Comparing line-intersect, fixed-area, and point relascope sampling for dead and downed coarse woody material in a managed northern hardwood forest

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Abstract: We present the results of a timed field trial comparing the bias characteristics and relative sampling efficiency of line-intersect, fixed-area, and point relascope sampling for downed coarse woody material. Seven stands in a managed northern hardwood forest in New Hampshire were inventoried. Significant differences were found among estimates in some stands, indicating a potential for difference in bias in field implementation of the methods. In terms of relative sampling efficiency, results for each method varied among stand. However, point relascope sampling had comparable or better time efficiency than the other methods in most stands.

Résumé : Nous présentons les résultats d'un essai chronométré sur le terrain visant à comparer les caractéristiques des biais et l'efficacité relative des méthodes d'échantillonnage par intersection de lignes, placettes circulaires à rayon fixe et placettes circulaires à rayon variable à l'aide du relascope pour les débris ligneux grossiers au sol. Sept peuplements ont été inventoriés dans une forêt de feuillus nordiques du New Hampshire. Des différences significatives ont été observées entre les estimations dans certains peuplements, laissant entrevoir la possibilité qu'il y ait des différences dans les biais liés à l'implantation des méthodes sur le terrain. En terme d'efficacité relative d'échantillonnage, les résultats pour chaque méthode variaient selon les peuplements. Cependant, l'échantillonnage au relascope était aussi ou plus efficace du point de vue du temps que les autres méthodes dans la plupart des peuplements.

[Traduit par la Rédaction]

Introduction

Management of dead and downed coarse woody material (CWM; also known as coarse woody debris, CWD) has become increasingly important in eastern forests as recognition of the value of this resource has grown (e.g., see Gore and Patterson 1986; McCarthy and Bailey 1994; Shifley et al. 1997; McGee et al. 1999). Management guidelines that provide for certain amounts or types (e.g., large and hollow pieces) of CWM may be included as components of forest management plans and stand prescriptions (NHFSSWT 1997). The need for obtaining efficient and reliable estimates of CWM is obvious for practitioners trying to realize management goals or meet established guidelines.

Several theoretically unbiased methods are available for sampling CWM. These include fixed-area sampling (FAS) (Harmon and Sexton 1996) and related methods (e.g., fixed-width strip cruising); line-intersect sampling (LIS) (Warren and Olsen 1964; Van Wagner 1968; Kaiser 1983) and planar-intersect sampling (Brown 1971); and more recently transect relascope sampling (TRS) (Ståhl 1997, 1998) and point relascope sampling (PRS) (Gove et al. 1999, 2001). However, many practitioners are not familiar with these methods or their appropriate implementation in the field.

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Fixed-area sampling methods for CWM are based on the frequency of occurrence of individual pieces of CWM. In practice, a plot of known area is laid out in the forest and each piece that lies within (or partially within) the plot is tallied and parameters of interest are recorded. Estimates of per-unit area values can be obtained by multiplying any parameters by the reciprocal of the plot size.

Line-intersect, transect relascope, and point relascope sampling are all probability-proportional-to-size sampling methods. Additionally, they were all developed specifically to sample CWM. With LIS and TRS, sampling is performed with probability proportional to the length of an individual piece of CWM. In practice, LIS is performed by establishing a sample line in the forest and tallying or recording parameters of interest for each piece of CWM that intersects the sample line. Similarly, TRS (analogous to horizontal line sampling (HLS) for overstory trees; see Beers and Miller 1976) is performed by establishing a sample line in the forest, but a wide- angle gauge is used to augment the tally by sampling pieces of CWM on each side of the line. Line-intersect and transect relascope tallies can be expanded to per-unit area values using a length factor (similar to a basal area factor in horizontal point sampling (HPS); see Grosenbaugh 1958). Point relascope sampling, analogous to HPS, is performed with probability proportional to the length squared of an individual piece of CWM. As in TRS, a

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Table 1. Characteristics of the seven stands sampled for coarse woody material at the Bartlett Experimental Forest (BEF) in New Hampshire.

