Downed Wood as Seedbed: Measurement and Management Guidelines

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Abstract

Eastern hemlock has exacting germination requirements, and availability of suitable microsites for germination can limit the development of hemlock regeneration. A major contributor to those microsites is coarse woody debris. New methods for quantifying coarse woody debris have recently been developed that are complementary to strategies typically used in timber cruising. We discuss practical issues in estimating the abundance of coarse woody debris and associated germination microsites, and illustrate the techniques with reference to preliminary guidelines for coarse woody debris abundance.

Introduction

Eastern hemlock (*Tsuga canadensis*) does not usually figure as a species of concern when regeneration is considered, at least in the Northeast, although the situation in the Lake States is different (Tubbs 1995). This may be because little economic value is usually attached to the species, despite its clear value for game habitat; perhaps, in part, it is because so many stands show abundant stocking in the seedling and sapling size classes, which conventionally have been taken to represent young age classes. However, the appearance of abundance may be deceiving, since suppressed "seedlings" and saplings may be decades old. An apparent exuberance of regeneration may mask an underlying demographic process of slow and infrequent establishment. Eastern hemlock is one of the more prolific and regular seed producers among the northeastern conifers (Godman and Mattson 1976). However, the seeds themselves are quite small, and viability can be low. Eastern hemlock requires a warm, moist seedbed for successful germination: both the temperature and moisture requirements are exacting (Godman and Lancaster 1990). These factors can combine to limit the establishment of hemlock seedlings and saplings, before other agents such as herbivory can come into play.

What substrates provide the conditions for hemlock regeneration? The leaf litter layer in mature forests is typically quite thick, and hemlock germinants fare poorly on such a dry, inhospitable substrate (Godman and Lancaster 1990). Tip-up mounds formed by the blowdown of large trees may form an important regeneration microsite in older forests, but tip-up mounds are rarely a significant feature in managed stands. While scarification along skid trails may provide good germination sites in recently cut stands, skid trails should form only a small component of total surface area when harvests are well-planned. Increasing attention to water quality issues, trends toward directional or mechanical felling with widely separated skid trails, and improvements in harvest mechanization have all combined to reduce scarification during harvest in much of hemlock's range. This "accidental" site preparation should not be relied on to stimulate much hemlock regeneration, and deliberate site preparation remains an expensive option. Without site preparation, either accidental or deliberate, the development of hemlock regeneration is usually restricted to downed coarse woody debris, or CWD (Godman and Lancaster 1990, Waller *et al.* 1995). For example, Corinth (1995) found that well-decayed CWD accounted for 57% of the hemlock regeneration in one stand in Wisconsin. Physically, CWD maintains an increased supply of available moisture, while its elevation above the forest floor may increase surface temperature, particularly in the spring germination period when soils are cold (Godman and Lancaster 1990). Tubbs (1995) suggests that hemlock logs may provide a refugium from competition with sugar maple (*Acer saccharum*) and yellow birch (*Betula alleghaniensis*) for young hemlock seedlings. CWD may not be an ideal substrate, but it can be inexpensive to manage. In addition to providing possible regeneration microsites, CWD also contributes to nutrient cycling and wildlife habitat (Hagan and Grove 1999).

It has not been common practice in the Northeast or Lake States to inventory CWD, either for operational or research purposes. Although guidelines have begun to appear (NHFSSWT 1997), they have not addressed the regeneration role of CWD, and baseline information on the abundance of CWD and its relationship to management is largely lacking (Hagan and Grove 1999). Fortunately, recent developments in CWD inventory techniques may reduce the difficulty of obtaining estimates at the stand level. Here, we review four methods of estimating CWD abundance, with particular attention to the variables which are most relevant for assessing regeneration microsites. Then, based on simple principles, we develop a preliminary stocking guide for CWD based on its potential in hemlock establishment. We illustrate how the guide can be used with a straightforward example.

What Aspects of Downed CWD Should be Measured?

Before any attempt at quantification begins, we should consider carefully what constitutes CWD, and what attributes of CWD are important in assessing regeneration potential. Perhaps the only attribute of CWD on which researchers can agree is that it is dead and woody. While studies and guidelines focusing on wildlife habitat attributes have often emphasized the amount of CWD in very large size classes, for example pieces >12" in diameter (NHFSSWT 1997), other studies have considered much smaller material in their definition of CWD. To be functional as a regeneration

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substrate, CWD must have sufficiently large diameter. First, it must be large enough to remain unburied by leaf litter until it has reached an advanced stage of decay. Second, it must still be elevated sufficiently above the surface of the litter layer that the young hemlock seedlings are not at risk of smothering under additional litterfall (Koroleff 1954, Tubbs 1995). Despite these considerations, Corinth (1995) found hemlock seedlings utilizing CWD as small as 4" in diameter. While there is a need for more data to assess these relationships, particularly in the Northeast, it seems that 4" is a reasonable lower diameter cutoff when measuring CWD for regeneration purposes, and it is consistent with previous definitions and procedures (Brown 1974).

