A practical modification of horizontal line sampling for snag and cavity tree inventory

M.J. Ducey, G.J. Jordan, J.H. Gove, and H.T. Valentine

Abstract: Snags and cavity trees are important structural features in forests, but they are often sparsely distributed, making efficient inventories problematic. We present a straightforward modification of horizontal line sampling designed to facilitate inventory of these features while remaining compatible with commonly employed sampling methods for the living overstory. The method is simpler in its implementation than traditional horizontal line sampling. We develop unbiased estimators and present methods for dealing with special cases, including boundary overlap. A field test of the method shows it to have time efficiency comparable with or better than ordinary prism cruising, and it requires far fewer sample locations to achieve similar confidence limits. The method may also be useful for inventorying other rare or unusual trees.

Résumé : Les chicots et les arbres avec des cavités sont des éléments structuraux importants dans les forêts mais ils sont souvent dispersés, ce qui les rend difficiles à inventorier de façon efficace. Nous présentons une modification simple de l'échantillonnage en ligne horizontale dans le but de faciliter l'inventaire de ces éléments tout en demeurant compatible avec les méthodes d'échantillonnage communément utilisées pour le couvert formé par les arbres vivants. La méthode est plus simple à appliquer que l'échantillonnage en ligne horizontale traditionnel. Nous développons des estimateurs non biaisés et présentons des méthodes pour tenir compte des cas particuliers, incluant le chevauchement des contours. En terme d'investissement en temps, un essai sur le terrain montre que la méthode est aussi efficace, sinon plus, que l'inventaire habituel au prisme et requière beaucoup moins de points d'échantillonnage pour obtenir les mêmes limites de confiance. Cette méthode peut être utile pour inventorier d'autres arbres rares ou inhabituels.

[Traduit par la Rédaction]

Introduction

Snags and cavity trees are important features for forest wildlife habitat (McComb and Noble 1981; DeGraaf and Shigo 1985; Tubbs et al. 1987; DeGraaf et al. 1992; McComb et al. 1993). Snags and cavity trees may also form an important sink for carbon or nutrients and are important features for inferences about ecosystem processes (Harmon et al. 1986; Tritton and Siccama 1990). However, snags and cavity trees are typically far less abundant than living overstory trees. As a consequence, if plot sizes (in the case of fixed-area sampling) or basal area factors (in the case of point sampling) typically used for conventional inventories are used to estimate snag and cavity tree abundance, managers are likely to encounter one of two disappointing situations: either significant additional expense will be required to establish many more sampling locations (i.e., points or plot centres), or the confidence limits from the inventory will be dismally wide (Bull et al. 1990).

Received 30 October 2001. Accepted 6 February 2002. Published on the NRC Research Press Web site at http://cjfr.nrc.ca on 10 July 2002.

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Here, we present a modified form of horizontal line sampling (HLS) that we have found useful for snag and cavity tree inventory. Horizontal line sampling using an angle gauge was originally developed by Strand (1957), and its basic theory was outlined by Grosenbaugh (1958); however, it has not been widely adopted for forest inventory. Our approach uses short segments for HLS and augments the horizontal line sample by completing the angle gauge sweep around the end of the line, effectively adding half of a conventional horizontal point sample to each end of the line. This modification eliminates some of the practical difficulties encountered with traditional HLS and gives a straightforward way of estimating abundance, basal area, volume, and other related attributes of snags and cavity trees in a forested tract.

Background

Both horizontal point sampling (HPS; also known as variable radius plot sampling, or simply prism sampling) and HLS can be considered cases of polyareal sampling (Beers and Miller 1967). In both cases, the forester determines what trees are to be included in the sample by sighting through an angle gauge, such as a prism. A tree is tallied if the distance to the tree is less than or equal to a critical distance calculated as a gauge factor, k, times the diameter at breast height (DBH) of the tree. The primary difference between the two methods is in the geometry of the location(s) from which the forester may view the tree through the gauge. In HPS, the gauge is turned around a sample point, so that the area within which a tree of a given DBH can be included in the tally is a circle of radius $k \times$ DBH centred on the point.

 DOI: 10.1139/X02-038

Alternatively, following Grosenbaugh (1958), we may think in terms of the "imaginary circle" or inclusion zone centred on each individual tree, which will also have radius equal to the critical distance $k \times$ DBH (Fig. 1). In HLS, the gauge is moved along a line or line segment, and a tree is tallied if it is closer than $k \times$ DBH to the line (measured perpendicular to the line). The area along the line within which a tree can be tallied is thus a variable-width strip, with width equal to $2k \times$ DBH and area $2kL \times$ DBH (taking L as the length of the sample line; the width is $2k \times$ DBH, because sampling occurs on both sides of the line). The line may span the entire tract of interest, or it may be a short segment; we concern ourselves with the latter case here. If the line is located by choosing its centre point at random (or systematically) and considering the line orientation for the moment as fixed (without loss of generality), we can also think in terms of a tree-concentric inclusion zone for HLS; the inclusion zone is an "imaginary box" of length L and width $k \times$ DBH centred on the tree of interest. In either case, an efficient and unbiased estimator for the number of trees in a tract of area, A, based on a tally from a single sample point (either the "centre" of an HPS point sample, or the centre of the line segment in HLS) is