Stand	BEF compartment no.	Sample area (ha)	Basal area (m^2/ha)	No. of samples	Management history[a]
I	2,13,14,15[b]	24	9.2–22.9	53	Density/thinning study, 1963, 1990; 12 treatment levels
II	22	8	27.6	20	Clearcut, 1933–1935; pre-commercial thinning study, 1959
III	28	21	25.3	24	Clearcut, 1967; scattered crop tree release, 1985–1990
IV	36	6	0.0	13	Diameter-limit cut, 1955; clearcut, 1999–2000
V	41	25	31.9	22	Single-tree selection, 1952–1953
VI	42	13	24.3	18	Single-tree selection, 1952, 1975, 1992
VII	43	25	19.7	21	Single-tree selection, 1957, 1999–2000

[a] All stands originated from clearing prior to or around 1900.
[b] Uncut stand in Compartment 15 used as control for thinning-density study.

wide-angle gauge is used to select individual pieces for the sample, but the angle gauge is operated around a discrete sample point rather than along a transect. Estimates of per-unit area values can be obtained with a length squared factor for PRS.

Studies comparing methods for sampling CWM have appeared in the literature (Pickford and Hazard 1978; Hazard and Pickford 1986; Ståhl 1998; Ringvall and Ståhl 1999; Brissette et al. 2003). However, treatments of the subject have either relied heavily on simulations or have been limited in scope. Consequently, the relative sampling efficiency of the methods is not firmly established and operational inventories of CWM remain largely neglected by practitioners.

In recent months, two other new methods for sampling CWM have appeared in the literature: perpendicular distance sampling (PDS) (Williams and Gove 2003) and prism sweep sampling (PSS) (Bebber and Thomas 2003). Unfortunately, while field comparisons including these methods would have proved interesting and useful, information about PDS and PSS was published subsequent to the completion of this field study and are therefore not included in the analysis. In addition, TRS was not examined because a preliminary study (unpublished data) showed the method to be most appropriate in stand types much different than the ones studied here. Methods were compared on the basis of relative sampling efficiency and bias that might arise through measurement error in field implementation. Our goal is to provide practitioners with assessment guidance for sampling CWM in northern hardwood stands.

Materials and methods

Sampling was conducted at the Bartlett Experimental Forest (44°0′ N, 71°22.5′ W; Bartlett Quadrangle), a 1052-ha tract of northern hardwoods located in the White Mountain National Forest, New Hampshire, during summer 2001. Forest composition there is typical of the northern hardwood type in New England, with mature stands dominated by sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britt.), and American beech (*Fagus grandifolia* Ehrh.). Common hardwood associates include paper birch (*Betula papyrifera* Marsh.), red maple (*Acer rubrum* L.), and white ash (*Fraxinus americana* L.). Important softwood components include eastern hemlock (*Tsuga canadensis* (L.) Carr.), with red spruce (*Picea rubens* Sarg.) and balsam fir (*Abies balsamea* (L.) Mill.) at higher elevations. Younger stands are dominated by pin cherry (*Prunus pensylvanica* L.f.) and quaking aspen (*Populus tremuloides* Michx.). All stands were cleared prior to or around 1900 (W.B. Leak, personal communication). A total of 171 sampling points were located in seven stands selected to include a range of conditions frequently encountered by practitioners in regional forests (Table 1).

In each stand, a systematic series of sampling points was located for the inventory of CWM. At each sampling point, we performed line-intersect sampling (LIS) with a line length of 40.25 m and random orientation of sample lines; circular FAS (with 0.02-ha plots); and PRS with small (PRS_S) and medium (PRS_M) angle gauges ($\nu 1$ = 28.07° and $\nu 2$ = 53.13°, respectively). For PRS, we followed slope correction procedures outlined by Ståhl et al. (2002). The order of imple-

Table 2. Estimates of logs per hectare, volume per hectare (m^3/ha), length per hectare (m/ha), and length squared per hectare (m^2/ha) for each sampling method and stand.