A second difficulty lies in deciding what variables (both at the individual piece and the stand level) are important in assessing CWD. In part because most studies of CWD abundance have focused on the role of CWD in wildfire potential or in nutrient cycling, most presentations of inventory methods have stressed evaluating volume (ft^3/acre) or biomass (tons/acre) (Brown 1974, Harmon and Sexton 1996). Unfortunately, these representations of CWD abundance are less useful in assessing regeneration potential. One variable which does seem appropriate is the total ground surface area covered by CWD (ft^2/acre). This measure directly reflects the area upon which hemlock seed rain might fall, and can also be used (with appropriate statistical caution) in evaluating whether regeneration is associated with particular CWD or other surface components. However, as we will show below, surface area may not be the most useful variable in assessing the potential future stocking of hemlock. The total number of pieces (pieces/acre), and total length of pieces (linear ft/acre) may prove more useful.

Finally, it is important to separate CWD in any inventory by stage of decay. Numerous studies have indicated that hemlock regeneration on CWD is confined to pieces in advanced stages of decay. For example, Corinth (1995) found abundant hemlock regeneration only on the two most heavily decayed classes in a 5-class system. This is not surprising, since undecayed material provides little or no rooting environment. The most appropriate scale for evaluating decay in Northeastern forests has been presented by Pyle and Brown (1998); it modifies the traditional 5-class system to account for the peculiarities of decay in some eastern species. Within that system, decay classes IV and V — primarily composed of wood with a soft, friable, or powdery surface — are most important for hemlock regeneration. Pyle and Brown (1999) discuss the heterogeneity of decay classes within pieces, and present a useful table of attributes for judging decay class. Since pieces in advanced stages of decay are less heterogenous than pieces in intermediate stages, using a single "average" decay class for a piece is not likely to pose a problem for the important decay class IV and V logs, at least in operational assessments.

While some authors (e.g. Tubbs 1995) have suggested that the species of CWD may have an influence on species composition of regeneration, those relationships remain speculative. Given the difficulty of obtaining reliable field identification of CWD to species, especially in advanced stages of decay, CWD species is probably not sufficiently important to record in any operational inventory. However, it could be valuable from a research standpoint.

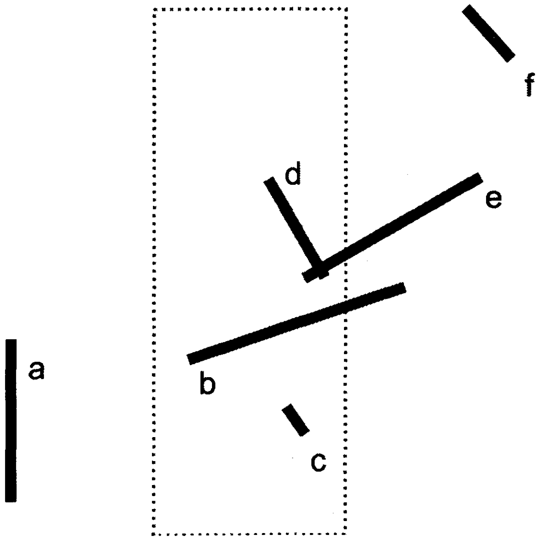

Figure 1.—Sampling CWD using a rectangular plot. Pieces *c* and *d*, which lie completely inside the plot, must be tallied; exactly how pieces such as *b* and *e* are tallied affects the bias of the method.

Methods for Sampling Downed Wood

Fixed-Area Plots

Perhaps the simplest and longest-used method for inventorying CWD is to tally pieces on fixed-area plots. Fixed-area plots are familiar to nearly all foresters and biologists through their use in vegetation assessment. A plot of known area is laid out; all the objects on the plot are tallied; their values for some variables of interest are measured; and the resulting numbers are expanded to per-acre values by multiplying by the reciprocal of plot size (Figure 1). Conceptually, three different approaches to using fixed-area plots for CWD inventory have appeared in the literature. These include:

1) Delineating the plot, then tallying all pieces which lie at least partially within the plot. The entire piece is measured to determine properties such as volume, surface area, or length per acre. Unfortunately, this method is biased; it is analogous to tallying all seedlings or understory plants which overhang the boundaries of a fixed quadrat, regardless of stem location. This approach provides an overestimate of pieces per acre and all derived quantities such as volume per acre and surface area per acre. The estimates of "per piece" quantities, such as the average volume or length of a piece, are also biased.

