Forest Research
Technical Report
Vancouver Forest Region
2100 Labieux Road, Nanaimo, BC, Canada, V9T 6E9, 250-751-7001

TR-021 Ecology March 2002

Efficiency of six line intersect sampling designs for estimating volume and density of coarse woody debris

by

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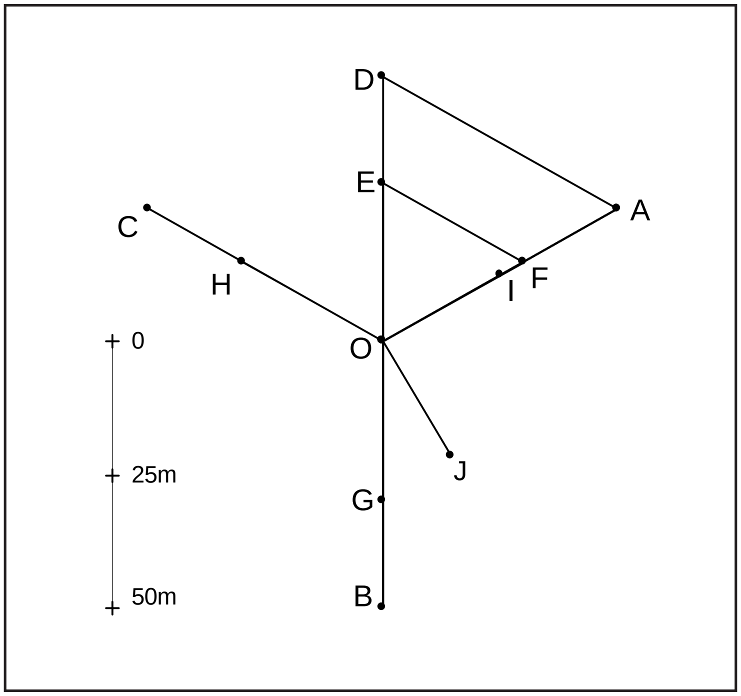

Research Disciplines: Ecology ~ Geology ~ Geomorphology ~ Hydrology ~ Pedology ~ Silviculture ~ Wildlife

Citation:
Nemec, A.F.L., and G. Davis. 2002. Efficiency of six line intersect sampling designs for estimating volume and density of coarse woody debris. Res. Sec., Van. For. Reg., B.C. Min. For., Nanaimo, B.C. Tec. Rep. TR-021/2002.

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Cover illustration: Arrangement of line transects for six LIS sampling designs.

TABLE OF CONTENTS

Abstract............ 2
Keywords............ 2
Acknowledgements............ 2
1. Introduction............ 2
2. Materials and Methods............ 3
  2.1 Study Sites............ 3
  2.2 Classes of Woody Debris............ 3
  2.3 Survey Methods............ 3
  2.4 Data Analysis............ 4
3. Results............ 5
  3.1 Volume and Density Estimates............ 5
  3.2 Survey Times............ 7
  3.3 Sampling Efficiency............ 7
4. Discussion............ 11
References............12

Tables:

1. LIS design specifications for data collection............4
2. Estimated volume and density of dead, down woody debris at Davie River and Roberts Creek............6
3. Mean layout and measurement times with (±) 95% confidence limits............7
4. Fitted standard deviation models. Model 1 assumes a random spatial distribution of pieces............7
5. Total sampling times and minimum sample sizes to achieve 15%, 25%, 35%, and 50% precision (95% confidence limits) in the estimated volume of CWD and large CWD pieces............9
6. Total sampling times and minimum sample sizes to achieve 15%, 25%, 35%, and 50% precision (95% confidence limits) in the estimated density of CWD and large CWD pieces. 10

Figures:

1. Arrangement of line transects for six LIS sampling designs............4
2. Estimated volume and density of CWD at Davie River and Roberts Creek............5
3. Davie River: standard deviation of estimated volume and density of CWD vs. total length of sampling unit............8
4. Roberts Creek: standard deviation of estimated volume and density of CWD vs. total length of sampling unit............8

ABSTRACT

Six line intersect sampling (LIS) designs were used to estimate the volume and number of pieces of coarse woody debris (CWD) per unit area in two forests in the Coastal Western Hemlock biogeoclimatic zone of British Columbia. Each design employed a different sampling unit: (1) a 150m array made up of three equally spaced 50m spokes; (2) a 150m equilateral triangle with 50m sides; (3) a 90m array comprising three equally spaced 30m spokes; (4) a 90m equilateral triangle with 30m sides; (5) a 50m L-shaped transect line with two 25m legs; or (6) a 25m single line. All sampling units were systematically located with random orientations. Sample sizes (i.e., the number of sampling locations) were chosen so that the total length of line was 900m for all six designs.

The relative efficiency of the six designs (i.e., cost of achieving a particular level of precision) depended on whether or not the CWD pieces had a random spatial distribution; the time needed to travel to, establish, and measure the sampling units; and logistical constraints (e.g., the maximum number of non-overlapping LIS units that could be installed in a survey area). Results for the two study sites suggest that 25m transects are most efficient when only moderate (25%-35%) precision is required. Otherwise, intermediate length (50m or 90m) transects appear to be the best option. The arrangement of transects (triangle or three spokes) had no obvious effect on design efficiency, but might be helpful in accommodating long transects or in reducing bias on sites that have a non-random pattern of CWD.

KEY WORDS

coarse woody debris, line intersect sampling, LIS, design, Davie River, Roberts Creek.

ACKNOWLEDGEMENTS

Funding for this project was provided by the BC Ministry of Forests, Vancouver Forest Region. Fieldwork was completed with the assistance of R. Boettger and K. MacPherson. P. Ott, P. Marshall and J. Parminter gave valuable comments on the manuscript. F. Dawkins completed the English edit and layout.

1.0 INTRODUCTION

Line-intersect sampling (LIS) is commonly used in British Columbia, and elsewhere, to estimate the attributes of dead, down woody debris in forest ecosystems. In LIS, a sample line, or transect, is established over an area based on a predetermined design. All dead, down woody debris crossed by the line transect that meets the sampling criteria is assessed; the specific attributes required to meet the study objectives are then recorded for each piece (e.g., species, piece tilt, diameter at transect, and length).

Historically, LIS was used after harvesting to determine fuel loading (van Wagner 1968, McRae et al. 1979) and to estimate logging residue volume (Bailey 1970). More recently, it has been used to monitor productivity, stand structure, and wildlife habitat in both harvested and unharvested settings (Huggard 2000, Waterhouse 1998, Hartwig 1999, Wells and Trofymow 1997).

Line intersect sampling is simpler and sometimes more cost-effective than sampling with fixed-area plots. Bailey (1970) used LIS and plot sampling to estimate coarse woody debris (CWD) volume at two tractor-logged sites in British Columbia. He determined that LIS with L-shaped lines was considerably more efficient than conventional plot sampling with strip or circular plots. Reductions in survey times (for 10% precision and 95% confidence) were found to be in the range 36% to 55%, depending on whether diameter was measured at the line intersection or at both ends of the CWD piece.