Stand	LIS	FAS	PRS_S	PRS_M
Logs/ha				
I	827.32	749.69	424.40**	516.21*
II	386.03	420.07	307.83	211.64*
III	488.37	455.08	240.63**	374.40
IV	2 073.72	1 262.11**	789.63**	856.09**
V	680.38	480.72*	255.45**	240.09**
VI	473.42	428.31	264.95*	265.77*
VII	866.28	673.05	434.36*	615.78
Volume/ha				
I	64.80	55.79	47.26**	63.93
II	15.38	15.89	17.78	20.75
III	30.48	23.43	15.76*	25.25
IV	63.40	53.76	30.96**	45.34*
V	55.75	51.64	29.41**	41.28
VI	25.38	16.31*	18.01	16.23
VII	71.03	56.90	32.46**	53.25
Length/ha				
I	1 064.24	946.55*	710.60**	930.37
II	434.49	496.70	415.69	447.40
III	954.57	972.19	578.21**	929.91
IV	2 746.72	2 272.54*	1 325.16**	1 874.61**
V	1 055.71	870.31	567.39**	685.01**
VI	640.77	518.57	407.65*	424.59
VII	1 151.12	962.79	670.47**	1 019.18
Length^2/ha				
I	14 329.76	12 971.09	10 165.08**	14 343.95
II	5 956.16	6 619.18	6 427.44	8 315.01
III	19 113.99	19 663.28	11 254.03**	19 401.69
IV	39 122.42	39 208.84	19 776.73**	31 798.06
V	17 365.53	15 651.34	10 307.53**	14 710.03
VI	7 582.65	5 800.40	5 296.01	5 279.37
VII	17 041.97	16 069.33	9 766.68**	16 290.63

Note: LIS, line-intersect sampling; FAS, fixed-area sampling; PRS_S, point relascope sampling for small angle gauge; PRS_M, point relascope sampling for medium angle gauge. *, $p < 0.05$; **, $p < 0.01$.

mentation was randomly determined at each sampling point, and the first method employed was timed with a stopwatch. Subsequent methods performed at each sampling point were not timed to avoid a potential underestimate of the time requirement for the method because of foreknowledge of the location and characteristics of pieces of CWM already tallied. All sampling was performed using a three-person crew.

All pieces of CWM with a 7.6-cm large-end diameter were included in the inventory. With FAS, a piece of CWM was tallied and its entire length measured if the pith of its large end was located within the plot boundaries (Ducey and Gove 1999). For each piece tallied, we measured large- and small-end diameters using tree calipers and total length using a standard distance tape. Each piece was assigned a species class (hardwood, softwood, or unknown), origin (natural, cut, or unknown), and decay class based on the five-class system following Pyle and Brown (1998). Though not presented here, the species class, origin, and decay class data collected were consistent with the type and level of information commonly collected in an operational inventory of CWM,. Those variables were assessed in the field so that time requirements would be consistent with those of a typical CWM inventory.

Estimates of logs per hectare (no./ha), volume per hectare (m^3/ha), length per hectare (m/ha), length squared per hectare (m^2/ha), sample variances, and coefficients of variation (CV%) were calculated for each method and stand. Volume of individual logs was calculated using Smalian's formula (see Avery and Burkhart 1994, p. 55).

$$[1]\ y_i = \frac{(B_i + b_i)}{2} l_i$$

where y_i represents the log volume in cubic meters (m^3), B_i indicates the cross-sectional area at the large end of the log, b_i indicates the cross-sectional area at the small end of the log, and l_i is the total length of the log.

Table 3. Summary statistics for estimates of logs per hectare for each method and stand.

Stand	LIS	FAS	PRS_S	PRS_M
s^2				
I	254 618.04	171 596.29	102 148.04	356 686.60
II	160 805.96	35 606.69	201 448.34	47 146.21
III	98 780.33	32 064.51	20 846.41	165 025.86
IV	577 366.08	389 803.15	307 948.48	433 816.11
V	109 576.82	41 445.71	28 920.06	62 611.16
VI	111 542.88	58 041.41	99 579.24	96 765.16
VII	486 786.95	221 880.45	154 879.57	385 659.15
bias^2				
I	0.00**	0.00*	155 606.88	85 253.39
II	0.00**	0.00*	0.00*	20 015.06
III	0.00**	0.00*	56 389.05	1 997.31
IV	0.00**	584 314.79	1 580 788.86	1 404 842.84
V	0.00**	32 999.55	174 271.41	186 029.13
VI	0.00**	0.00*	31 733.81	31 549.03
VII	0.00**	3 588.75	155 993.18	21 201.63
MSE				
I	254 618.04	171 596.29	257 754.92	441 939.99
II	160 805.96	35 606.69	201 448.34	67 161.27
III	98 780.33	32 064.51	77 235.46	167 023.17
IV	577 366.08	974 117.94	1 888 737.34	1 838 658.95
V	109 576.82	74 445.26	203 191.20	248 640.29
VI	111 542.88	58 041.41	131 313.05	128 314.19
VII	486 786.95	225 469.20	310 872.75	406 860.78
CV (%)				
I	60.99	55.25	75.31	115.70
II	103.88	44.92	145.81	102.60
III	64.36	39.35	60.00	108.50
IV	36.64	49.47	70.28	76.94
V	48.65	42.35	66.57	104.26
VI	70.55	56.25	119.10	117.05
VII	80.54	69.99	90.60	100.85

Note: See Table 2 for definitions of terms.
*Negative bias^2 values are assigned a value of zero.
**All bias^2 values for LIS are assumed to be zero.