2) Delineating the plot, then tallying all pieces which lie at least partially within the plot. Only the portion of the piece which falls in the plot is measured to determine properties such as volume, surface area, or length per acre. This method does produce unbiased estimates of derived quantities such as volume and surface area per acre. However, estimates of the number of pieces per acre, as well as "per piece" quantities, are still biased.

3) Delineating the plot, then tallying only those pieces for which some uniquely determined point falls within the plot. The point can be any predetermined place on the log, such as the midpoint, or the location of the pith at the large end, so long as it can be readily and consistently identified in the field. Then, the entire piece is measured to estimate quantities such as volume and surface area per acre. This method provides unbiased estimates of densities, derived quantities, and "per piece" quantities.

An additional source of potential bias may arise when volumes and surface areas of irregular pieces must be measured. For relatively simple pieces, formulas such as Smalian's, Huber's, or Newton's formulas (Avery and Burkhart 1994, p. 55; Husch *et al.* 1982, pp. 99-101) for the volume of a solid of rotation may be used with little bias (Harmon and Sexton 1996). Even for pieces with moderate complexity, the bias introduced by using one of these reasonable approximations is likely to be quite small relative to the sampling error of an operational inventory. For pieces with more complex shapes, or in truly exacting research situations, more sophisticated measurement schemes such as randomized branch sampling (Gregoire *et al.* 1995) may be needed to obtain truly unbiased estimates.

Simplicity is both the greatest strength and the greatest weakness of using fixed area plots to estimate CWD abundance. The method is seemingly simple to implement in the field, but the time cost of locating the plot boundaries accurately, then scouring the area for hidden pieces of debris, can be quite time-consuming. In managed forests, a plot may contain a frustratingly large number of relatively small pieces, all of which must be measured. Once the field work is done, the calculations are relatively straightforward. When the plot itself is the population of interest, as in some research applications, interpretation of the results is easy. However, in the context of an operational inventory, where multiple plots are used to subsample a larger area of interest, the performance of fixed plots can be poor, with confidence limits remaining quite wide even after a significant investment of time and energy.

Line Intersect Sampling

Line intersect sampling is a probability-proportional-to-size technique for estimating the densities of many types of objects, but its most common use in forestry has been in the inventory of logging slash (Warren and Olson 1964), fuel loadings (Van Wagner 1968), and other coarse woody debris. Straightforward introductions to the method can be found in Brown (1974) and Shiver and Borders (1996); more detailed mathematical consideration is given in Kaiser (1983) and de Vries (1986). In practice, a series of sampling lines are laid out in the woods. Every piece which crosses a line is tallied and measured. If a piece crosses multiple lines, or crosses a single line multiple times, it is tallied multiple times (Figure 2). The resulting tally is then converted back into per-acre estimates of the required variables.

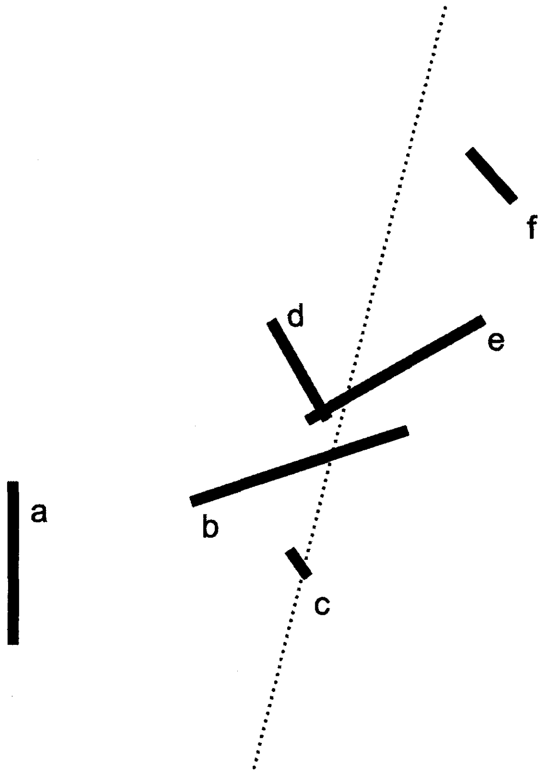

Figure 2.—Sampling CWD using line intersect sampling (LIS). Pieces *b, c,* and *e* will be tallied. Because LIS samples with probability proportional to length, piece *c* will count as more pieces per acre than either *b* or *e*.

