# Cost-effective Methods for Monitoring Coarse Woody Debris in Northeastern Forests

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**Abstract.** Across boreal and temperate biomes, the area of old forests is in global decline, with the consequent extinction of dependent species posing a major threat to biodiversity. As such, current sustainable forestry certification programs position management for biodiversity as a fundamental goal. Yet, to do so necessitates both the use of effective indicators, of which downed coarse woody debris (CWD) is well-established, and the establishment of reference levels, which are most often based on comparable old growth systems. However, the extreme spatial variability of CWD makes inventorying and monitoring this structural attribute problematic. Trade-offs exist between costs, sampling methods, sample area, and the statistical ability to detect change. Faced with vast uncertainty regarding the effectiveness of monitoring approaches, large-scale inventories of CWD are largely neglected in the Northeast.

The objectives of this project were two-fold: 1) to develop cost-effective methods for monitoring coarse woody debris volume at a scale appropriate to northeastern forest management and 2) to discern the potential impacts of forest management on CWD attributes. A systematic sampling approach was used to inventory CWD in a managed and an old growth forest in Northern Maine. Two promising methods for measuring CWD—line intersect sampling and perpendicular distance sampling—were compared in the managed landscape, using different sampling areas for each approach. Perpendicular distance sampling exhibited high sampling costs and poor statistical efficiency relative to line intersect sampling. As such, it cannot be recommended for large-scale forest inventories. Only line intersect sampling was used in the old growth forest. Doing so enabled comparison of the statistical efficiencies of varying transect length and CWD attributes between landscapes. Power analyses were conducted to determine the tradeoffs between statistical precision and sample effort in using a particular transect length for inventorying CWD in managed and unmanaged forests. Variance was reduced with increasing transect length. However, choosing the appropriate transect length for a large-scale inventory depends on the level of precision required and the sensitivity to change in CWD volume for a given landscape. Land managers can consult these graphs to determine the appropriate minimum sample size required on average to detect a specific change in CWD volume at an accepted power and alpha level. Further, the old growth forest had more than twice the mean CWD volume than in the managed landscape, and landscapes differed in how this volume was distributed across size and decay classes, suggesting insight into the impacts of forest management on CWD.

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## 1. Introduction:

Across boreal and temperate biomes, retention of old growth forests is paramount for biodiversity conservation given the pandemic loss of such forests and the subsequent threat to dependent species (Freedman et al. 1996, Noss 1999, Hanski 2000, Berg et al. 1994). In many countries, such as Sweden, with an extensive history of forest management, intensive practices have spurred this decline by reducing the structural diversity of forest systems —the effects of which have only recently been recognized. In response, the forest management paradigm has shifted focus from fiber production towards a more holistic ecosystem-based approach (Hansen et al. 1991, Swanson and Franklin 1992), evidenced in the fact that many forestry certification programs include biodiversity as a fundamental goal. However, biodiversity is an overly complex entity to manage for, necessitating the use of efficient and effective indicators (Noss 1999, Lindenmayer et al. 2000, Hagan and Whitman 2006).

Old growth forests are characterized by unique structural features that develop over long time scales and as such, are largely absent from younger stands. Among these, perhaps the most important, recognized as indicators for forest health, are the density of large trees and snags and downed coarse woody debris (CWD) attributes. The structural heterogeneity provided by large trees, large snags, and downed woody debris both affects resource availability for an abundance of species across taxa and alters abiotic conditions, leading to increased forest biodiversity (Maser et al. 1979, Harmon et al. 1986).