$$[1] \qquad \hat{N} = Ac\sum_i \frac{1}{a_i}$$

where a_i is the area of the inclusion zone for the ith tree, and the summation is taken over the tallied trees. The constant c represents the conversion from the units of a_i to those of A (i.e., 10000 m^2/ha or 43560 ft^2/ac). The quantity c/a_i is the expansion factor for the ith tree. Likewise, the estimator for any total quantity, Y, to which an individual tree contributes y_i units, is

$$[2a] \qquad \hat{Y} = Ac\sum_i \frac{y_i}{a_i}$$

again summing over the sample trees. Equations 1 and $2a$ can be considered as special cases of the Horvitz–Thompson estimator, with $\pi_i = a_i/(cA)$ (Horvitz and Thompson 1952).

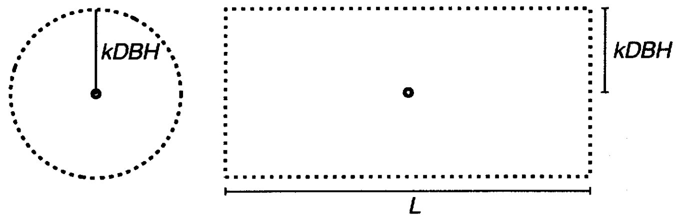
The sampling can also be approached as a Monte Carlo integration (Valentine et al. 2001), where a point on the tract is selected at random with probability density $1/(cA)$. The density of the quantity y_i in the inclusion zone of the ith snag is simply y_i/a_i. If the inclusion zone only of tree i includes the random point, then

$$[2b] \qquad \hat{N} = Ac\frac{1}{a_i} \qquad \hat{Y} = Ac\frac{y_i}{a_i}$$

If the inclusion zones of more than one snag include the random point, then eqs. 1 and $2a$ apply.

Provided the samples are of the same type, when multiple sample points are selected at random within a tract, the best combined estimate of N or Y is the mean of the individual-point estimates, and the standard error of the individual-point estimates serves to describe the possible influence of sampling variability on the combined estimates.

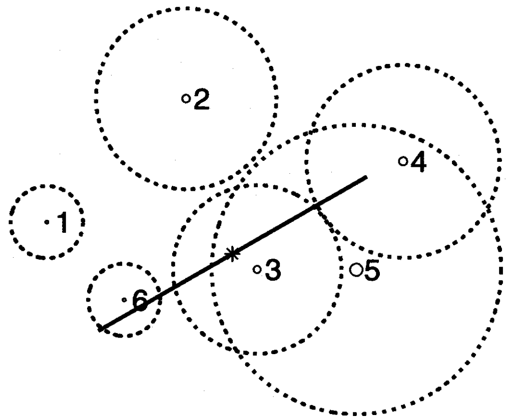
Fig. 1. Example inclusion zones for horizontal point sampling (HPS) and horizontal line sampling (HLS). The parameter k is the characteristic factor of the angle gauge; the limiting distance for a tree is $k \times$ DBH. L represents the length of the sample line in HLS. The orientation of the HLS inclusion zone is determined by the orientation of the sample line.



Consider for the moment a survey of snags and (or) cavity trees using HPS. If the density of snags is low, then the expected number of snags tallied at a sample point will be low, but the variance of estimates calculated using eqs. 1 and $2a$ will be high. Restricting ourselves to HPS, three solutions immediately present themselves.

(1) Use an angle gauge with a reduced basal area factor (BAF), so that more snags or cavity trees will be included from each point. While mathematically plausible, this solution is often practically unacceptable. Reducing the BAF involves increasing the value of k. As a consequence, snags and cavity trees can be farther away and still be tallied. At some point, bias in implementation will arise, because snags that should have been tallied will not be detected and because measurement of the distance to "borderline" snags becomes increasingly problematic (Wensel et al. 1980; Wiant et al. 1984).
(2) Install a larger number of points. If the survey is being conducted using random sampling, this involves visiting many more randomly selected points, which may increase the travel time for the survey. If, as is more common in practice, the survey is being conducted systematically, e.g., by a line-plot cruise, the problem can be solved by installing points more densely along the line without increasing the travel time. A difficulty with this approach is that in practice, snags and cavity trees are rarely the sole or even primary focus of most forest inventories, and the number of sample points used is often dictated by concern with the cost-effective inventory of the live overstory, whether for economic or ecological purposes. Contending with two separate inventory intensities may prove confusing to field crews and can present challenges for data management. Where these concerns are at issue, it would be desirable to develop a snag and cavity tree inventory system that can provide acceptable estimates using the same number of sample points as used, for example, in the live overstory cruise.
(3) Employ the same number of primary points but increase the sample size by deploying a cluster of secondary points around each primary point and conduct HPS at each of these secondary points. A practical challenge, or at least a psychological one, with this approach is that while taking the time to locate the outlying points, the forester may walk past snags or cavity trees that are of interest but are not included in the tally from any of the

