	LIDS volume factor ($F = \frac{10000\pi}{2k}$)
L	m	total length of a LIS transect
n_{s_t}	–	number of CWD particles selected by a transect at s_t
$\mathscr{C}_{s_t,m}$	–	set of particles selected by the m^{th} segment of the transect at s_t
l_i	m	length of the central axis of particle i
ϕ_i	$^\circ$	tilt of the central axis of particle i from the horizontal
$x_{m,i}$	(m, m)	intersection point of the central axis of particle i and transect segment m
$a(x_{m,i})$	m^2	cross-sectional area of particle i in the vertical plane containing $x_{m,i}$ and oriented perpendicular to the central axis of particle i
$\widehat{V}$	$\text{m}^3\cdot\text{ha}^{-1}$	estimated aggregate CWD volume per unit tract area
$\widehat{N}$	ha^{-1}	estimated CWD abundance per unit tract area
$\widehat{L}$	$\text{m}\cdot\text{ha}^{-1}$	estimated total length of CWD central axes per unit tract area
$s(\widehat{V})$	$\text{m}^3\cdot\text{ha}^{-1}$	estimated standard error of $\widehat{V}$
$s(\widehat{N})$	ha^{-1}	estimated standard error of $\widehat{N}$
$s(\widehat{L})$	$\text{m}\cdot\text{ha}^{-1}$	estimated standard error of $\widehat{L}$
$\bar{\text{t}}$	min	average sampling time per transect

Appendix B: Line Intersect Sampling Estimators

Corresponding to the LIDS estimators in equations 1-3 are design-unbiased LIS estimators of, respectively, aggregate volume ($\text{m}^3\cdot\text{ha}^{-1}$), abundance ($\#\cdot\text{ha}^{-1}$), and length ($\text{m}\cdot\text{ha}^{-1}$):

$$\widehat{V}_s = F_{\text{LIS}} \sum_{m=1}^{M} \sum_{i \in \mathscr{C}_{s,m}} a(x_{m,i}) \tag{4}$$

$$\widehat{N}_s = F_{\text{LIS}} \sum_{m=1}^{M} \sum_{i \in \mathscr{C}_{s,m}} \frac{1}{l_i \cos(\phi_i)} \tag{5}$$

$$\widehat{L}_s = F_{\text{LIS}}\, n_s\,, \tag{6}$$

where $F_{\text{LIS}} = \frac{10000\pi}{2L}$ is the LIS length factor ($\text{m}\cdot\text{ha}^{-1}$) that is determined by the total transect length L.

Appendix C: LIDS Reference Table

Table 6: Critical distances for fixed minimum round diameter (MRD), and MRDs for fixed critical distances, across varying volume factors (F in $m^3 \cdot ha^{-1}$) for a three-segment LIDS transect.

MRD	D_{crit} (m)[a]			D_{crit}	Minimum round diameter (cm)[b]		
(cm)	$F = 8$	$F = 10$	$F = 15$	(m)	$F = 8$	$F = 10$	$F = 15$
1	0.05	0.04	0.03	1	4.4	4.9	6.0
2	0.21	0.16	0.11	2	6.2	7.0	8.5
3	0.46	0.37	0.25	3	7.6	8.5	10.5
4	0.82	0.66	0.44	4	8.8	9.9	12.1
5	1.29	1.03	0.69	5	9.9	11.0	13.5
6	1.85	1.48	0.99	6	10.8	12.1	14.8
7	2.52	2.02	1.34	7	11.7	13.0	16.0
8	3.29	2.63	1.75	8	12.5	13.9	17.1
10	5.14	4.11	2.74	10	13.9	15.6	19.1
12	7.40	5.92	3.95	12	15.3	17.1	20.9
14	10.08	8.06	5.37	14	16.5	18.5	22.6
16	13.16	10.53	7.02	16	17.6	19.7	24.2
20	20.56	16.45	10.97	20	19.7	22.1	27.0
25	32.13	25.70	17.13	25	22.1	24.7	30.2
30	46.26	37.01	24.67	30	24.2	27.0	33.1

[a] $D_{crit} = \frac{\pi^2 \text{MRD}^2}{8MF}$

[b] $\text{MRD} = \sqrt{\frac{8MF}{\pi^2 D_{crit}}}$