In another early study, Howard and Ward (1972) compared LIS survey times and sample-size requirements for L-shaped lines with a fixed orientation, unidirectional straight lines, and randomly oriented straight lines [all with a fixed length of 200ft (61m) and CWD diameter measured at the point of intersection]. Randomly oriented straight lines took more time to establish than unidirectional lines, but resulted in a relatively small coefficient of variation in CWD volume, and were recommended by the authors as a means of avoiding bias in situations where non-random patterns of CWD are likely to arise (e.g., downhill logging, cable yarding, or sloped sites). The authors also concluded that very large samples would be required to achieve more than 15% precision in the estimated volume of CWD at the two clearcut sites where the methods were tested.

In a more recent comparative study of LIS and plot sampling, Clark et al. (1995) found that, for a sample of 14 stands (with one sampling unit per stand), LIS estimates of CWD volume correlated well ($r > 0.85$) with those based on a 900m^2 square plot, regardless of whether the LIS unit was an equilateral triangle (with 40m sides) or a square (with 30m sides).

Pickford and Hazard used a series of simulations to investigate the statistical properties of LIS estimates in the case of randomly distributed CWD (Pickford and Hazard 1978), and later carried out simulations for non-random spatial distributions such as those that might arise at sites that have been logged by cable or tractor (Hazard and Pickford 1986). These simulations confirmed that LIS estimates tend to be highly variable, and therefore, very large samples are required to achieve 10% precision. In general, the precision of LIS estimates depends both on the sampling design and on various site factors. Key elements of design that determine the sampling error are: (1) the length and configuration of line at each sample point; (2) the orientation of the sampling units (e.g., random or unidirectional); (3) the number and type of CWD measurements (diameter at point of intersection with line, diameter at both ends, length, etc.); and (4) the number and arrangement of sample points (e.g., systematic or random). Site factors, which are beyond the control of an investigator, include the sizes, shapes, and density of CWD pieces; the spatial distribution of pieces; and various other factors not investigated by Pickford and Hazard, such as slope and terrain (which affect sampling costs).

Van Wagner (1982) combined LIS theory with empirical results (primarily those of Pickford and Hazard 1978) to develop some basic design principles for sampling randomly distributed CWD: (1) sampling precision depends mainly on the total length of line (i.e., the length of a sampling unit x the number of sampling units; the length and arrangement of individual lines is immaterial); (2) the size of the area to be sampled is theoretically irrelevant (although, in practice, the dimensions of the survey area limit the total number of non-overlapping lines that can be established); and (3) sampling precision increases as the number of CWD intersections per unit length of sample line increases (i.e., precision depends on the density and size of pieces). These principles do not take into account sampling costs and do not necessarily apply when CWD has a clustered, directional, or otherwise non-random spatial pattern.

Hazard and Pickford (1984) proposed a simple (linear) cost function for LIS and used it in their study of the relative efficiency of various LIS designs for sampling non-random patterns of CWD (Hazard and Pickford 1986). Among the designs considered – systematically or randomly located sample points, unidirectional or randomly oriented lines, and sampling units comprising one, two, or three (61m) lines – two lines were found to be the most efficient unit for sampling (simulated) cable-logged patterns – that is, two lines yielded the most accurate results for a fixed cost – while three lines were more efficient for tractor-logged patterns (and for sites with randomly distributed CWD). Systematic location and random orientation of the sampling units were recommended in both cases.

A study by Delisle et al. (1988) produced a somewhat different result. Using data from five natural lodgepole stands and the same type of cost function as that of Hazard and Pickford (1986), they compared the efficiency of measuring one, two, or three legs of an equilateral triangle (with 30m sides), and concluded that single-line sampling units might, in some applications, be more efficient than triangles.

Research to date suggests that the choice of sampling unit is an important element of LIS design. Various configurations and lengths of line are currently in use (e.g., Parminter 1998). Popular choices in British Columbia include: three equally spaced spokes (e.g., Nelson Forest Region 1993), an equilateral triangle (e.g., Trowbridge et al. 1986), two lines at right angles (e.g., BC Ministry of Forests 2000), or a single line (e.g., Taylor 1997), with the total length of line (per sampling unit) varying between 25m and 150m. To help provide a more objective basis for choosing an appropriate sampling unit, the current efficiency study of six LIS designs was undertaken at two study sites in the Coastal Western Hemlock (CWH) biogeoclimatic zone of British Columbia. Measurements of coarse woody debris and survey times were recorded for each design and used to compare the relative costs of estimating volume and density of CWD, with varying degrees of precision.

2.0 MATERIALS AND METHODS

2.1 STUDY SITES

The study sites are two forested areas located in the BC Ministry of Forests' Vancouver Forest Region. The Davie River site is situated adjacent to the middle reaches of the Davie River on northeastern Vancouver Island, British Columbia. It lies in the Very Dry Maritime Coastal Western Hemlock biogeoclimatic subzone (CWHxm), which is characterized by warm, dry summers, moist, mild winters with relatively little snowfall, and long growing seasons with water deficits (Green and Klinka 1994). The last natural fire in the area is estimated to have occurred in the 1400s.[1] The site is level with a predominantly zonal site series. The stand is old growth (i.e., >300 years old), with no prior history of harvesting. Western hemlock (*Tsuga heterophylla*) represents over 50% of the overstorey volume; the remaining volume is divided equally between Douglas fir (*Psuedotsuga menziesii*) and western red cedar (*Thuja plicata).*

The Roberts Creek study area is located approximately 40km northwest of Vancouver, BC, in the Dry Maritime Coastal Western Hemlock biogeoclimatic subzone (CWHdm) of the Sunshine Coast. This subzone variant has warm, relatively dry summers and moist, mild winters with little snow. Growing seasons are long with summer moisture deficits on zonal sites (Green and Klinka 1994). The study area has a gentle slope and the site series is predominantly zonal. The stand is approximately 90-120 years old, originating from a natural fire in the 19th century. The overstorey is dominated by Douglas-fir (*Psuedotsuga menziesii*), with approximately 30% of the stand volume comprising western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*). Periodic extraction of cedar shingle bolts has occurred in the area since the 1870s (D'Anjou 2001).

2.2 CLASSES OF WOODY DEBRIS

For the purposes of this paper, three classes of dead, down woody debris were defined as follows: (1) **fine woody debris**, which includes pieces with large end diameter (LED) < 10cm and total length <1m; (2) **coarse woody debris (CWD)**, which includes all non-supporting pieces that have LED ≥ 10cm and length ≥ 1m; and (3) **large CWD**, a subset of the previous class, which refers to CWD pieces with LED ≥ 50cm and total length ≥ 8m. The minimum LED (50cm) for large CWD corresponds to the upper 10% of the LED distribution for all pieces of CWD (i.e., an estimated 10% of the total number of CWD pieces per hectare have LED ≥ 50cm); the minimum length (8m) was chosen such that approximately 5% of all pieces of CWD meet both the minimum diameter and length requirements. To facilitate comparison with similar ecosystems (e.g., Wells and Trofymow 1997, Spies et al. 1998), volume and density estimates were also obtained for CWD with LED ≥ 60cm.