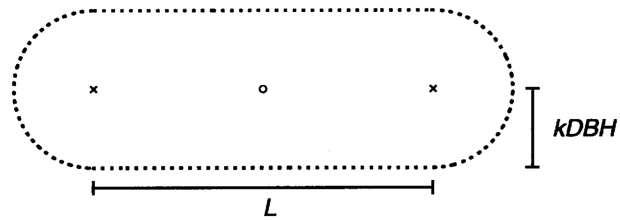
Fig. 2. Implementation of modified horizontal line sampling. The centre of the sample line (*) is located in the field, and the sample line is run at a predetermined distance and bearing. All trees close enough to the line to tally (i.e., those for which the sample line crosses their HPS inclusion zone) are included in the sample. In this example, trees 3, 4, 5, and 6 would be tallied in MHLS. Ordinary HLS would ignore tree 4, because it is beyond the end of the line. Only trees 3 and 5 would be tallied in HPS.



points. This is especially likely if the secondary points are located far enough apart that few snags are tallied from more than one secondary point. Intuitively, it would be desirable to design a method that takes full advantage of the time expended in locating the clusters.

As an alternative, we might consider HLS in its original form. HLS is appealing, because the segment length L can be controlled completely in the inventory design. Thus, in principle, L can be increased arbitrarily to increase the number of snags or cavity trees tallied and, hence, to reduce the variance between sample locations in parameter estimates without incurring the problems associated with decreasing the BAF of the angle gauge. Our initial interest in HLS for snag and cavity tree inventory was motivated by this flexibility. However, in practice, two irksome and related problems presented themselves. The first problem, from a certain standpoint psychological but hinting at an underlying inefficiency, was the frequent presence of snags or cavity trees near the end of an HLS segment but beyond it and not within the "variable width strip". Again, it seemed intuitively wasteful to expend the time laying out the strip, only to ignore trees of interest that were clearly visible and close by. The second problem compounded the first: when snags or cavity trees were very close to the end of the HLS segment (Beers and Miller (1976) term such trees "end" trees), it was necessary to determine accurately whether the trees should be included in the sample, using an angle mirror, right angle prism, or an accurate compass. It was particularly vexing to expend effort determining whether such trees should be included in the sample, despite their proximity. While an accurate tally is important to an unbiased probability sample, a method designed on the one hand to increase the tally of rare objects but, on the other hand, frequently ignoring such objects, or even requiring special effort to discard some of them, demanded improvement. Ultimately, we concluded that with a simple modification of the method, both problems could be alleviated.

Fig. 3. Inclusion zone for modified horizontal line sampling. The parameter k is the characteristic factor of the angle gauge; the limiting distance for a tree is $k \times$ DBH. L represents the length of the sample line. The orientation of the sample line determines the orientation of the inclusion zone. If the centre of the sample line falls inside a tree's inclusion zone, it will be tallied; otherwise, it will not.



Modified line sampling: theory and estimation

In the field, our modification of HLS is extremely straightforward. An ordinary HLS sample is taken, but at the both endpoints of the segment, the angle-gauge sweep continues in a semicircle to include all those "end" trees which would be included in an HPS sample from that point. Effectively, this sandwiches the variable-width strip of HLS between two halves of an HPS sample. Alternatively, one can consider the modified horizontal line sample (MHLS) as augmenting the HPS samples of a two (or more) point cluster falling on a line with those trees not on the points but falling near the line, thus eliminating the problem of "walk-by" trees.

The implementation of the method is depicted graphically in Fig. 2. A centre point is selected within the tract with uniform probability, and as in HLS, a line segment is laid out on either side of this centre point. All trees close enough to this line segment to appear "in" with the angle gauge are tallied, whether they are past the end of the line segment or not.

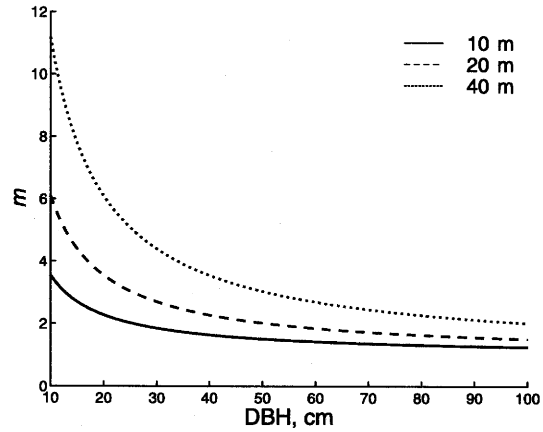
The inclusion zone in MHLS is simply the sum or union of the inclusion zones in HLS and HPS, consisting of a rectangle of length L and width $2k \times$ DBH, plus two semicircles each of radius $k \times$ DBH (Fig. 3). If the centre of the sample line falls inside this sausage- or cigar-shaped zone located around the tree, the tree will be tallied. Thus, the area of the inclusion zone for the ith tree is a quadratic in $k \times$ DBH, viz.:

$$[3] \qquad a_i = 2kL \times \mathrm{DBH}_i + \pi k^2 \times \mathrm{DBH}_i^2$$

Substituting a_i into eq. 1 or 2*a* yields an unbiased estimator of N or Y, following either the Horvitz–Thompson or Monte Carlo approaches. The expansion factor for the ith tree is c/a_i, as before.