The easiest variable to obtain using LIS is the total length (feet/acre) of pieces of CWD. Line intersect sampling selects pieces with probability proportional to length, so each tallied piece on a sampling line counts as a certain amount of length per acre. We can think of this amount of length as being a length factor, directly analogous to the basal area factor in prism cruising. The length factor of a sampling line is

$$F = 43560\pi/(2L)$$

where F is the length factor in feet per acre and L is the length of the sampling line in feet. For example, if we are using a sampling line that is 4 chains or 264 feet long, then $F=43560\pi/[(2)(264)]=259$ feet per acre. Suppose we lay out n sampling lines of equal length in a stand, and score m tallies in total. Then our estimate of the length per acre of CWD is simply mF/n. Confidence limits can be calculated using the standard error of the values calculated from the individual sampling lines, multiplied by the appropriate value of Student's t from a t-table (n-1 degrees of freedom must be used to find the value of t). The formulas to use when lines are of unequal length are detailed in Shiver and Borders (1996).

Estimates for other variables are only slightly more complicated to calculate. Suppose we are interested in some variable X for a stand, and measurement of a tallied piece for that variable is x. For example, if X were the total cubic volume per acre of CWD, then x would be the cubic volume of an individual tallied piece. The amount that the tallied piece contributes to the estimate of X is simply Fx/l, where F is the length factor as before, and l is the length of the piece in feet. To get the estimate of X that a single sampling line provides, we simply sum the values of Fx/l for all the tallies on that line. To combine estimates from multiple lines of equal length, we simply take the mean of the estimates, and confidence limits can be calculated in the usual way.

How does this translate into methods for the CWD variables in which we are interested, specifically volume per acre, surface coverage per acre, length per acre, and number of pieces per acre? For volume per acre, recall that the volume of a piece equals Al, where A is the mean cross-sectional area of the piece in ft^2. Substituting Al for x, we find that the contribution of a piece to the estimate for volume is just FA, or the length factor multiplied by its average cross-sectional area. It turns out that we can use the cross-sectional area at the point where the sampling line crosses the piece instead of A, with no bias and little loss in accuracy (de Vries 1986). So, when a sampling line crosses a piece, we simply measure the diameter of the piece at the intersection using calipers and record the measurement, convert that diameter measurement to cross-sectional area (assuming a circular cross-section; for decaying wood, using two diameter measurements and assuming an ellipse is often more appropriate), and then sum the values of FA for each sampling line. That same measurement of diameter will also give us an estimate of surface area coverage. If diameter, D, is measured in inches, then a fair estimate of the surface area of an individual piece in ft^2 is $Dl/12$. Substituting $Dl/12$ for x, we find that the contribution of a piece to the estimate for surface area coverage should be $FD/12$. If the variable in which we are interested is the length of pieces per acre, then we substitute l for x, and find that the contribution of a piece to the estimate of length is just F – which is why we can estimate length of pieces per acre directly from the number of tallies. Note that for all three of these variables – volume per acre, surface area coverage per acre, and length per acre – the measurement of l has disappeared in the formulas! That means we can estimate all three of these variables using only the number of tallies and the diameter measurements associated with each tallied piece.

Unfortunately, the situation changes slightly when we consider number of pieces per acre as the variable of interest. Here, the value of x for each piece is just 1, since each piece is a single piece of CWD. If we substitute 1 for x, we find that the contribution of a tallied piece to the estimate of pieces per acre should be F/l. This means that we must measure piece length to get estimates of number of pieces per acre in LIS. Measuring piece length is easy when pieces are approximately straight, like logs; however, when pieces form complex shapes like the tops of hardwood trees, obtaining accurate measurements of piece length can be difficult.

Under ideal conditions, LIS is very fast and efficient. Because sampling is with probability proportional to length, little time is spent performing measurements on the numerous small pieces of CWD which seem to pervade the forest floor; time is spent instead on the less frequent but typically more important large pieces. LIS as presented here does make some assumptions, however, and those assumptions must be upheld or corrections will be needed. The first assumption is that the lines are laid out from randomly or systematically located centers in random directions. If the directions of the lines are not random, then the angle of intersection of every piece with the sampling line must also be measured, and additional mathematics are required to obtain the estimates (Kaiser 1983). Second, the pieces are assumed to lie in the horizontal plane. This assumption is frequently violated by fine materials such as those within the tops of downed trees, and will also be violated by coarse material in sloping terrain. In these cases, a simple correction based on the slope of the pieces is required (Brown and Roussopoulos 1974). Harmon and Sexton (1996) note that the correction is always required for fine materials, but rarely for coarse materials; we suggest that the correction should be applied to all sizes of materials whenever the topography includes slopes greater than 30%.