2.3 SURVEY METHODS

Six different LIS units were used to estimate the amount of woody debris at the two study sites: (1) 150m spoke comprising three equally spaced 50m lines; (2) 150m equilateral triangle (50m sides); (3) 90m spoke comprising three equally spaced 30m lines; (4) 90m equilateral triangle (30m side); (5) 50m "L" shaped transect (25m legs); and (6) a single 25m line. The arrangement

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[1] Personal communication: John Deal, Wildlife Ecologist, Canfor Corporation, Woss, BC, October 2001.

Table 1. LIS design specifications for data collection.

Sampling unit	Configuration	Length (m) of sampling unit, *L*	Distance (m) between sample points, *d*	Total number of sampling units, *n*
1	3 × 50m spokes	150	100	6
2	3 × 50m sides of triangle	150	100	6
3	3 × 30m spokes	90	70.7[1]	10
4	3 × 30m sides of triangle	90	70.7	10
5	2 × 25m legs of L	50	50	18
6	1 × 25m line	25	50	36

[2] The distances in Table 1 do not necessarily satisfy the equation $d = (140{,}000/n)^{0.5}$ due to the rectangular shape of the survey area, avoidance of the boundaries, and the desire to minimize distances traveled between sampling points for all six designs (a constraint that would not normally be a concern). In the case of designs 3 and 4, the distance between sampling points is not 60 m because one half of these plots overlapped the sampling points for designs 1 and 2, while the remaining one-half were located along the diagonal (the diagonal of a 100 m square is 70.7 m). Given the above considerations, the theoretical maximum number of plots was not established at either of the study sites (e.g., only six, rather than 14, 150m sampling units could be accommodated at each site).

of lines in each sampling unit is illustrated in Figure 1. Sampling units were located systematically on a square grid with a common starting point; all units were randomly oriented at each point (i.e., the direction of the first line, OA, was randomly assigned). Sampling intervals and sample sizes (Table 1) were chosen so that the total length of line was 900m for all six designs. The area surveyed at both sites was ~14ha. Sampling units were laid out and measured by a two-person crew with one common member working at both sites.

All pieces of dead, down woody debris that intersected the line transects (and had diameters >1cm at the point of intersection) were measured. Approximate shape (round, rectangular, etc.), width and height at the point of intersection[3], and angle relative to the horizontal were recorded for each piece. Additional measurements were made for the CWD pieces, including: total length, large and small end diameters (LED, SED), species, and decay class.

Survey times were measured with a stopwatch. Three times were recorded for a sub-sample of points: (1) t_T = time to travel from one sample point to the next (t_T was used to estimate the average speed at which crews moved between sample points); (2) t_L = the time required to establish a random orientation and to lay out all lines in a sampling unit; and (3) t_M = the time needed to locate, measure, and record all pieces of woody debris that crossed the transect line(s).

2.4 DATA ANALYSIS

Standard LIS formulas (see Marshall et al., 2000) were used to estimate the volume and density of woody debris[4] for each sampling location and sampling unit (Table 1):

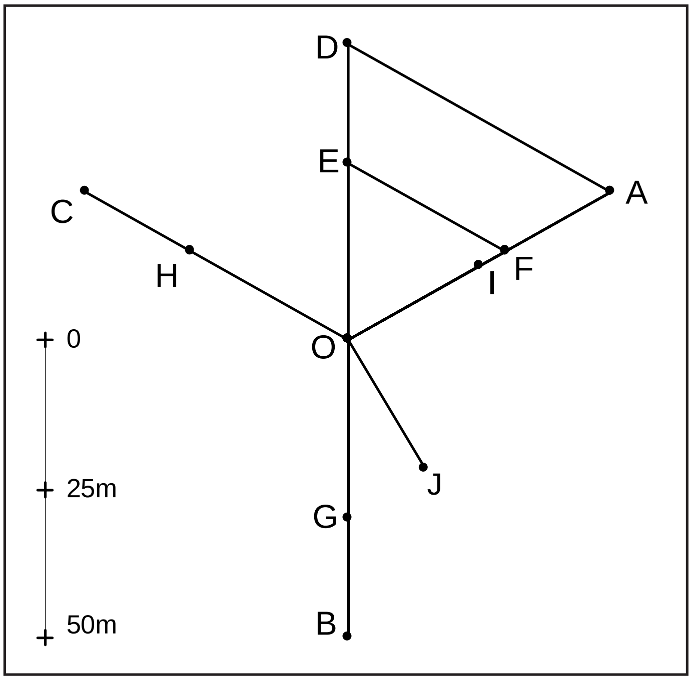

Figure 1. Arrangement of line transects for six LIS sampling designs: (1) 3 x 50m spokes (OA, OB, OC); (2) 3 x 50m triangle (OAD); (3) 3 x 30m spokes (OF, OH, OG); (4) 3 x 30m triangle (OFE); (5) 2 x 25m lines at right angles (OI, OJ); and (6) 25m line (OI).

Volume (m^3/ha) at sample point i = $$\frac{\pi}{2L}\sum_{j=1}^{m_i}\frac{a_{ij}}{\cos\lambda_{ij}} \qquad [1]$$

Density (number of pieces/ha) at sample point i =

$$\frac{\pi}{2L}\sum_{j=1}^{m_i}\frac{a_{ij}}{v_{ij}\cos\lambda_{ij}} \qquad [2]$$

where the indices i and j denote respectively the sample point and piece number; m_i is the number of pieces that intersect the line(s); L is the total length of line (measured in m) in the sampling unit (see Table 1); a_{ij} is the cross-sectional area (measured in cm^2) of piece j where it intersects the line transect; l_{ij} is the (acute) angle between the piece and the horizontal (l_{ij} = 0 for pieces lying flat on the ground); and v_{ij} is the volume of the piece (volume of cylinder, frustum of a cone, etc.).

Values for individual sample points were averaged to produce an estimate ($\bar{y}$) of the overall mean volume (m^3/ha) or density (pieces/ha):

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n} \qquad [3]$$

where y_i is the estimated volume (Eqn. 1) or density (Eqn. 2) at

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[3] For semi-round pieces an equivalent "round" cross sectional diameter was determined and used to calculate cross-sectional area.

[4] All pieces of CWD were truncated to exclude any part at the top that had diameter less than 10cm.

point i and n is the sample size (i.e., total number of points – see Table 1). A 95% confidence interval was constructed by applying the formula for simple random sampling:

$$\bar{y} \pm t_{0.025,n-1} \times \frac{s}{\sqrt{n}} \qquad [4]$$

where s is the sample standard deviation:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{n-1}} \qquad [5]$$

and $t_{0.025,n\text{-}1}$ is the number that corresponds to 2.5% probability in the upper tail of a t distribution with n -1 degrees of freedom. Volume estimates were obtained for total (fine and coarse) woody debris, CWD, and large CWD; density estimates were calculated for all classes except total woody debris.