One sacrifice made in exchange for the convenience of the modified method is the easy interpretability of the count of tallied trees. Recall that in HPS, the number of trees tallied times the BAF of the gauge gives a direct estimate of the basal area per acre or hectare of the tract. Likewise, in HLS, the number of trees tallied multiplied by a factor that depends on k and L gives a direct estimate of the sum of the DBHs of the trees on the tract. In MHLS there is no such simple correspondence; in a sense, we need a "stand table

Fig. 4. Ratio of number of trees tallied in MHLS to HPS (m), as a function of line length (L) and snag diameter (DBH). The figure assumes a BAF 4 m^2/ha prism will be used, such that when DBH is in centimetres and L is in metres, k = 0.25.



factor" for both trees per hectare and basal area per hectare. However, calculation of quantities such as basal area is so straightforward that this hardly seems to be an obstacle.

Survey design considerations

In addition to the usual considerations of sampling method (e.g., random vs. systematic) and sample size (number of sample locations), a user of MHLS must determine two parameters in advance: the BAF of the angle gauge (or equivalently, choice of k) and the length of the line segment at each sample location, L. As discussed above, the choice of an appropriate BAF is somewhat constrained by two opposing sources of error in practical applications, specifically errors from "pushing the point" (Oderwald and Gregoire 1985) and nondetection errors (Wiant et al. 1984). We focus here on the choice of L, based on practical and theoretical considerations.

Like k, L may be constrained by practical considerations that depend in part on forest type, terrain, equipment, and crew size. To obtain accurate inclusion areas, L must be measured accurately in the horizontal plane, and it must be possible for crews to locate themselves accurately on the line segment while determining what trees to tally. In rough terrain or in forests where a heavy understory is present, these factors argue strongly for relatively small values of L, especially when a physical tape must be used to determine distance from the centre point. Using an electronic distance measurement device reduces these concerns somewhat, but care must still be taken that the line is clearly identifiable over its entire length. In open forests on level terrain, a simple flag or range pole at the line centre and at each end may be used, and crews can always locate the line exactly by sighting or back-sighting on these markers with a compass. Under those conditions, restrictions on L may be relaxed and the line segment may become quite long. Note, however, that the estimators presented here depend on L being identical for all segments used in a tract (or in a single stratum of a stratified sample).

Another way of choosing L is to consider the expected increase in the number of tallied trees. While simple "rules of thumb" about the number of trees to tally at a sample location often provide poor guidance to sample design (Wiant et al. 1984), it is also true that samples giving only zero, one, or two tallies per sample location are likely to require many sample locations to give confidence limits of reasonable width for most target parameters. If such were the expected tally from an ordinary HPS cruise, it might be desirable to increase the expected tally by some predetermined factor. At the same time, if the survey designer has some advance knowledge about the kind of forest to be encountered in a tract, that may be translated into some expectation about typical sizes of snags or cavity trees that will be encountered. For example, Lee (1998) and Spetich et al. (1999) found that the diameter distribution of snags closely paralleled that of live trees at their study sites. Thus, advance knowledge about the size class of dominant trees in the living overstory may provide some indication of the size of snags that will likely be encountered.

Suppose we wish to increase the expected number of tallied trees of some particular diameter by a predetermined multiplicative factor, m, above that which would be achieved in an HPS sample. Now, the ratio of number of trees tallied in MHLS to that for HPS will be given by the ratio of the inclusion areas for the two methods, i.e.:

$$[4] \qquad m = \frac{a_{\text{MHLS}}}{a_{\text{HPS}}} = \frac{2kL \times \text{DBH} + \pi k^2 \times \text{DBH}^2}{\pi k^2 \times \text{DBH}^2}$$

This relationship is shown graphically in Fig. 4. Taking m as a known target, and solving for L, we obtain

$$[5] \qquad L = \left(\frac{m-1}{2}\right) \times \pi k \times \text{DBH}$$

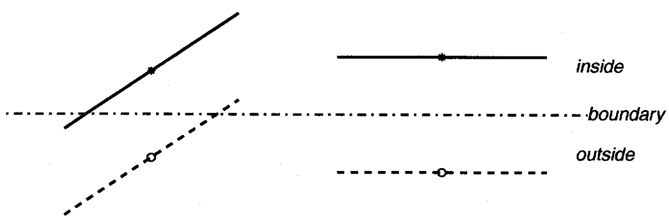
As an example, suppose we would like to increase the tally of 50 cm DBH snags by a factor of m = 4 in a survey. We will use a prism with BAF 4 m^2/ha, i.e., with k = 0.25 when DBH is in centimetres and a is in square metres. Substituting into eq. 5, we find that we should use a line segment with L = 58.9 m.