Perhaps the greatest weakness of LIS is the tendency on the part of workers to underestimate the amount of sampling line that is required for good estimates (Harmon and Sexton 1996). Under typical conditions in New England, for example, dozens if not hundreds of chains of sampling line per stand are required to obtain 95% confidence limits of plus or minus 20% on the estimates of most variables. If CWD is being inventoried at the same time as the overstory, this can be accomplished by centering a sampling line perhaps 4-8 chains long on the center of every plot center (in a fixed-area plot cruise) or point (in a prism cruise). Keeping sampling lines straight and of accurate length can be problematic in stands with dense understories or well-developed shrub layers. Thus, while LIS almost certainly represents and improvement over fixed plots in operational inventories of CWD, obtaining good numbers with LIS still requires a considerable time investment.

Transect and Point Relascope Sampling

Two new methods of inventorying CWD based on using an angle gauge may provide improvements over LIS, at least in some circumstances. Transect relascope sampling, or TRS, uses an angle gauge along a line to tally pieces of debris (Ståhl 1998). Point relascope sampling, or PRS, uses the angle gauge around a point, much like prism cruising of the overstory (Gove *et al.* 1999). The term *relascope* in both methods refers to an angle gauge generally, following European usage of the word; the familiar Spiegel-relascope used for overstory sampling uses too narrow an angle to be

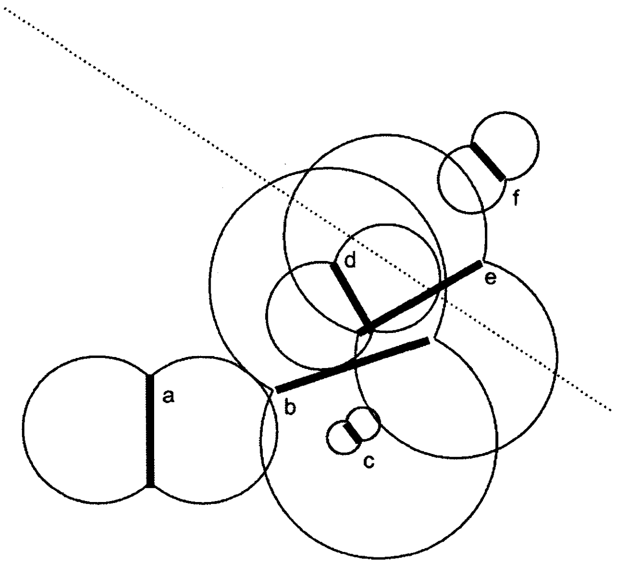

Figure 3.—Sampling pieces using transect relascope sampling (TRS). The inclusion zones are shown around each piece; the inclusion zone is the area within which the piece appears larger than the angle gauge. Pieces *b*, *d*, and *e* are tallied because the sampling line crosses their inclusion zone; the other pieces are not.

useful for CWD. Typical gauges for TRS and PRS use angles in the range of 20 to 90 degrees.

TRS was developed in Sweden to increase the efficiency of LIS, by tallying more pieces per length of line that must be run (Ståhl 1998). In TRS, sampling lines are laid out from edge to edge in a stand, and every piece which appears larger than the angle gauge from any point on the line is tallied once (Figure 3). This means that in addition to all the pieces which cross the line, pieces which are not on the line will be tallied. However, larger pieces can lie farther from the line and still be tallied, while small pieces must lie close to the line to be tallied. We can envision the process using the concept of an inclusion zone. In prism sampling of the overstory, each tree has an "imaginary circle" located around it. If a sample point falls within the circle, that tree is tallied. In TRS, each piece of CWD has an "imaginary blob" located around it, the shape of which is determined by the angle of the angle gauge. If the gauge has an angle of 90°, the blob will be a circle centered on the midpoint of the piece (Ståhl 1997). If the sample line crosses the blob, the piece is tallied. Like LIS, TRS is sampling with probability proportional to length, so every sampling line is associated with a length factor. Details of calculating the length factor, estimates for different variables, and confidence limits are given by Ståhl (1998).

PRS uses the same sort of angle gauge as TRS, so the inclusion zone of a piece of CWD is exactly the same. However, in PRS the angle gauge is turned around a sample point, just as in prism cruising. So, just as in prism cruising, if a sample point falls within the inclusion zone of a piece, the piece is tallied (Figure 4; Gove *et al.* 1999). PRS samples CWD with probability proportional to the length squared of each piece. The angle of the gauge determines a length squared factor *G*; each tallied piece counts as *G* ft^2 of length squared. Unfortunately, length squared is not a particularly useful variable in itself, and the calculation of *G* is rather involved. Fortunately, once *G* is known, it is easy to obtain estimates of all four main CWD variables: pieces per acre, length per acre, surface area per acre, and volume per acre.