To compare the relative efficiencies of the six LIS designs (Table 1), Eqn. 4 was solved for n, for different levels of precision (expressed as a percentage of the mean), and the associated sampling cost (time) was calculated by applying a cost equation similar to that proposed by Hazard and Pickford (1984):

$$\text{Total time to sample } n \text{ locations} = (n - 1) \times t_T + n \times (t_L + t_M), \qquad [6]$$

where t_T, t_L, and t_M are the expected travel, layout, and measurement times. The travel time (t_T) was found to be approximately proportional to the distance (d) between points, which (assuming sample points are located systematically throughout the 14ha sample area) was calculated (in meters) as $d = (140{,}000/n)^{0.5}$; while layout and measurement times (t_L and t_M) were proportional to L. A minimum distance requirement (i.e., d ³ $2x$, where x is the length of the individual lines that make up a sampling unit) was imposed to ensure that no sampling unit overlapped another. For a 14ha (square) survey area (excluding any buffer zone around the boundary), the minimum distance requirement translates into a maximum theoretical sample size[5] of 14 for Designs 1 and 2, 38 for Designs 3 and 4, and 56 for Designs 5 and 6.

3.0 RESULTS

3.1 VOLUME AND DENSITY ESTIMATES

The estimated total volume of fine and coarse woody debris (average for all six LIS designs) was 278.2m^3/ha for Davie River

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[5] See Footnote 2, Page 4.

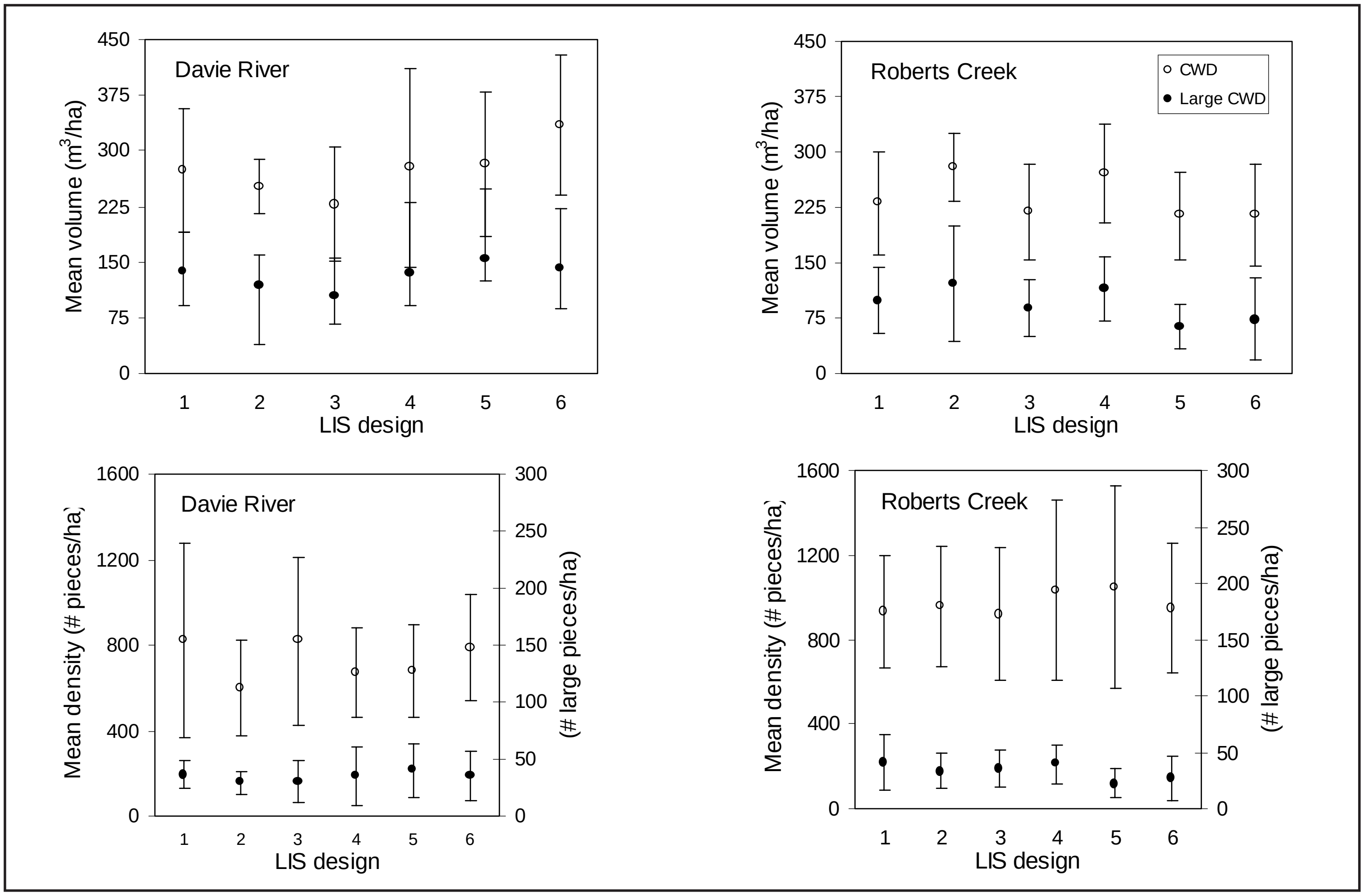

Figure 2. Estimated volume (upper panels) and density (lower panels) of CWD at Davie River and Roberts Creek. Open (solid) circles denote the sample means for all (large) pieces of CWD; the corresponding 95% confidence limits (Eqn. 4) are shown as vertical error bars. Estimates are based on the six LIS designs listed in Table 1, with a total of 900m of line.

Table 2. Estimated volume and density of dead, down woody debris at Davie River and Roberts Creek.

			Volume (m^3/ha)						
			Method						
Class	Site		1	2	3	4	5	6	Mean
Fine and coarse woody debris	Davie River	Mean	275.3	254.8	229.3	278.8	285.9	345.3	278.2
		Std. Dev.	78.1	33.0	94.3	164.8	162.5	219.9	
		Std. Err.	31.9	13.5	29.8	52.1	38.3	36.6	
	Roberts Creek	Mean	238.9	293.7	231.2	289.2	224.8	242.3	253.4
		Std. Dev.	78.5	50.4	88.1	93.8	95.1	167.5	
		Std. Err.	32.0	20.6	27.8	29.7	22.4	27.9	
CWD	Davie River	Mean	274.3	251.4	228.1	277.5	282.0	334.5	274.6
		Std. Dev.	78.8	34.5	94.7	164.2	162.3	220.9	
		Std. Err.	32.2	14.1	29.9	51.9	38.3	36.8	
	Roberts Creek	Mean	231.1	279.5	218.6	270.8	213.6	214.3	238.0
		Std. Dev.	66.6	43.9	79.2	81.7	99.0	159.1	
		Std. Err.	27.2	17.9	25.0	25.8	23.3	26.5	
Large CWD (LED ≥ 50cm, Length ≥ 8m)	Davie River	Mean	137.1	117.6	104.1	134.9	154.3	141.2	131.5
		Std. Dev.	50.5	39.2	62.3	116.8	156.9	190.3	
		Std. Err.	20.6	16.0	19.7	36.9	37.0	31.7	
	Roberts Creek	Mean	98.8	121.3	88.5	114.8	63.0	73.9	93.4
		Std. Dev.	43.1	74.2	46.4	53.9	49.4	128.2	
		Std. Err.	17.6	30.3	14.7	17.0	11.6	21.4	
Large CWD (LED ≥ 60cm)	Davie River	Mean	108.9	124.0	83.5	122.2	154.0	141.1	122.3
		Std. Dev.	69.4	33.4	71.9	135.8	137.6	170.5	
		Std. Err.	28.3	13.6	22.7	42.9	32.4	28.4	
	Roberts Creek	Mean	79.9	120.3	72.8	99.3	53.9	54.6	80.1
		Std. Dev.	17.6	62.1	57.8	70.8	70.2	97.9	
		Std. Err.	7.2	25.4	18.3	22.4	16.6	16.3	