Testing for bias in estimates was performed relative to LIS in the absence of a true measure of accuracy. Therefore, bias in field implementation with LIS was assumed to be zero, as workers should physically cross each piece of CWM to be included in the sample. However, LIS may be subject to biases not accounted for by the assumptions of this study (see Ringvall and Ståhl 1999). In the absence of a true measure of accuracy, FAS, PRS_S, and PRS_M may be put at an a priori disadvantage for not realizing the same estimates as LIS.

Usually, testing for bias in the estimates of logs per hectare, volume per hectare, length per hectare, and length squared per hectare would be determined with a parametric paired-sample t-test. However, because the distribution of differences between the estimates for each method at each sampling point was highly non-normal, we used a two-tailed bootstrap percentile test on the mean difference (Efron and Tibshirani 1993) to assess whether bias in field implementation of the sampling methods was different. Total mean squared error (MSE) for volume per hectare, logs per hectare, length per hectare, and length squared per hectare was calculated for each method and stand. MSE was calculated as

$$[2]\quad \text{MSE} = s_{\bar{X}}^2 + \text{bias}^2$$

where $s_{\bar{X}}^2$ is the sampling variance of an estimate

$$[3]\quad s_{\bar{X}}^2 = \frac{\Sigma(X_i - \bar{X})^2}{n-1}$$

and bias^2 is

$$[4]\quad \text{bias}^2 = \overline{d_i^2} - \left(s_{\bar{X}1}^2 + s_{\bar{X}2}^2 - 2\text{cov}\left[X_1, X_2\right]\right)$$

where $\overline{d_i^2}$ is the mean squared difference between an estimate for a variable obtained with LIS and the estimate obtained with FAS, PRS_S, or PRS_M; $s_{\bar{X}i}^2$ is the sampling variance of an estimate for a method; and cov is the covariance of estimates ob-

Table 4. Summary statistics for estimates of volume per hectare (m^3/ha) for each method and stand.

Stand	LIS	FAS	PRS_S	PRS_M
s^2				
I	1 600.92	1 530.72	2 753.24	1 009.82
II	328.61	233.81	350.42	512.74
III	1 097.45	359.56	223.44	1 533.39
IV	751.03	784.44	235.06	743.95
V	1 143.63	1 640.19	383.92	1 186.45
VI	536.01	285.27	216.97	269.24
VII	1 938.13	1 284.42	233.09	1 637.74
bias²				
I	0.00**	22.19	258.25	0.00*
II	0.00**	0.00*	0.00*	0.00*
III	0.00**	0.00*	161.57	0.00*
IV	0.00**	0.00*	976.48	210.96
V	0.00**	0.00*	624.35	103.50
VI	0.00**	36.56	12.38	38.88
VII	0.00**	46.34	1 384.66	145.87
MSE				
I	1 600.92	1 552.90	3 011.49	1 009.82
II	328.61	233.80	350.42	512.74
III	1 097.45	359.56	385.01	1 533.39
IV	751.03	784.44	1 211.55	954.92
V	1 143.63	1 640.20	1 014.27	1 290.00
VI	536.01	321.83	229.35	1 617.75
VII	1 938.13	1 330.76	1 617.75	1 783.61
CV (%)				
I	61.75	70.13	67.23	82.08
II	117.85	96.22	105.31	109.11
III	108.69	80.92	94.84	155.06
IV	43.23	52.10	49.53	60.15
V	60.66	78.42	66.62	83.44
VI	91.24	103.56	81.78	101.09
VII	61.98	62.99	47.04	76.00

Note: See Table 2 for definitions of terms.
*Negative bias² values are assigned a value of zero.
**All bias² values for LIS are assumed to be zero.