Slope correction and boundary overlap

Slope correction in MHLS follows in a straightforward fashion from slope correction in HPS and HLS. As noted above, it is important for the length of the line segment to be correct in the horizontal plane. Where terrain is irregular, "breaking chain" or the use of a topographic trailer tape is required. Some, but not all, electronic distance measurement tools will correct automatically for topography. When sighting individual trees using a prism as the angle gauge, rotating the prism through the slope angle, as commonly done in HPS and HLS (Bruce 1955; Beers 1969; Beers and Miller 1976), will also provide appropriate but approximate correction in MHLS. Use of a Spiegel-Relascope would provide exact compensation.

Boundary overlap (or "slopover"; Grosenbaugh 1958) occurs whenever the inclusion zones of trees fall partially outside the boundary of the tract. If no corrective action is taken, this leads to bias, as trees near the border (whether tallied or not) will have an actual inclusion area, and hence inclusion probability, lower than that calculated using eq. 3.

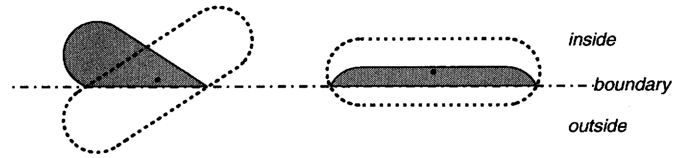
Fig. 5. Implementing the mirage method for boundary correction with modified horizontal line sampling: on the left for a line at an angle to and crossing the boundary, and on the right for a line parallel to the boundary. When any portion of a sample line falls near a boundary, the original plot centre (*) is reflected through the boundary to establish a mirage plot centre (o), and a mirage sample line (broken line) is run parallel to the original sample line (solid line). The tally from the mirage sample line is added to the tally from the original line. Note that the entire length of both lines should be used and that some trees may be tallied on the mirage line that were not tallied on the original line.



Boundary correction is a greater concern with MHLS than with HPS using the same angle gauge, because the inclusion zones of trees will be larger and, hence, more likely to overlap tract boundaries. While several methods of boundary overlap correction are available (reviewed by Schreuder et al. 1993, pp. 297–301), and most of these are modifiable to accommodate MHLS, the mirage method requires specific discussion. The mirage or "reflection" method was originally developed by Schmid-Haas (1969), and Gregoire (1982) gives a proof of its unbiasedness when the tract boundaries are composed of straight sections and certain restrictions on corner shape apply. Our initial conjecture was that the variant of the mirage method proposed by Gregoire and Monkevich (1994), which is unbiased for line intersect sampling, would also be appropriate for MHLS. Under that approach, whenever the line segment crossed the boundary, the unsampled portion would be folded back into the interior of the tract, and trees tallied from this folded portion would be double-counted. However, this approach fails to correct for boundary overlap when the line segments are parallel to some portion of the boundary and the inclusion zones for some trees slop over that portion of the boundary. It may also fail when trees are very close to the boundary, and the line segment approaches at any angle not strictly perpendicular to the boundary. Hence, our implementation of the mirage method for MHLS adheres closely to the original method developed by Schmid-Haas (1969), as follows.

(1) When a line segment falls "close" to the boundary, a mirage segment should be installed. A line segment is close to the boundary whenever the distance is less than k times the DBH of the largest snag standing between the line segment and the boundary, whether or not that snag is tallied from the original line segment.
(2) When a line segment crosses the boundary, the primary tally is composed of all those trees inside the boundary tallied from the entire line segment, including the portion of the segment lying outside the boundary. Note that for some trees very close to the boundary, the closest point on the line segment may lie outside the tract boundary; restricting the tally only to the portion of the segment inside the tract would cause these trees to be missed erroneously in the primary tally.
(3) The original line centre is reflected through the boundary to a mirage line centre (i.e., by moving through twice the perpendicular distance to the boundary; Fig. 5). The mirage line is run from this mirage centre using the same distance and bearing as the original line.
(4) All trees inside the tract that may be counted as "in" from the entire length of this mirage line, including the portion of the line outside the boundary, are tallied in the mirage tally. Note that because the inclusion zones in MHLS are not circular, some trees may be tallied in the mirage tally that were not in the primary tally (Ducey et al. 2001). Thus, adding the mirage tally to the primary tally may result in some trees being tallied twice and some new trees being added that were not tallied before.

Fig. 6. Inclusion zones and mirage inclusion zones for trees near the boundary of the tract when (a) the line segment is at an angle to the boundary and (b) the line segment is parallel to the boundary. If the original sample point falls in the shaded region, the mirage point will fall inside the original inclusion zone (outside the boundary), and the tree will be tallied from the mirage line.



The inclusion zones for trees near the boundary, and their mirage inclusion zones, are shown in Fig. 6. If the original line centre falls in the mirage inclusion zone of a tree, then the tree will be tallied from the mirage line. Note that the mirage inclusion zone is always a reflection of the portion of the original inclusion zone that fell outside the boundary, and has the same area. Thus, the mirage method for MHLS is unbiased, following the proof of Gregoire (1982).