Both when alive and dead, large trees serve as critical substrate for many forest species currently recognized as rare or threatened, including several epiphytic bryophytes and lichens (Lesica et al. 1991, Rose 1992, Selva 1994, Samuelsson et al. 1994, Esseen et al. 1996). Large trees further provide shelter for wildlife (e.g. dens for furbearers); cavities for large-bodied birds, such as woodpeckers, and later secondary cavity species (DeGraff and Rudis 1986, Tubbs et al. 1987, Hagan and Grove 1999); perching, nesting, foraging, and roosting sites for a variety of other bird species (DeGraff and Rudis 1982, Tubbs et al. 1987); and specialized habitat for arthropods (Harmon et al. 1986, Warren and Key 1991). Once dead, large trees serve as food and foraging substrate for many vertebrate and invertebrate species (Harmon et al. 1986, Samuelsson 1994, Hagan and Grove 1999). More over, the residence time of a dead tree may extend centuries, prolonging its ecological importance (Franklin et al. 1987). Both brought about by and exerting positive feedback on forest disturbance processes (Tinker and Knight 2001, Turner et al. 2003), large and downed coarse woody debris (CWD) is ecologically important in terrestrial and aquatic systems (Harmon et al. 1986). Ecosystem processes influenced by CWD include nutrient cycling through the storage and slow release of nutrients (Harmon et al. 1986, Harmon and Hua 1991, Jurgensen et al. 1997); soil development (Harvey and Neuenschwander 1991) and forest floor microtopography by providing organic material, altering runoff, reducing soil erosion and constructing pit-and-mound formations; and fire intensity and return interval (Beatty and Stone 1986, Harmon et al. 1986). CWD is a critical store for carbon (Harmon and Hua 1991, Turner et. al 1994) and moisture in forested systems (Harmon et al. 1986, Fraver 2002). Downed woody debris serves as important growing substrate for fungi, lichen, moss, and liverwort species (Berg et al. 1994), habitat for forest vertebrate and invertebrate species (Harmon et al. 1986, Niemela 1997), and a seedbed for many vascular plant species (Maser et al. 1979, Marie-Josee et al. 1998).

Given the value of large trees, snags, and CWD as indicators of forest health and recognizing their role in ecosystem processes, most contemporary forest policies mandate management for these attributes. For example, Criterion no. 5, as devised in the 1994 Montréal process and specified in the 1995 Santiago Declaration, requires maintenance of forest contribution to the global carbon cycle through quantifying carbon fluxes in standing, dead, and downed plant biomass, as well as soil. Thus, measurement of these attributes have become more frequently incorporated into monitoring programs at various scales, ranging from national and regional inventories to those on forest industry lands (Ståhl et al. 2001). In Maine, the two predominant forestry certification programs require the management of structural attributes and the assessment of forest habitat types. Specifically, the Sustainable Forestry Initiative (SFI) requires landowners to “have programs to promote biological diversity at stand and landscape levels” (1) to manage for important “stand-level wildlife habitat elements . . . [such as] snags . . . [and] down woody debris” (Indicator 4.1.4), (2) to conduct assessments of “forest cover types and habitats” (Indicator 4.1.5), and (3) to support the “conservation of old-growth forests in the region” (Indicator 4.1.6) (AFPA 2004). Likewise, compliance with the Northeastern Forest Stewardship Council (FSC) standard mandates landowners (1) “maintain . . . large fallen trees, large logs, and snags of various sizes” (Indicator 6.3.b3) and (2) manage for “a distribution of age classes appropriate to the size of ownership” (Indicator 6.3.a4) (Northeast Region Working Group 2005).

Yet, the objectives are vaguely stated and lack clear direction regarding the best approaches for inventorying and monitoring changes in these structural attributes. Regarding CWD, a consistent definition is lacking (Helms 1998), and as such, existing studies often differ in the dimensional and positional constraints of CWD based on project or management objectives. Researchers and managers furthermore conduct measurements at different locations along CWD pieces and differ in how these measurements are converted to volume estimates, based on assumptions and taper equations (Stahl et al. 2001). Meta-analysis and other comparisons among studies are therefore difficult. Adding to the management dilemma, CWD parameters are challenging to inventory with great precision due to extreme variance in the distribution and abundance of CWD within and between stands and across landscapes (Ståhl et al. 2001). Equally prohibitive to monitoring CWD is the lack of financial return provided in contrast to relatively high costs of estimation. Therefore, for a given inventory, methods should be chosen so as to be (1) cost-efficient, (2) robust with regards to measurement error, (3) easy to understand and simple to conduct, and (4) capable of providing additional contextual information (Ståhl et al. 2001).