tained with LIS and FAS, LIS and PRS_S, or LIS and PRS_M. Negative numbers obtained with this estimator were assigned a value of zero (no bias). The contribution to the MSE for each variable from LIS is assumed to be entirely from the sampling variance of the estimates for the method because bias with the method is assumed to be zero. Relative efficiency (E) for all methods was calculated as

$$[5]\quad E = \frac{\bar{t}_1 \times s^2_{X2}}{t_2 \times s^2_{X2}}$$

where $\bar{t}$ indicates the mean time required per sample point for one of the four sampling methods, and s^2_{X1} is the sampling variance of the estimates. Relative efficiency is the time required to achieve any specified confidence limit width using one method, expressed as a fraction of the time required to achieve the same confidence limit width using another method. FAS, PRS_S, and PRS_M were compared relative to LIS ($E = 1$). Thus, when $E > 1$, LIS is more efficient than the method to which it is being compared. When $E < 1$, LIS is less efficient than the method to which it is being compared. Because times were not obtained for all methods at each sampling point, the mean time requirement for each method was estimated by regressing time requirement on number of pieces tallied at each sampling point for all methods in each stand. The resulting linear regression was applied to the mean number of pieces tallied using each method in each stand.

Results

Estimates for logs per hectare, volume per hectare, length per hectare, and length squared per hectare are given for each method and stand in Table 2. Summary statistics are given for estimates of each variable and for each method and stand in Tables 3–6. Some differences among the estimates obtained with LIS and FAS, LIS and PRS_S, and LIS and PRS_M were found to be statistically significant using the bootstrap paired-sample t-test, indicating a potential difference in bias in field implementation of the four sampling methods in some stands. Where bias in field implementation relative to LIS was found, it always resulted in underestimates for each variable, method, and stand. If estimates obtained with LIS are accepted as the true measure of accuracy, this result suggests that bias in field implementation was the likely result of non-detection errors on the part of the search-based methods. That is, bias was the result of failing to tally pieces of CWM that should have been included in the sample but were not. This bias was most pronounced in the recently managed stand (i.e., stand IV), where a confusing array of slash made finding and or sighting individual pieces of CWM very challenging. This was especially the case with PRS_S, which leads to theoretical inclusions that can be relatively far away from the sample point.

Mean time requirement as a function of the number of pieces of CWM tallied per sampling location over all stands is shown in Fig. 1. The mean time requirement per piece tallied (min/piece) was 1.50, 0.81, 1.30, and 0.84 for LIS, FAS, PRS_S, and PRS_M, respectively. This result suggests that, mean time requirement per sampling location is influenced by other factors as well as number of pieces of CWM tallied. For LIS, mean time requirement per sampling location was partially driven by line set-up and sloping topography in some stands, which necessitated the use of slope correction techniques to obtain accurate horizontal line lengths. For FAS and PRS, no set-up time was needed because, in the former case, an electronic distance measuring device (Haglof DME) was used to check borderline logs; in the latter case, the method is a variable radius plot technique with no fixed boundaries. Mean time requirement per sampling location with FAS and PRS was partially driven by time spent searching for candidate pieces of CWM, which appears to increase as the theoretical area of inclusion of pieces of CWM increases for a given method. Relative efficiency scores (E) are given for each of four variables and for each method and stand in Table 7. As expected, E for each sampling method varied based on the variables of interest, size and distribution of pieces of CWM, and stand conditions. In general, a method was most efficient for sampling CWM where the variable of interest and the probability of selecting

Table 5. Summary statistics for estimates of length per hectare (m/ha) for each method and stand.

Stand	LIS	FAS	PRS_S	PRS_M
s^2				
I	189 287.99	224 184.54	119 533.37	490 064.23
II	83 757.59	51 403.92	77 795.10	107 236.33
III	155 159.80	262 802.73	65 348.42	345 739.43
IV	1 982 641.84	1 191 874.56	410 030.95	1 302 060.84
V	179 226.02	146 689.24	82 492.14	426 724.11
VI	168 786.08	88 686.68	102 241.46	193 857.72
VII	567 017.74	335 375.50	157 429.92	512 584.31
$bias^2$				
I	0.00**	6 050.98	119 238.45	5 103.09
II	0.00**	0.00*	0.00*	0.00*
III	0.00**	0.00*	132 453.91	0.00*
IV	0.00**	0.00*	1 836 776.45	507 898.09
V	0.00**	19 555.95	226 559.08	109 875.05
VI	0.00**	628.58	39 285.67	26 584.54
VII	0.00**	0.00*	196 528.04	0.00*
MSE				
I	189 287.99	230 235.52	238 771.82	495 167.32
II	83 757.59	51 403.92	77 795.10	107 236.33
III	155 159.80	262 802.73	197 802.33	345 739.43
IV	1 982 641.84	1 191 874.56	2 246 807.40	1 809 958.93
V	179 226.02	166 245.19	309 051.22	453 308.65
VI	168 786.08	89 315.26	128 826.00	220 442.26
VII	567 017.74	335 375.50	353 957.96	512 584.31
CV (%)				
I	40.88	50.02	48.65	75.24
II	66.61	45.65	67.10	73.19
III	41.27	52.73	44.21	63.23
IV	51.26	48.04	48.32	60.87
V	40.10	44.01	50.62	95.36
VI	64.12	57.43	78.44	103.70
VII	65.42	60.15	59.18	70.25