Materials and methods

Field test

To test whether MHLS was, in fact, an efficient sampling method, we conducted a timed field trial comparing the efficiency and implementation bias of MHLS and HPS. We wished to examine whether MHLS would perform well in a snag and cavity tree inventory by showing (*i*) reduced sample variance, and hence narrower confidence limits at the same sample size, as HPS; (*ii*) no detectable bias due to unforeseen difficulties in field implementation; and (*iii*) comparable or better time efficiency than HPS when estimating number or basal area of snags and cavity trees. We did not address snag volume or biomass directly in this field test but hypothesize that as with volume and biomass of living trees, those parameters would be highly correlated with basal area and, hence, that basal area would serve as a suitable proxy in assessing the relative efficiency of the methods. HPS is typically very efficient in estimating volume or biomass because of relatively constant volume/basal area ratios (VBARs) within stands (Husch et al. 1982; Avery and Burkhart 2002).

VBAR can be estimated using either the complete sample or a subsample under HPS or MHLS, provided an appropriate ratio estimator is used. To the degree that HPS outperforms MHLS in estimating basal area, or vice versa, similar performance should be expected for volume or biomass.

Methods

We inventoried snags and cavity trees in two compartments of the University of New Hampshire's College Woods, located in Durham, N.H. The first compartment was the College Woods Natural Area, a 25-ha administratively reserved tract. The forest on this area developed following agricultural abandonment in the early 19th century and has been unmanaged since salvage harvests following a hurricane in 1938. The current forest has a well-developed multicohort structure with many trees considered large by regional standards (DBH > 60 cm) and the obvious presence of large snags and dead and downed woody material. Current basal area in this compartment is 43 m^2/ha, with an overstory dominated by *Pinus strobus* L., *Quercus rubra* L., *Quercus velutina* Lam., *Acer rubrum* L., and *Tsuga canadensis* (L.) Carrière commonly ranging to 80 cm DBH. However, quadratic mean diameter is only 19.2 cm, because of a high abundance of small, shade tolerant trees including *T. canadensis*, *Fagus grandifolia* Ehrh., and *A. rubrum*. We selected this stand, because it represents an ecological end member for regional forests and, we conjectured, would provide a test of the methods under conditions of a high abundance of large snags and cavity trees.

The second compartment was Compartment F in College Woods, an 18-ha younger stand that has received periodic management including heavy thinnings. While most of the stand is in the stem-exclusion stage typical of most managed stands in central New England, the horizontal structure is heterogeneous. Snags and cavity trees, especially in large diameter classes, are not a dominant structural feature in this compartment upon visual examination. Current basal area in this compartment is 36 m^2/ha, dominated by sawtimber-sized (>30 cm DBH) *Q. rubra*, *P. strobus*, *Q. velutina*, and *T. canadensis*. Quadratic mean diameter is 23.3 cm. We selected this stand as being more representative of managed stands than the Natural Area and providing a test under sparse snag and cavity tree distributions.

In each compartment, we laid out a systematic array of plot centres. At each plot centre, we performed HPS using a 4.59 m^2/ha prism. We also performed MHLS using the same prism, with a line length of 30.5 m. As we had few preconceived notions about snag size and density in the compartments, and even less preliminary data, this line length was determined by convenience rather than by calculation as outlined above. Lines were located using a hand compass and an electronic distance measurer (Haglof DME). We alternated the order of HPS and MHLS at each plot centre and timed the first method used at each point with a stopwatch. The second method was not timed, since foreknowledge of the location and characteristics of some sample trees might lead to an underestimate of time requirements for that method. A total of 45 points were located in the Natural Area and 22 points in Compartment F. We tallied all snags >7.5 cm DBH. For each snag tallied, the species, DBH, and presence or absence of cavities or other hollows was recorded. Decay class was also classified according to the five-class system following Thomas et al. (1979). Although analysis of the species and decay-class data will not be presented here, those variables were assessed in the field so that time requirements would be consistent with those of a typical snag and cavity tree inventory. All work was performed using a one-person crew, in keeping with common forest inventory practice on private lands in the region.

Estimates, sample variances, standard errors, and coefficients of variation were calculated for both HPS and MHLS in each compartment using the appropriate expansion factors and standard equations for simple random sampling (Thompson 1992). Ordinarily, a preferred method for testing for bias in the estimates of snags per hectare and basal area would be to use a parametric paired-sample t test in each plot. However, because the distribution of differences between estimates from the two methods at each point was highly non-normal, we used a two-tailed bootstrap percentile test on the mean difference (Efron and Tibshirani 1993) to assess the significance of differences in the estimates between the two methods.

We calculated relative efficiency of HPS and MHLS as

$$[6] \qquad E = \frac{\bar{t}_{\mathrm{MHLS}} \times s^2_{\mathrm{MHLS}}}{\bar{t}_{\mathrm{HPS}} \times s^2_{\mathrm{HPS}}}$$

where $\bar{t}$ is the mean time required per sample point for a method, and s^2 is the sample variance. E is the time required to achieve any specified confidence limit width using MHLS, expressed as a fraction of the time required to achieve the same confidence limit width using HPS. When $E < 1$, MHLS is more efficient than HPS; when $E > 1$, the converse is true. Because times were obtained for each method on only half of the points, we estimated mean time requirement per point by regressing time requirement on number of snags tallied at each point for both methods and applying the resulting linear regression to the mean number of snags tallied using each method in each compartment.