Various studies have examined the efficiency of current sampling techniques for CWD (e.g., Ståhl et al. 2001, Bebber and Thomas 2001, Williams and Gove 2003); however they have been insufficient in addressing the needs of northeastern forest managers: they are largely based on computer simulations, limited in scope and scale, and applied in different geographic regions. Further, none have examined the tradeoffs for methods between cost, effort (sample area and sample size), and the statistical ability to detect change in CWD volume at the management scale typical in the Northeast. Given these uncertainties, large-scale inventories of CWD are largely neglected in the region. Yet, the ecological role of downed CWD in supporting forest biodiversity is not withstanding: over 30% of mammals, 45% of amphibians, and 50% of reptiles in New England utilize downed logs as foraging habitat or cover (DeGraff and Rudis 1986).

The objectives of our project are two fold. First, we sought to develop cost-effective methods for monitoring CWD volume in northeastern forests by comparing the two most promising inventory techniques for CWD across a range of management types. By presenting the trade-offs between sampling effort—and thus cost—and the ability of land managers to detect actual changes in CWD volume based on empirical, regionally-specific data, we hope to direct the planning of future monitoring programs. Reference standards and management goals for CWD volume and other attributes are most often based on old-growth conditions (Spies and Franklin 1991, Keddy and Drummond 1996); however, estimation of these properties varies greatly with the inventory methods used and the spatial scale of study (Shifley et al. 1994). Therefore, our second objective was to discern the potential effects of forest management on CWD through using similar methods to inventorying an intermediately managed and an old growth forest in Northern Maine.

## 2. Methods:

### *2.1. Study areas*

With ninety-percent of the land-cover (17.8 million acres) in forests, Maine remains the most heavily forested state in the country (McWilliams et al. 2003). Unique to the state, forest ownership in northern Maine is dominated by the commercial sector, with tracts typically exceeding 50,000 hectares, much of which is certified under FSC or SFI (McWilliams et al. 2003). Regional cover types consist primarily of northern hardwood (NH) and upland spruce-fir (SF) forests (40% and 33%, respectively), which is consistent throughout the Acadian Forest—a region spanning northern New England and the Canadian Maritimes (McWilliams et al. 2003). Dominant NH canopy species for sampled sites were *Acer saccharum* L. and *Betula alleghaniensis* Britt. with *Picea rubens* Sarg., *Betula papyrifera* Marsh. var. *cordifolia* (Regel) Fernald, *Abies balsamea* (L.) P. Mill as co-dominants. NH stands were typically located on moderately drained loams and silt loams on mesic slopes and hilltops ranging from 150 to 700 meters in elevation (Whitman and Hagan 2003). SF stand were dominated by *A. balsamea* and *P. rubens* with *A. saccharum* and *Betula* spp. frequent co-dominants. These stands occurred at elevations between 150 and 1000 meters on moderately well-drained loams to mesic, clay loams on hilltops, rocky slopes, and lower slopes (Whitman and Hagan 2003).

To meet the project objectives, the study was conducted in two landscapes: (1) an intermediately managed, FSC-certified, commercial timberland spanning ~27,500-acres and typical of forests in the region and (2) a ~5,400-acre old growth forest (Big Reed Reserve) representative of the successional trajectory of Acadian forests with minimal anthropogenic impact. Inventory of the managed landscape enabled development of sampling recommendations for similar intermediately managed forests; whereas, the old growth forest provided an approximation of appropriate sampling methods in unmanaged landscapes. Modification of the sampling protocol for the old growth forest provided an adequate sampling intensity to compare CWD attributes between the two landscapes.