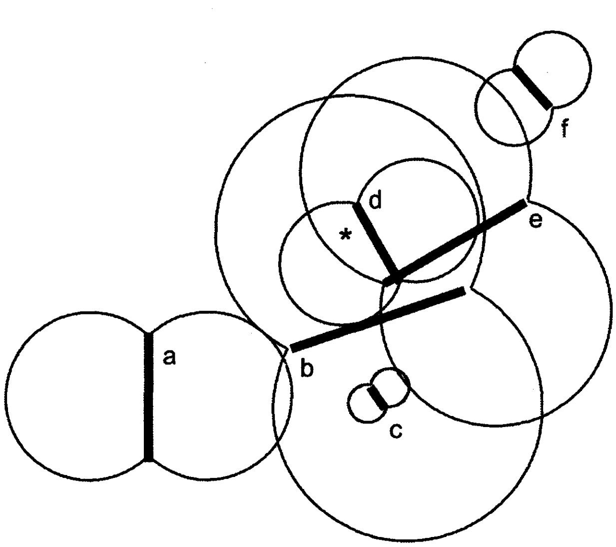

Figure 4.—Sampling pieces using point relascope sampling. The sample point (*) falls within the inclusion zones of pieces *b*, *d*, and *e*; the other pieces are not tallied.

Suppose we are using an angle gauge which uses a 20" wide target held 20" from the user's eye, which is located over the sample point. Such a gauge will have a length squared factor *G* of 20694 ft^2/acre. So, every piece tallied on a point will count as 20694 ft^2/acre of length squared. Now, for every tallied piece, we could measure its length and one or more diameters to determine surface area and volume, just as we would in sampling on a fixed area plot. If we tallied a piece that were 20 ft long, its length squared would be 400 ft^2. That piece would count as 20694/400, or 51.7, toward the estimate of pieces per acre for that point. If the surface area coverage of the piece were 25 ft^2, the piece would count as 51.7´25, or 1293 ft^2/acre, toward the estimate of surface area coverage for that point. If the piece contained 30 ft^3 of volume, then the piece would count as 51.7´30, or 1551 ft^3/acre, toward the estimate of volume per acre for that point. The estimate of any variable for each point is calculated as the sum of the contributions of each of the pieces tallied on the point. Just as in prism cruising, the best estimate of each variable for the stand is simply the mean of the individual point estimates, and calculation of confidence limits is straightforward.

TRS and PRS are new techniques, and their efficiency relative to LIS has not been firmly established. Both simulations (Ståhl 1998) and field studies (Ringvall and Ståhl 1999) suggest that TRS is significantly more efficient, in terms of the relationship of time spent to the width of confidence limits, than LIS. Likewise, early tests of PRS in a variety of stand structures in Maine suggest that PRS is quite competitive with LIS (Brissette *et al.* 1999). PRS has the further advantage of being centered on a sample point, making it complementary to typical strategies for overstory measurements, and therefore easy to combine with them (Gove *et al.* 1999). While these results are promising, further field comparisons would be invaluable in help practitioners choose between methods confidently.

As with the other methods, both TRS and PRS make certain assumptions which must be satisfied or corrected. Like LIS, TRS typically assumes the orientation of the sample lines is random. This assumption is not required for PRS, because the sample unit for PRS (a point) is nondirectional. TRS and PRS also assume that CWD is composed of simple shapes, such as straight logs. If this assumption is violated, additional measurements on each piece may be needed (Gove *et al.* in review). Finally, slope compensation in TRS is somewhat complex, although relatively simple field techniques may alleviate the problem (Ståhl *et al.* in review).

How Much Downed Wood is Enough?

We can quantify the amount of CWD in a stand, but how do measured levels relate to levels we might desire for management? In many ways, this question parallels the traditional distinction between density and stocking as those terms apply to the overstory: density is a quantitative measure of abundance, but stocking is a measure relative to goals and objectives for the stand. As Hagan and Grove (1999) point out, most ecological discussions assume that the more CWD, the better, with some exceptions when fire or other unwanted disturbances are at issue. While many studies have focused on CWD levels in old-growth stands, old-growth levels of CWD should not be considered realistic or normative in younger, managed stands, particularly those in post-agricultural landscapes where few legacies remain from previous rotations. We should expect desired levels of CWD to vary depending on management objectives, much as the desired stocking of the overstory depends on silvicultural objectives. Here, we step through a conceptual pathway based on hemlock regeneration, and develop a preliminary set of guidelines for CWD abundance.