			Density (number of pieces/ha)						
			Method						
Class	Site		1	2	3	4	5	6	
CWD	Davie River	Mean	822	597	820	672	678	788	729
		Std. Dev.	433	215	485	257	358	583	
		Std. Err.	177	88	153	81	84	97	
	Roberts Creek	Mean	934	957	920	1032	1047	950	973
		Std. Dev.	254	268	383	527	792	713	
		Std. Err.	104	110	121	167	187	119	
Large CWD (LED ≥ 50cm, Length ≥ 8m)	Davie River	Mean	36	29	30	35	40	35	34
		Std. Dev.	12	10	23	32	39	50	
		Std. Err.	5	4	7	10	9	8	
	Roberts Creek	Mean	41	33	36	39	23	27	33
		Std. Dev.	23	15	20	21	22	47	
		Std. Err.	10	6	6	7	5	8	
Large CWD (LED ≥ 60cm)	Davie River	Mean	31	34	22	38	47	42	36
		Std. Dev.	25	13	18	41	46	63	
		Std. Err.	10	6	6	13	11	11	
	Roberts Creek	Mean	29	37	24	35	28	22	29

Table 3. Mean layout and measurement times with (±) 95% confidence limits (*n* is the number of sampling units with recorded times).

		Time (minutes/sampling unit)					
		Method					
Task	Site	1	2	3	4	5	6
Layout	Davie River	28.6 ± 6.7	29.4 ± 8.1	17.0 ± 2.7	26.7 ± 16.1	11.5 ± 3.3	5.0 ± 0.6
		n = 5	*n* = 5	*n* = 7	*n* = 7	*n* = 12	*n* = 22
	Roberts Creek	33.7 ± 8.6	33.8 ± 4.5	24.1 ± 5.1	22.7 ± 4.3	14.0 ± 2.0	5.5 ± 0.6
		n = 3	*n* = 4	*n* = 7	*n* = 8	*n* = 11	*n* = 23
Measurement	Davie River	183.4 ± 35.5	187.8 ± 86.3	104.6 ± 21.4	106.4 ± 20.8	56.9 ± 7.2	32.7 ± 4.1
		n = 5	*n* = 5	*n* = 9	*n* = 9	*n* = 16	*n* = 34
	Roberts Creek	219.6 ± 57.8	216.0 ± 65.8	133.9 ± 26.3	136.4 ± 26.5	72.0 ± 13.6	31.7 ± 5.1
		n = 5	*n* = 5	*n* = 9	*n* = 9	*n* = 17	*n* = 35

and 253.4m^3/ha for Roberts Creek. Coarse woody debris accounted for 94-99% of the total volume at the two sites, with 39-48% of the CWD volume in the form of large pieces. Table 2 compares the estimated mean volumes and densities, standard deviations (Eqn. 5), and standard errors of the means for the six LIS designs. Differences between the sample means (Figure 2) were not statistically significant for any class of woody debris (i.e., $p > 0.05 \div 15$ for all 15 pairs of means corresponding to the six designs[6]). Therefore, bias was not considered in the assessment of design efficiency (i.e., any bias was assumed to be equal for all six designs).

3.2 SURVEY TIMES

Crews traveled from one sample point to the next at an estimated rate of 4.09m per minute (both sites). Average layout and measurement times, which were approximately proportional to the length of the line transects and did not depend on configuration, are given in Table 3.

3.3 SAMPLING EFFICIENCY

Figures 3 and 4 illustrate (by site) the empirical relationships between s and L for the four CWD variables of interest (volume and density of total CWD and large CWD), where each point represents a different design (Table 1). In general, s is expected to decrease as the length of an LIS unit (L) increases and, in particular, it is expected to decrease as $L^{-0.5}$ when the CWD pieces have a random spatial distribution (Pickford and Hazard 1978). The observed trends (Figs. 3, 4) are consistent with the theory that s decreases with L. However, owing to the small sample sizes and correspondingly large errors in s, the exact nature of the relationship was difficult to determine. Similarly, the apparent absence of a systematic difference between the three-spoke (Designs 1 and 3) and triangular (Designs 2 and 4) configurations was suggestive but not definitive evidence that both designs were equally efficient.

In order to compare the efficiencies of the designs, and taking into account uncertainty about the relationship between s and L, three types of non-linear trends were fitted (by least squares) to the data for the six designs: (1) $s = a\ L^{-0.5}$ (random spatial

Table 4. Fitted standard deviation models. Model 1 assumes a random spatial distribution of pieces.

Variable	**Model**	Davie River	Roberts Creek
CWD density	1	$3122\ L^{-0.5}$	$4116\ L^{-0.5}$
	2	$1529\ L^{-0.32}$	$3776\ L^{-0.48}$
	3	$931 - 286.68 \log_{10}(L)$	$1763 - 672.46 \log_{10}(L)$
Large CWD density	1	$242\ L^{-0.5}$	$207\ L^{-0.5}$
	2	$425\ L^{-0.64}$	$262\ L^{-0.56}$
	3	$124.27 - 51.05 \log_{10}(L)$	$82.98 - 30.85 \log_{10}(L)$
CWD volume	1	$1085\ L^{-0.5}$	$751\ L^{-0.5}$
	2	$1528\ L^{-0.59}$	$980\ L^{-0.57}$
	3	$516.13 - 206.15 \log_{10}(L)$	$473.48 - 126.13 \log_{10}(L)$
Large CWD volume	1	$905\ L^{-0.5}$	$552\ L^{-0.5}$
	2	$1763\ L^{-0.67}$	$677\ L^{-0.55}$
	3	$473.48 - 195.89 \log_{10}(L)$	$207.32 - 74.72 \log_{10}(L)$

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[6] A Bonferroni adjustment for multiple comparisons was applied by dividing the level of significance (0.05) by the total number of sample pairs (15).