Note: See Table 2 for definitions of terms.
*Negative $bias^2$ values are assigned a value of zero.
**All $bias^2$ values for LIS are assumed to be zero.

an individual piece of CWM into the sample were coincident (Schreuder et al. 1993, pp. 56–58).

Discussion

This field trial suggests that no single sampling method is to be preferred in every stand. The usefulness of a sampling method for CWM depends on factors such as topography, sighting conditions, and past stand management. Practitioners should find that a few pre-cruise sample points, or even casual ocular examination, will be useful for selecting an appropriate sampling method, line length, plot size, or relascope angle for CWM in any given tract. In stands judged to have heavy amounts of CWM, LIS may always be the preferred method, regardless of relative sampling efficiency, because it tends to minimize non-detection errors. If PRS is the preferred method in stands with heavy amounts of CWM, practitioners should consider an angle that approaches $\nu = 90°$ to minimize non-detection of pieces of CWM that lie far away from the plot center (Gove et al. 2001).

The relative sampling efficiency for each method was based on measuring each piece tallied for cubic volume. Measurements of large-end diameter, small-end diameter, and total length were made for each piece to be used in Smalian's formula for cubic volume. Special cases exist for each method, however, where the number of measurements needed to be taken for an estimate is reduced. In these cases, practitioners may find that the relative sampling efficiency of a method is improved. For logs per hectare, FAS may be used, where estimates are obtained with a simple tally of pieces on a plot multiplied by the reciprocal of the plot size. For volume per hectare, LIS may be used, where estimates may be obtained with only measurement of the intersecting diameter of each piece tallied (Van Wagner 1968). Additionally, LIS may be used for estimates of length per hectare, where a simply tally of intersections is multiplied by a length factor. For length squared per hectare, PRS may be used, where each piece tallied represents a certain amount of length squared given the angle gauge used. Length squared is correlated with volume and is therefore of particular interest as an auxiliary variable in two-phase sampling where es-

Table 6. Summary statistics for estimates of length squared per hectare (m²/ha) for each method and stand.

Stand	LIS	FAS	PRS_S	PRS_M
s^2				
I	45 376 810.38	71 919 161.52	17 970 370.25	91 598 787.60
II	23 410 372.59	20 707 648.69	12 401 898.08	42 478 765.91
III	120 757 698.09	212 154 395.59	31 198 486.32	145 108 876.43
IV	640 232 775.36	402 388 460.83	59 242 673.83	355 139 849.26
V	116 683 941.87	114 419 559.78	24 497 021.91	181 031 590.37
VI	42 514 455.61	17 366 141.13	8 835 662.10	23 609 022.05
VII	83 513 760.75	180 051 599.93	18 547 293.60	89 336 961.03
bias²				
I	0.00**	0.00*	16 149 365.72	0.00*
II	0.00**	0.00*	0.00*	2 269 713.53
III	0.00**	0.00*	55 447 361.73	0.00*
IV	0.00**	0.00*	320 450 115.34	0.00*
V	0.00**	0.00*	43 398 010.69	0.00*
VI	0.00**	0.00*	2 375 905.68	1 631 555.38
VII	0.00**	0.00*	48 069 863.93	0.00*
MSE				
I	45 376 810.38	71 919 161.52	34 119 735.97	91 598 787.60
II	23 410 372.59	20 707 648.69	12 401 898.08	44 748 479.44
III	120 757 698.09	212 154 395.59	86 645 848.05	145 108 876.43
IV	640 232 775.36	402 388 460.83	379 692 789.10	355 139 849.26
V	116 683 941.87	114 419 559.78	67 895 032.60	181 031 590.37
VI	42 514 455.61	17 366 141.13	11 211 567.78	25 240 577.43
VII	83 513 760.75	180 051 599.93	66 617 157.53	89 336 961.03
CV (%)				
I	47.01	65.38	41.70	66.72
II	81.23	68.75	54.79	78.38
III	57.49	74.07	49.63	62.09
IV	64.68	51.16	38.92	59.27
V	62.20	68.34	48.02	91.47
VI	85.99	71.84	56.13	92.04
VII	53.62	83.50	44.10	58.02

Note: See Table 2 for definitions of terms.
*Negative bias² values are assigned a value of zero.
**All bias² values for LIS are assumed to be zero.