Picture a downed log or similar piece of CWD, well-decayed, and providing a good substrate for hemlock germination and growth. The volume or biomass of that log may be useful for understanding carbon or nutrient cycling, and a log with large volume may be more valuable for hemlock regeneration, but the relationship of volume to regeneration potential is rather indirect. A more direct relationship exists with the surface area of the log. If viable hemlock seeds fall at a certain density in seeds per ft^2, the larger the log, the more seeds it will receive. However, the number of germinants is not really critical, so long as there are enough of them to fully occupy the log in some sense. Just as small plots are usually counted as adequately stocked or unstocked when the substrate is the 2-dimensional ground surface, it is the presence or absence of stocking on segments of the log that are important for the subsequent dynamics of hemlock regeneration. Since hemlock is a prolific seeder (Godman and Mattson 1976), if germination conditions are right, and if neither browse pressure nor competition with other shade-tolerants in the overstory are heavy, it is reasonable to assume that a good substrate will eventually be well-occupied by small hemlocks.

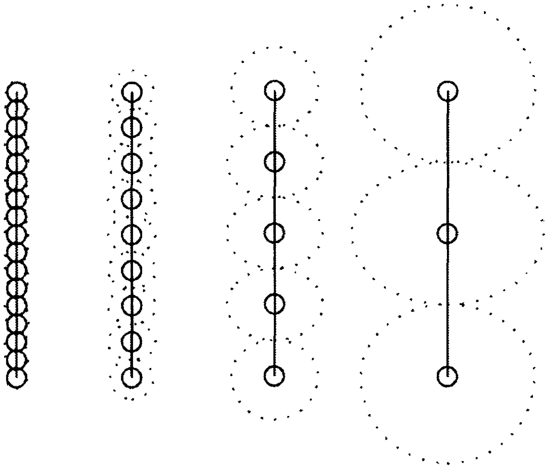

Figure 5.—Conceptual diagram of a cohort of hemlocks self-thinning along a piece, starting from seedlings or saplings on the left and moving toward large trees on the right.

Now, consider how a cohort of small hemlocks would grow and develop along a linear feature such as a downed log (Figure 5). Two things are readily apparent as we move across the figure. First, as the trees grow, their numbers must decline through the usual process of self-thinning, though competition is along a line and not through space. Second, despite the decline in numbers, the amount of crown area occupied by the cohort increases as tree size increases. Therefore, a given log can support a greater crown area of hemlocks as the hemlock cohort grows and develops. This amount depends on how tightly packed the crowns can be; if the crowns can form elliptical rather than circular shapes, more crown area can be supported. The amount of crown area also depends on the length of the log, since the hemlocks at the ends are always free to grow on one side.

If the mean crown area of a hemlock in ft^2 is C, then the amount of crown area that a single log of length l can support is about $C+l$ sqrt(C). That simple formula assumes that the ratio of the short axis through a hemlock crown to the long axis is p/4, or about 78%, which is not unusual for hemlock crown data. How much CWD is required to fill an acre with hemlock crowns? The answer to that question is the formula

$$l_{total} = -\mathrm{sqrt}(C) \times m + 43560/\mathrm{sqrt}(C)$$

where l_{total} is the total length of CWD in feet/acre, and m is the number of pieces per acre. Both are variables which can