Results

Estimates of the number and basal area per hectare of snags on the two compartments is shown in Table 1. Overall, the estimates are similar, although the HPS data have a higher standard error and coefficient of variation. This was expected, as the "imaginary plot sizes" for trees in HPS are smaller. The one strikingly different estimate, that for snags per hectare in the Natural Area, is driven by the tally of a few small-diameter snags, which produced very high estimates at two HPS points. Differences among the estimates were not statistically different using the bootstrap paired-sample t test, indicating no detectable difference in bias in field implementation of the two methods.

Time requirement as a function of number of snags tallied for the two methods is shown in Fig. 7. HPS did require less time per sample point on average than MHLS (1.7 min per point vs. 8.2 min per point in the Natural Area, and 1.8 min per point vs. 9.0 min per point in Compartment F). However, because the variability of the MHLS estimates is much lower, relative efficiency of the two methods is comparable. In the Natural Area, E was 0.37 for snags per hectare, and

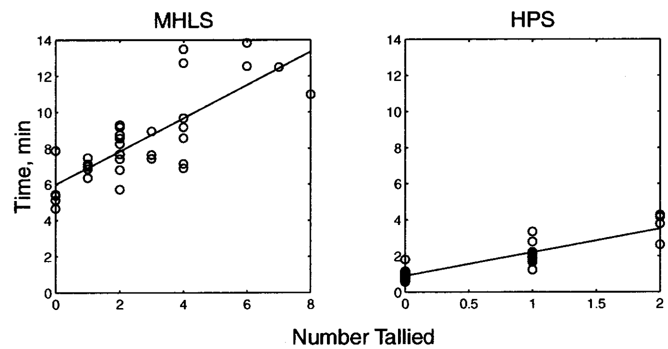
Table 1. Results of the field test of horizontal point sampling (HPS) and modified horizontal line sampling (MHLS) for snag inventory.

	HPS			MHLS		
	Estimate	SE	CV (%)	Estimate	SE	CV (%)
Natural area (n = 45)						
Snags/ha	191	49	172	97	14	95
Basal area, m^2/ha	2.96	0.51	115	2.48	0.28	77
Compartment F (n = 22)						
Snags/ha	130	65	235	127	22	83
Basal area, m^2/ha	3.12	1.15	172	2.75	0.46	79

1.46 for snag basal area per hectare, indicating that MHLS was more efficient than HPS in estimating the density of snags but less efficient for estimating basal area. By contrast, in Compartment F, E was 0.60 for snags per hectare and 0.82 for snag basal area per hectare, indicating MHLS was a better performer overall. Note that these figures do not include any time that would be consumed by locating additional sample points if the number of HPS points were increased to match the confidence limit widths attained by MHLS. Thus, these relative efficiency figures would overestimate the efficiency of HPS if additional points were laid out in a cluster or if the method of laying out additional points required additional travel time between points. For example, to achieve confidence limits on basal area in the Natural Area comparable with those achieved on the 45 MHLS points, 146 HPS points would be needed. Using the mean times from this study, 254 min of measurement time would be required for HPS versus 371 min for MHLS. If an additional 48 s per HPS point were required for additional point location or travel, that time savings would be completely consumed. Note that for snags per hectare in the Natural Area and for either variable in Compartment F, achieving comparable confidence limits would already require less time with MHLS than HPS.

Interestingly, our initial supposition that the number and size of snags would both be greater in the Natural Area than in Compartment F was not borne out by the data. The differences in efficiency between the methods in these two compartments appear to be driven more by differences in spatial aggregation of snags than by their density alone. This surprising result highlights the need for assessment beyond casual ocular examination when snags or cavity trees are important to overall management objectives.

Fig. 7. Time requirement per point for horizontal point sampling (HPS) and modified horizontal line sampling (MHLS) in the field trial. Times shown do not include travel time between points.



While promising, our field test is limited in geographical scope and in the stand types investigated. Relative efficiency will likely also vary with differences in crew size and equipment. Additional field trials, especially in forest types quite different from those examined here, would be especially welcome. While our efforts have focused on snags and cavity trees, we speculate that MHLS may also be useful for inventorying other kinds of rare or unusual trees. For example, the method might also be useful in obtaining improved estimates of the density, volume, and value of veneer-grade hardwoods in mixed-species forests. As such, it may provide a simple alternative to methods such as adaptive cluster sampling (Roesch 1993) that are analytically and operationally more involved.

Discussion and conclusions

Our modified form of HLS is easy to implement in the field and appears to be at least competitive with, and in some cases better than, HPS for estimating stand parameters for snags and cavity trees. It offers the additional advantage that meaningful estimates can be obtained with sample sizes (number of line segment centres) comparable with the number of inventory points often used for timber inventories and other assessments of the living overstory. The method requires no extra equipment and uses basic techniques already familiar to many practitioners.

Acknowledgements

We are grateful to Dr. Kim Iles and an anonymous reviewer for their comments and suggestions. This research was funded by USDA National Research Initiative grant No. 23-0628, "Efficient Methods for Assessing Coarse Woody Material in Forest Ecosystems".