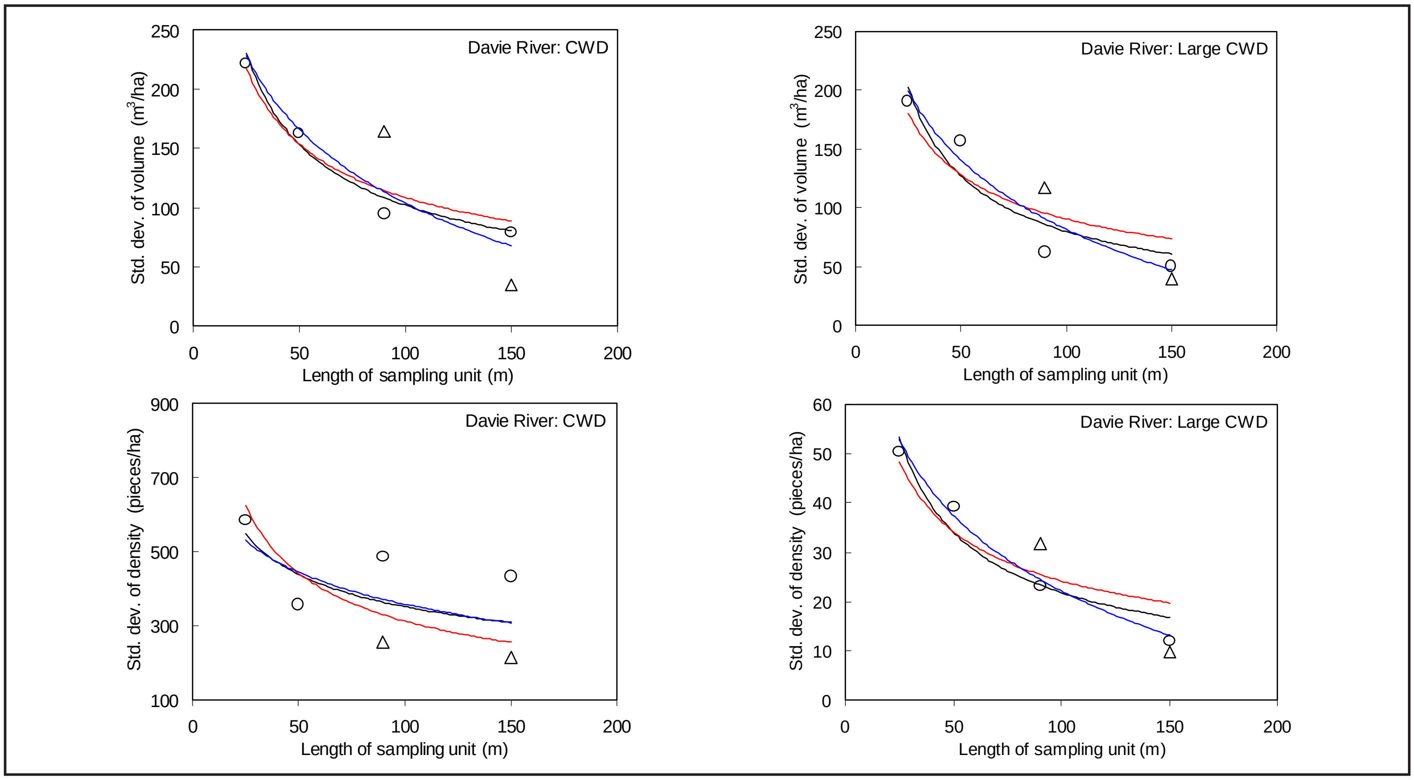

Figure 3. Davie River: Standard deviation of estimated volume (upper panels) and density (lower panels) of CWD versus total length of sampling unit. Fitted models (Table 4) are shown as blue (Model 1), red (Model 2), and black (Model 3) curves. Circles denote the sampling units for Designs 1, 3, 5, and 6; sampling units for Designs 2 and 4 are plotted as triangles.

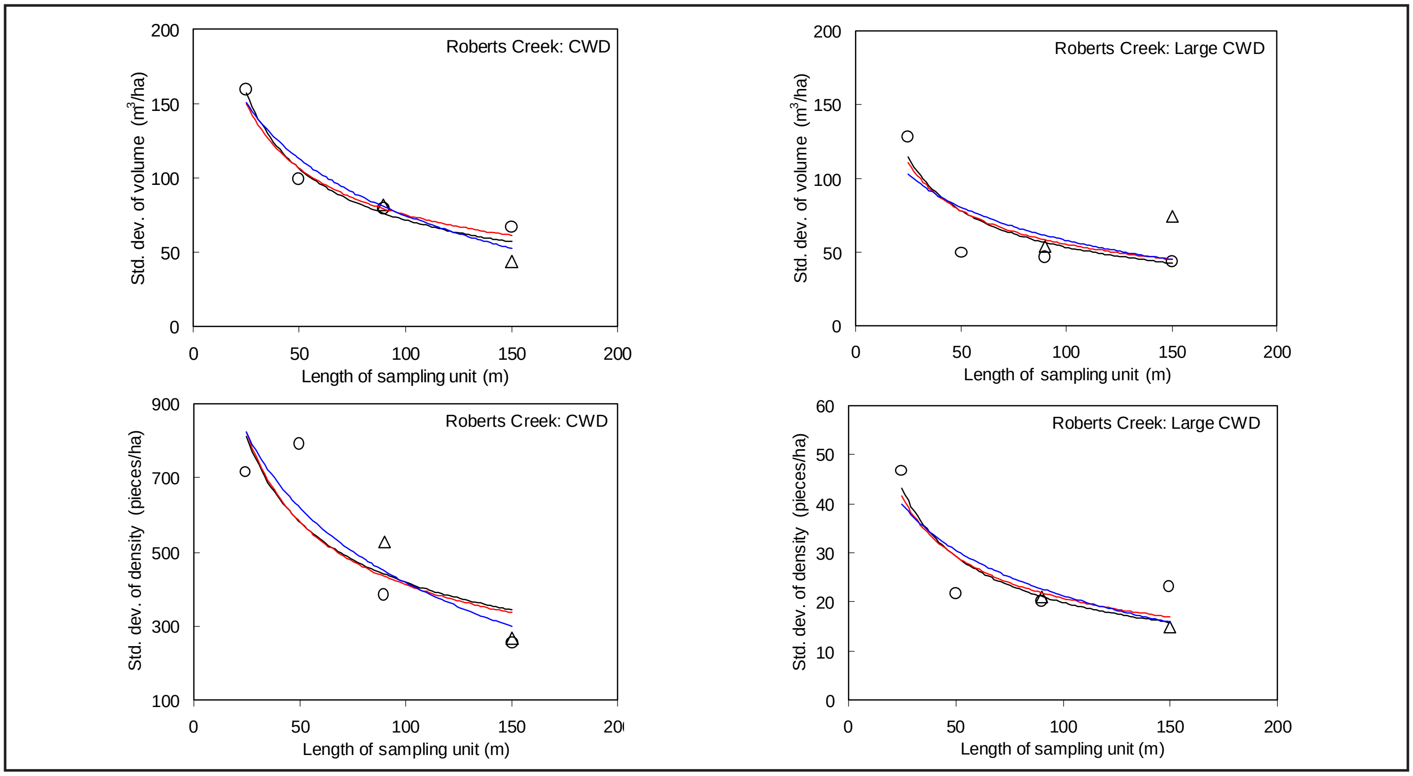

Figure 4. Roberts Creek: Standard deviation of estimated volume (upper panels) and density (lower panels) of CWD versus total length of sampling unit. Fitted models (Table 4) are shown as blue (Model 1), red (Model 2), and black (Model 3) curves. Circles denote the sampling units for Designs 1, 3, 5, and 6; sampling units for Designs 2 and 4 are plotted as triangles.