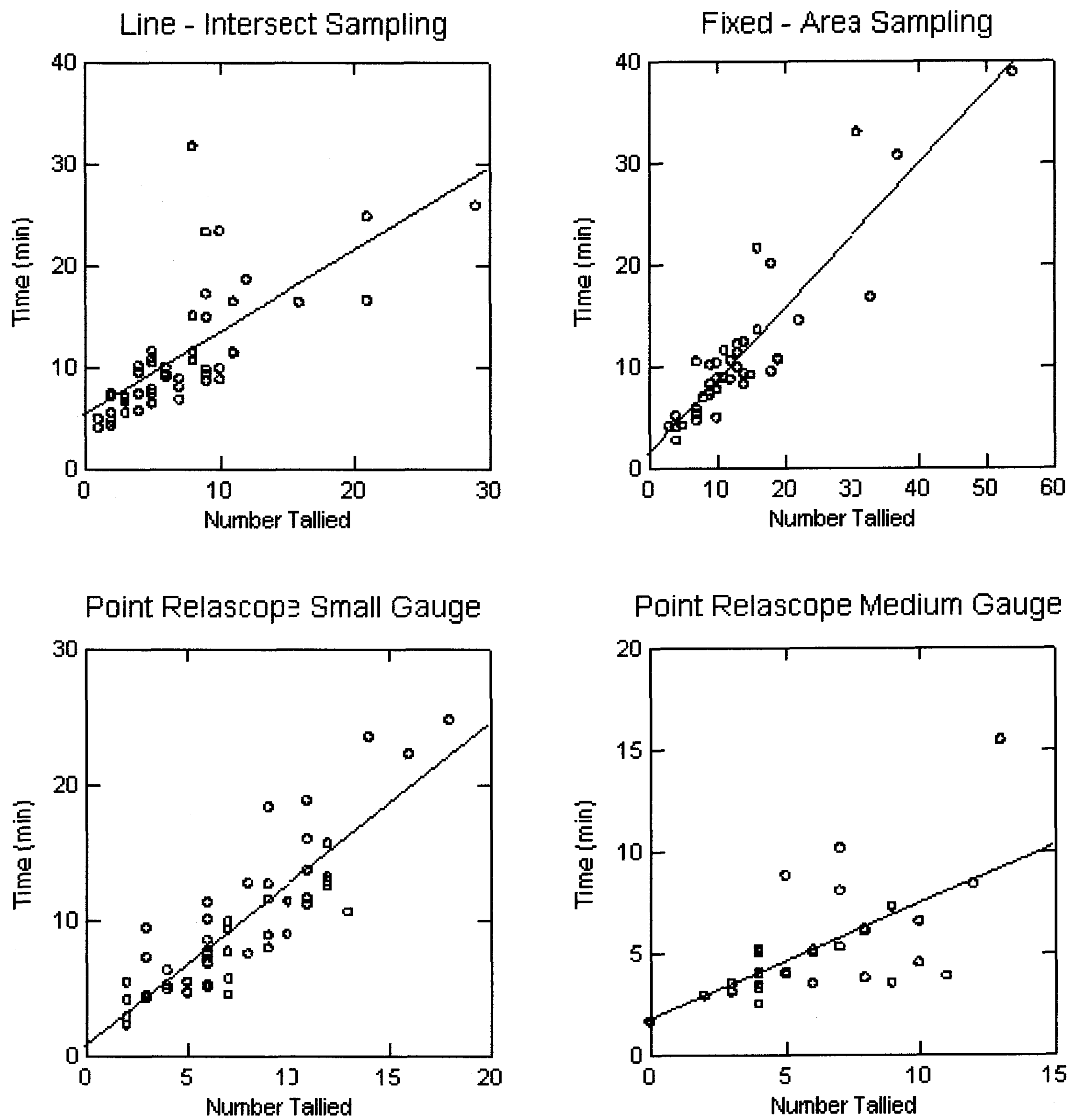
timates of cubic volume are desired (Gove et al. 2001; Ringvall et al. 2001). Further on, besides the special cases, relative sampling efficiency for each method may vary depending on how error and costs are defined, the minimum size of pieces tallied, plot sizes and line lengths employed, crew size, and equipment used.