References

Avery, T.E., and Burkhart, H.E. 2002. Forest measurements. 5th ed. McGraw-Hill, New York.
Beers, T.W. 1969. Slope correction in horizontal point sampling. J. For. **67**: 188–192.

Beers, T.W., and Miller, C.I. 1967. Polyareal plot sampling: terminology, symbolism and formulism. Purdue Univ. Agric. Exp. Stn. Res. Bull. 838.

Beers, T.W., and Miller, C.I. 1976. Line sampling for forest inventory. Purdue Univ. Agric. Exp. Stn. Res. Bull. 934.

Bruce, D. 1955. A new way to look at trees. J. For. **53**: 163–167.

Bull, E.L., Holthausen, R.S., and Marx, D.B. 1990. How to determine snag density. West. J. Appl. For. **5**: 56–58.

DeGraaf, R.M., and Shigo, A.L. 1985. Managing cavity trees for wildlife in the Northeast. USDA For. Serv. Gen. Tech. Rep. NE-101.

DeGraaf, R.M., Yamasaki, M., Leak, W.B., and Lanier, J.W. 1992. New England wildlife: management of forested habitats. USDA For. Serv. Gen. Tech. Rep. NE-144.

Ducey, M.J., Gove, J.H., Ståhl, G., and Ringvall, A. 2001. Clarification of the mirage method for boundary correction, with possible bias in point and plot sampling. For. Sci. **47**: 242–245.

Efron, B., and Tibshirani, R.J. 1993. An introduction to the bootstrap. Chapman & Hall, New York.

Gregoire, T.G. 1982. The unbiasedness of the mirage correction procedure for boundary overlap. For. Sci. **28**: 504–508.

Gregoire, T.G., and Monkevich, N.S. 1994. The reflection method of line intercept sampling to eliminate boundary bias. Environ. Ecol. Stat. **1**: 219–226.

Grosenbaugh, L.R. 1958. Point-sampling and line-sampling: probability theory, geometric implications, synthesis. USDA. For. Serv. South. For. Exp. Stn. Occas. Pap. 160.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, K., Jr., and Cummins, K.W. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15. pp. 133–302.

Husch, B., Miller, C.I., and Beers, T.W. 1982. Forest mensuration. 3rd ed. John Wiley & Sons, New York.

Lee, P. 1998. Dynamics of snags in aspen-dominated midboreal forests. For. Ecol. Manage. **105**: 263–272.

McComb, W.C., and Noble, R.E. 1981. Nest box and natural cavity use in three mid-South forest habitats. J. Wildl. Manage. **45**: 284–289.

McComb, W.C., Spies, T.A., and Emmingham, W.H. 1993. Stand management for timber and mature-forest wildlife in Douglas-fir forests. J. For. **91**(12): 31–42.

Oderwald, R.G., and Gregoire, T.G. 1995. Overstated volumes from pushing the point. South. J. Appl. For. **19**: 162–165.

Roesch, F.A., Jr. 1993. Adaptive cluster sampling for forest inventories. For. Sci. **39**: 655–669.

Schreuder, H.T., Gregoire, T.G., and Wood, G.B. 1993. Sampling methods for multiresource forest inventory. John Wiley & Sons, New York.

Schmid-Haas, P. 1969. Sampling at the forest edge. Mitt. Schweiz. Anst. Forstl. Versuchswes. **45**: 234–303.

Spetich, M.A., Shifley, S.R., and Parker, G.R. 1999. Regional distribution and dynamics of coarse woody debris in midwestern old-growth forests. For. Sci. **45**: 302–313.

Strand, L. 1957. Relascopic height and cubic volume determination. Nor. Skogbruk, **3**: 535–538.

Thomas, J.W., Anderson, R.G., Maser, C., and Bull, E.L. 1979. Snags. *In* Wildlife habitats in managed forests: the Blue Mountains of Oregon and Washington. *Technical coordinator*: J.W. Thomas. U.S. Dep. Agric. Agric. Handb. 553. pp. 60–77.

Thompson, S.K. 1992. Sampling. John Wiley & Sons, New York.

Tritton, L., and Siccama, T.G. 1990. What proportion of standing trees in forests of the northeast are dead? Bull. Torrey Bot. Club, **117**: 163–166.

Tubbs, C.H., DeGraaf, R.M., Yamasaki, M., and Healy, W.M. 1987. Guide to wildlife tree management in New England northern hardwoods. USDA For. Serv. Gen. Tech. Rep. NE-118.

Valentine, H.T., Gove, J.H., and Gregoire, T.G. 2001. Monte Carlo approaches to sampling forested tracts with lines or points. Can. J. For. Res. **31**: 1410–1424.

Wensel, L.C., Levitan, J., and Barber, K. 1980. Selection of basal area factor in point sampling. J. For. **78**: 83–84.

Wiant, H.V., Jr., Yandle, D.O., and Andreas, R. 1984. Is BAF 10 a good choice for point sampling? North. J. Appl. For. **2**: 23–25.