distribution), (2) $s = a L^b$, and (3) $s = a + b \log_{10}(L)$. Differences between the three-spoke and triangular designs were, for the purposes of this exercise, ignored. The fitted models are given in Table 4 and are plotted in Figures 3 and 4 (blue, red, and black curves). These models were used to estimate the minimum sample size n_{min} required to obtain a 95% confidence interval with half width (precision) equal to 15%, 25%, 35% and 50% of the overall mean (i.e., the average of the means for all

Table 5. Total sampling times and minimum sample sizes to achieve 15%, 25%, 35%, and 50% precision (95% confidence limits) in the estimated volume of CWD and large CWD pieces. A dash (-) denotes a sample size that exceeds the maximum for a 14 ha survey area.

CWD			Total sampling time (days)				Number of sampling units			
			LIS design				LIS design			
Model (Table 4)	Site	Sampling error (%)	1,2	3,4	5	6	1,2	3,4	5	6
1	Davie River	15	-	9.0	8.4	-	-	33	56	-
		25	4.2	3.9	3.3	3.1	9	14	22	41
		35	2.8	2.2	2.0	1.7	6	8	13	23
		50	2.3	1.7	1.2	1.0	5	6	8	13
	Roberts Creek	15	7.6	7.2	6.7	-	14	22	37	-
		25	3.8	3.3	2.7	2.4	7	10	15	27
		35	2.8	2.0	1.6	1.4	5	6	9	15
		50	2.2	1.7	1.1	0.8	4	5	6	9
2	Davie River	15	-	8.2	8.4	-	-	30	56	-
		25	3.7	3.6	3.3	3.5	8	13	22	46
		35	2.8	2.2	2.0	1.9	6	8	13	25
		50	1.9	1.4	1.2	1.1	4	5	8	14
	Roberts Creek	15	7.1	6.5	6.7	-	13	20	37	-
		25	3.8	3.0	2.7	2.7	7	9	15	30
		35	2.8	2.0	1.6	1.5	5	6	9	17
		50	2.2	1.7	1.1	0.9	4	5	6	10
3	Davie River	15	6.0	8.7	-	-	13	32	-	-
		25	3.2	3.6	3.8	3.4	7	13	25	45
		35	2.3	2.2	2.1	1.9	5	8	14	25
		50	1.9	1.7	1.4	1.1	4	6	9	14
	Roberts Creek	15	6.0	7.5	7.4	-	11	23	41	-
		25	3.3	3.3	3.1	2.5	6	10	17	28
		35	2.8	2.3	1.8	1.4	5	7	10	16
		50	2.2	1.7	1.1	0.8	4	5	6	9

Large CWD			Total sampling time (days)				Number of sampling units			
			LIS design				LIS design			
Model (Table 4)	Site	Sampling error (%)	1,2	3,4	5	6	1,2	3,4	5	6
1	Davie River	15	-	-	-	-	-	-	-	-
		25	-	9.5	-	-	-	35	-	-
		35	6.0	5.2	5.0	-	13	19	33	-
		50	3.7	3.0	2.7	2.4	8	11	18	32
	Roberts Creek	15	-	-	-	-	-	-	-	-
		25	-	8.8	8.3	-	-	27	46	-
		35	5.5	4.9	4.5	4.2	10	15	25	47
		50	3.8	3.0	2.5	2.2	7	9	14	24
2	Davie River	15	-	-	-	-	-	-	-	-
		25	-	7.9	-	-	-	29	-	-
		35	4.6	4.4	4.9	-	10	16	32	-
		50	2.8	2.8	2.6	3.0	6	10	17	39
	Roberts Creek	15	-	-	-	-	-	-	-	-
		25	-	8.1	8.3	-	-	25	46	-
		35	5.5	4.6	4.5	4.5	10	14	25	50
		50	3.3	3.0	2.5	2.3	6	9	14	26
3	Davie River	15	-	-	-	-	-	-	-	-
		25	5.1	8.7	-	-	11	32	-	-
		35	3.2	4.9	5.9	-	7	18	39	-
		50	2.3	2.8	3.2	2.9	5	10	21	38
	Roberts Creek	15	-	-	-	-	-	-	-	-
		25	-	9.4	8.6	-	-	29	48	-
		35	5.5	5.2	4.7	3.7	10	16	26	41
		50	3.8	3.3	2.5	2.0	7	10	14	22

six samples, Table 2). The corresponding total cost of sampling was calculated by substituting $n_{\min}$ into Eqn. 6, with the following (per sampling unit) estimates of travel, layout, and measurement times (Table 3): $t_T = d \times 0.2443$ (Davie River and Roberts Creek); $t_L = L \times 0.2073$ and $t_M = L \times 1.2177$, for Davie River; and $t_L = L \times 0.2357$ and $t_M = L \times 1.4623$, for Roberts Creek.

Table 5 summarizes the efficiency calculations for estimating

Table 6. Total sampling times and minimum sample sizes to achieve 15%, 25%, 35%, and 50% precision (95% confidence limits) the estimated density of CWD and large CWD pieces. A dash (-) denotes a sample size that exceeds the maximum for a 14 ha survey area.