The sampling efficiency and bias of each method was determined relative to LIS because true population values were not known. Though this comparison is very meaningful for sampling efficiency, comparisons of bias in field implementation are subject to a number of limitations. Choice of LIS as the baseline for comparison does not necessarily indicate that estimates obtained with the method are close to true population values. The method was chosen as the baseline for comparison only because it is widely used by practitioners and because a low rate of surveyor-induced bias can be assumed with the method (Ringvall and Ståhl 1999). Indeed, a simulation study by Pickford and Hazard (1978) found that more than 8500 m of sample line was needed to obtain estimates within 10% of the actual volume of CWM with 95% confidence in a Pacific Northwest clearcut. Total sample line in this field trial did not approach this length in any stand. Therefore, bias found in estimates obtained with FAS, PRS_S, or PRS_M may be either the product of error in field implementation or inaccuracy on the part of the estimates obtained with LIS. Determination of the potential for bias in field implementation of these sampling methods could be more firmly established through field trials or controlled experiments where estimates obtained with each method can be directly compared with a true measure of accuracy.

Conclusions

Though judgments of bias, in the absence of a true measure of accuracy, are problematic in this study, the estimates obtained with PRS_S were consistently the lowest among all methods for each variable and stand. This suggests that PRS_S may be poorly matched for use in some of the stand condi-

Fig. 1. Time requirement per sampling location for each method compared in the field trial. Times shown do not include travel time between sampling locations.



tions examined here because of non-detection bias. However, this result does not preclude the use of PRS on the whole, or PRS_S in other stand conditions, but suggests the need for more field trials to determine the appropriate relascope angles to use in northern hardwood forests. Just as many field trials were needed to arrive at the most appropriate basal area factors for use in stands of differing structure and basal area with HPS (Wensel et al. 1980; Wiant et al. 1984), regional practitioners may need to make similar field trials in different forest conditions and geographic regions for PRS.

While more study on the appropriate relascope angles to use in northern hardwood forests is needed, some recommendations for sampling CWM with PRS can be offered.

- Use an angle gauge greater than v = 40° for general use.
- Increase the angle gauge used in stands where recent harvesting or blowdown has occurred. In recent clearcuts an angle gauge approaching v = 90° is preferable to minimize both non-detection errors and field work.
- Increase the angle gauge used in stands where topography or vegetation limit sighting distance.
- Increase the angle gauge used in stands where very long pieces of CWM, such as recent blowdowns, are encountered.
- Decrease the angle gauge used in stands where CWM is small or scattered.

Inasmuch as this is the first extensive field trial of PRS, practitioners may look favorably upon the performance of PRS, particularly for estimating volume, length, and length squared of CWM. Further study and use of the method is warranted.

Table 7. Relative efficiency scores (E) for each sampling method and stand.

Stand	FAS	PRS_S	PRS_M
Logs/ha			
I	0.82	1.33	1.67
II	0.19	1.72	0.45
III	0.38	0.76	1.32
IV	1.83	3.22	2.04
V	0.76	1.64	2.13
VI	0.64	2.49	1.28
VII	0.76	1.11	0.73
Volume/ha			
I	0.80	1.04	0.82
II	0.13	0.14	0.08
III	0.56	0.67	0.94
IV	1.46	1.15	0.90
V	3.16	2.08	1.73
VI	5.77	3.13	2.53
VII	1.04	0.50	0.70
Length/ha			
I	1.50	1.24	1.57
II	0.47	0.89	0.56
III	1.64	1.00	1.09
IV	0.88	0.78	0.65
V	1.21	1.39	2.62
VI	0.81	1.31	1.21
VII	0.85	0.72	0.53
Length²/ha			
I	1.94	0.69	0.93
II	0.72	0.40	0.43
III	1.67	0.65	0.54
IV	0.63	0.32	0.39
V	1.21	0.52	1.00
VI	0.70	0.37	0.53
VII	2.44	0.59	0.54

Note: E for line-intersect sampling is 1.00. See Table 2 for definitions of terms.

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