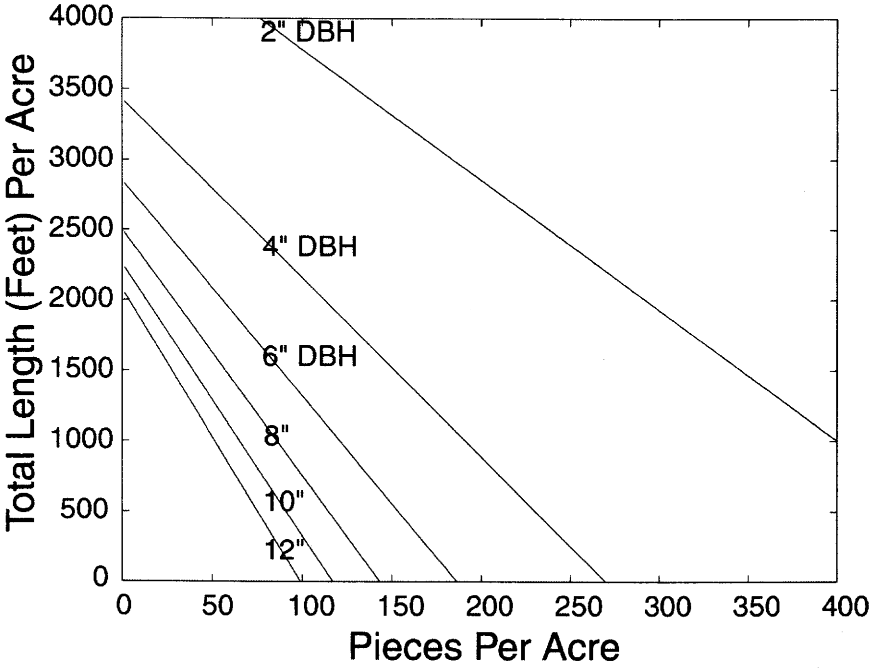

Figure 6.—A preliminary stocking diagram for coarse woody debris, based on the potential for hemlock regeneration. The number per acre and total length per acre of pieces of well-decayed (class IV or V) CWD are used to locate a stand on the diagram; the lines indicate the DBH at which a regenerating cohort of hemlock would be expected to form a closed canopy stratum.

be estimated easily using any of the four sampling methods discussed above. We see that the required amount of total length is a linear function of the number of pieces, with the slope and intercept depending on the mean crown area C.

To translate that linear function into stocking guidance for CWD, it is useful to relate C back to a more easily measured and visualized number, specifically the DBH of hemlock trees. Based on 24 hemlocks growing in Durham, NH under ordinary conditions, spanning a range of 0.3 to 31.6" DBH, the estimated relationship is

$$\ln(C) = 3.8171 + 0.9136 \times \ln(\text{dbh})$$

where ln is the natural logarithm. Using this equation, we can construct a stocking guide which answers the following questions:

1) In a stand with a certain number of pieces per acre and total length per acre of CWD, if that CWD were well stocked with hemlocks, at what DBH would that hemlock cohort form a closed canopy stratum?

2) If a silvicultural goal is to achieve a closed canopy hemlock stratum at a target DBH, how much well-decayed CWD (expressed in possible combinations of number of pieces and total length of pieces) would be required as seedbed?

3) If a silvicultural goal is to achieve a hemlock stratum with some specified percent closure at a target DBH, how much well-decayed CWD (expressed in possible combinations of number of pieces and total length of pieces) would be required as seedbed?

The stocking guide is presented in Figure 6.

As an example of answering the first question, suppose we had performed an inventory of a stand, and found that we had 100 pieces per acre of well-decayed class IV or V CWD, with a total length of 1500 feet/acre. At what DBH would a new cohort of hemlocks be expected to form a closed canopy? Locating the point on the chart corresponding to our data, we find that the stand is just above the 6" DBH line, and well below the 4" DBH line. We would conclude that we have adequate seedbed to form a closed stratum when the hemlocks reach 5.5" DBH.

As an example of answering the second question, suppose we would like to form a closed stratum when the hemlocks reach 8" DBH, to provide initial training trees for a cohort of red oaks, and then provide winter deer yarding habitat late in the rotation. However, an inventory shows our stand has only 50 pieces per acre of well-decayed CWD, totaling only 500 feet/acre in length. It is clear that we do not have enough CWD as seedbed, since our stand is well below the 8" DBH line. If there is enough relatively undecayed (classes I-III) CWD, we may not need to intervene, since our seedbed is already "in the pipeline." However, if not, we might consider inexpensive silvicultural means of creating CWD, such as reducing the utilization of cull trees and tops in a coming thinning.

As an example of answering the final question, suppose instead that we only wish to form a stratum with 60% closure at 12" DBH in the same stand. To answer this question, we must divide our inventory data by 60% or 0.6. So, in the stand above, we would use the values 50/0.6=83 pieces per acre, and 500/0.6=833 pieces per acre. These numbers place our stand above the 12" DBH line, so we conclude that enough seedbed is in place. We can now concentrate on other factors inhibiting hemlock regeneration, such as browsing.

Conclusions

Coarse woody debris is not the best seedbed for eastern hemlock, but it is practically free and easy to manage. Thus, it provides a ready source of seedbed in areas where regenerating hemlock is a silvicultural goal. Continuing improvements in inventory methods for CWD make it possible to obtain estimates of CWD abundance in a reasonable time frame, but it is not always easy to say how much CWD is needed in a stand. In the case of hemlock regeneration, simple geometric assumptions can be translated into a CWD stocking guide which relates the number of pieces and total length per acre of CWD into expected dynamics of a regenerating hemlock cohort. Though rough and preliminary, guidelines such as these should provide reassurance to foresters when their stands are "on track". We stress, however, that guidelines such as these remain largely conceptual; more empirical data would be invaluable in refining them and allowing greater confidence in their use.

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