CWD			Total sampling time (days)				Number of sampling units			
Model		Sampling	LIS design				LIS design			
(Table 4)	Site	error (%)	1,2	3,4	5	6	1,2	3,4	5	6
1	Davie River	15	-	10.4	-	-	-	38	-	-
		25	4.6	4.1	3.8	3.6	10	15	25	48
		35	3.2	2.5	2.1	2.0	7	9	14	26
		50	2.3	1.7	1.4	1.1	5	6	9	14
	Roberts Creek	15	-	12.0	-	-	-	37	-	-
		25	5.5	4.9	4.5	4.2	10	15	25	47
		35	3.8	3.0	2.5	2.3	7	9	14	25
		50	2.8	2.0	1.5	1.3	5	6	8	14
2	Davie River	15	-	-	-	-	-	-	-	-
		25	6.4	4.9	3.8	2.8	14	18	25	37
		35	4.2	3.0	2.1	1.6	9	11	14	21
		50	2.8	1.9	1.4	0.9	6	7	9	12
	Roberts Creek	15	-	12.3	-	-	-	38	-	-
		25	6.0	5.2	4.5	4.1	11	16	25	46
		35	3.8	3.0	2.5	2.3	7	9	14	25
		50	2.8	2.0	1.5	1.3	5	6	8	14
3	Davie River	15	-	-	-	-	-	-	-	-
		25	6.4	5.2	3.9	2.7	14	19	26	35
		35	4.2	3.0	2.3	1.5	9	11	15	20
		50	2.8	1.9	1.4	0.8	6	7	9	11
	Roberts Creek	15	-	-	-	-	-	-	-	-
		25	4.9	5.2	5.0	4.2	9	16	28	47
		35	3.3	3.3	2.9	2.3	6	10	16	25
		50	2.2	2.0	1.6	1.3	4	6	9	14
Large CWD			Total sampling time (days)				Number of sampling units			
Model		Sampling	LIS design				LIS design			
(Table 4)	Site	error (%)	1,2	3,4	5	6	1,2	3,4	5	6
1	Davie River	15	-	-	-	-	-	-	-	-
		25	-	10.1	-	-	-	37	-	-
		35	6.0	5.5	5.2	-	13	20	34	-
		50	3.7	3.0	2.7	2.5	8	11	18	33
	Roberts Creek	15	-	-	-	-	-	-	-	-
		25	-	9.7	9.1	-	-	30	51	-
		35	6.0	5.5	5.0	4.7	11	17	28	52
		50	3.8	3.3	2.7	2.4	7	10	15	27
2	Davie River	15	-	-	-	-	-	-	-	-
		25	-	8.5	-	-	-	31	-	-
		35	4.6	4.7	5.2	-	10	17	34	-
		50	3.2	2.8	2.7	3.0	7	10	18	40
	Roberts Creek	15	-	-	-	-	-	-	-	-
		25	-	9.1	9.1	-	-	28	51	-
		35	5.5	5.2	5.0	-	10	16	28	-
		50	3.8	3.0	2.7	2.6	7	9	15	29
3	Davie River	15	-	-	-	-	-	-	-	-
		25	5.5	9.3	-	-	12	34	-	-
		35	3.7	5.2	6.1	-	8	19	40	-
		50	2.3	3.0	3.2	3.0	5	11	21	39
	Roberts Creek	15	-	-	-	-	-	-	-	-
		25	-	10.4	10.0	-	-	32	56	-
		35	5.5	5.9	5.4	4.4	10	18	30	49
		50	3.8	3.3	2.9	2.3	7	10	16	25

the volume of (large) CWD at the two study sites; Table 6 summarizes the density results. A dash (-) denotes a sample size that exceeds the maximum number of transect lines that can (theoretically) be installed, without overlap, on a uniform grid that covers a 14ha survey area. In general, sampling with more, shorter sampling units was more efficient than increasing the length and reducing the sample size. At Roberts Creek, where there was little difference between the three fitted *s-L* models (Table 4, Figure 4), the sampling unit comprising a single 25m line (Design 6) was found to be more efficient, for estimating the volume and density of (large) CWD, than longer sampling units (Designs 1-5), provided that relatively large (^{3}25%) sampling errors were acceptable. The sample size required to reduce the sampling error below 25% of the mean typically exceeded the maximum sample size of 56 (14ha survey area) for a 25m line. Therefore, in many applications, designs with sampling units with length less than 25m might not be practical. This situation was exacerbated in the case of large CWD pieces, which were substantially fewer in number and subject to considerably more sampling variability than total CWD.

The findings were similar for Davie River, where decreasing the length of the sampling units and increasing the sample size tended to improve sampling efficiency for randomly distributed CWD (Model 1), up to the limits imposed by the 14ha survey area (which corresponded to sampling errors in excess of 15% for total CWD and 35% for large pieces of CWD; Tables 5 and 6). If the standard deviation (Fig. 3) was assumed to decrease more rapidly than the random case (for sampling units with lengths up to ~50-100m), and the required sampling error was <25%, then the longest (Designs 1 and 2) or intermediate length (Designs 3, 4, 5) sampling units were more efficient than shortest units (Design 6), except when estimating the density of CWD.

4.0 DISCUSSION

The relative efficiency of different LIS designs, as measured by the cost of achieving a particular level of precision, depends on various factors, including:

- The spatial distribution of pieces and functional form of the relationship between sampling variability (*s*) and the length of the sampling unit (*L*);
- travel speed and the time (per unit length) needed to establish the line transects and to make measurements; and
- logistical considerations.

In theory, any level of precision can be achieved either by increasing the length of line in each LIS unit (thereby decreasing *s*) or by increasing the sample size (thereby decreasing the standard error of the mean). The results of this study suggest that the latter tended to be a more efficient strategy than the former when only moderate (25%-35%) precision was required and the spatial distribution of CWD was assumed to be random. If more precise estimates of CWD volume or density were needed, then the sample size for short (25m) sampling units tended to be prohibitively large, especially in the case of large CWD. In such cases, intermediate length (50m or 90m) sampling units appeared to be the best option. On the other hand, if CWD pieces have a non-random (i.e., clustered or uniformly) spatial distribution then *s* is expected to decrease more or less rapidly than $L^{-0.5}$ (random model). In these situations, increasing the sampling unit length might be more efficient than increasing the sample size, with the optimum length dependent on the nature of the *s-L* relationship.

Re-configuring the line transects, without changing the total length of the sampling units, appears to have had a tenuous, and possibly, non-existent effect on sampling variability, at least for the Davie River and Roberts Creek study sites. This apparent absence of an effect does not rule out the possibility that changing the configuration (e.g., from a straight line to an "L") might be helpful in accommodating large samples or in reducing bias on sites that have a non-random pattern of CWD.

To determine the most cost-effective LIS design for a particular application, the rate at which the sample standard deviation decreases with increasing length *L* (Figures 3 and 4) must be determined and weighed against the rate at which the total sampling cost (Eqn. 6) increases. Both rates are site specific and depend on the amount, spatial distribution, shape, and size distribution of CWD, which in turn are governed by a variety of factors, such as stand history and origin (i.e., fire, windthrow, prior harvesting), stage of stand development, stem distribution (i.e., clumpy or dispersed), species composition, terrain, and harvesting operations (e.g., yarding method). In addition, measurement costs depend on whether or not piece length or the diameter of both ends is measured (e.g., these measurements are generally required to classify pieces by size, to estimate the volume of individual pieces, and to estimate the number of CWD pieces per unit area).

Finally, field logistics must be considered in the design of an LIS survey. If the individual lines that make up the sampling unit are too long, or the sample size is too big, then systematic location of the sampling units, without overlap, may not be feasible for small or irregularly shaped survey areas. For example, although a 14ha (square) survey area should accommodate up to 14 (three-spoke or triangular) 150m sampling units (Design 1 or 2), only six such non-overlapping units could be installed at the Davie River and Roberts Creek sites. In such situations, the size and shape of the survey area might dictate the design. Similarly, on sites with steep and gullied terrain, and on those with dense vegetation, shorter transects might be preferable to longer transects, regardless of efficiency considerations, because the former facilitate slope correction, determination of direction, and might be easier to weave through dense vegetation than the latter. In studies requiring repeated measurement of the sampling units (especially where understorey vegetation is dense or the topography is complex), a triangular sampling unit might be preferred over a three-spoke configuration because it is easier to relocate. Thus, in many practical applications of the LIS method, logistics might outweigh efficiency considerations.

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