Natural disturbance processes in these forests consist of frequent, small-scale gap formation events from windthrow and snow. Large-scale, stand replacing disturbances are infrequent, with the return interval at least an order of magnitude longer than gap-processes (Seymour et al. 2002, Lorimer and White 2003). Infrequent spruce-budworm outbreaks have also had an impact with a return interval several decades in length and the last outbreak from 1975-1985. The harvest history of the managed landscape reflects that of northern Maine at large. Northern hardwood forests have been high-graded for spruce since the 1800’s; for high-quality hardwoods beginning in the 1900’s; and managed with selection harvesting since the 1960’s, transitioning to shelterwood systems in the 1980’s (Whitman and Hagan 2007). Spruce-fir stands in the managed landscape have been high-graded for conifers since the 1800’s. Heavy partial harvesting and commercial clearcutting of SF stands began in the 1900s, with a transition to silvicultural clearcutting or shelterwood systems continuing since in the 1960’s (Whitman and

Hagan, 2007). Though affected by natural disturbance processes, Big Reed Reserve exhibits minimal impacts from timber harvesting according to both historical records and field observations (Chokkalingam and White 2000).

### *2.2. Approach*

Within the two landscapes, a systematic sampling approach using a random start was chosen to replicate the standard approach for large-scale forest inventories; to ensure adequate spatial coverage; and to minimize field crew travel costs (Marshall et al. 2000). For each landscape, a kilometer-squared grid was overlain on a Universal Transverse Mercator projected map using Arc GIS 9.x from which sampling blocks were randomly selected. Sample points were then positioned at 200-meter intervals northward from the southwest to the northwest corners of a block, with another line of sample points positioned 500-meters to the east. Where inventory approaches would have intersected stand boundaries, sample points were randomly shifted to the east or west to preclude boundary effects. Sites delineated as inoperable from stand maps and ground-truthing in the managed landscape were randomly relocated at 200-meter spacing north or south of the respective line of samples. A total of 108 sample points were established in the managed landscape and 50 in the old growth stand. All sample points were located in the field using a handheld GPS unit and compass.

Sampling approaches differed between the two landscapes to meet project objectives. In the managed landscape, two methods for estimating CWD volume were performed at each sample point to allow direct comparison between methods. Only one of these methods (LIS with 50-meter transects) was then used in the old growth. Inequality of sample size and sample area (transect length) between landscapes was designed to capture the greater anticipated spatial variance in CWD volume for the managed landscape and to enhance inventory recommendations.

### *2.2.1. CWD Field Methods*

Coarse woody debris was defined as dead tree boles, large limbs, and other large wood pieces either lying on the ground or elevated less than 45° from horizontal and not self-supporting having an average diameter $\geq$ 7.5 cm at the point of measurement. Live material, standing dead trees, stumps, dead foliage, and separated bark were not included. Constraints were chosen to correspond with large-scale inventory approaches, such as the Forest Inventory Analysis of the U.S. Forest Service and the Vegetation Resources Inventory in British Columbia, Canada. The size-constraint further approximates the minimum diameter of 1000-hour fuels used by the US Forest Service (Rothermel 1972). Length restrictions were not imposed.

Based on primary literature, the two methods chosen for estimating CWD volume were line intersect sampling (LIS) and perpendicular distance sampling (PDS), due to their high suitability for large-scale inventories. First applied to logging residue by Warren and Olson (1964), LIS is one of the oldest and the most commonly used techniques for measuring CWD. Preeminence and longevity have made LIS the most well-developed and adaptable method, requiring minimal training time while providing high statistical efficiency in relation to sampling cost (e.g., Canfield 1941, Warren and Olsen 1964, Van Wagner 1968, De Vries 1973, Kaiser 1983).

In the managed landscape, a 100-meter transect was established with fixed orientation (east-west) and centered on the sample point. CWD pieces were then sampled if the central, long-axis of the log was intersected. For curved logs or branched pieces with multiple intersections, each intersection was measured independently when all other constraints were met. At the point of intersection, two diameter measurements to the nearest centimeter were taken perpendicular to the long axis of the log with metal calipers. Diameter was measured at the point of intersection because of the unbiased nature of the measurement and the time efficiencies gained by not leaving the transect (Van Wagner and Wilson 1976). Additional parameters recorded for each piece included the species, decay class, and location along the transect (to nearest 10 meter interval). Although decay is heterogeneous across individual logs (Pyle and Brown 1999), overall decay stage can be accurately and rapidly estimated based on general structural features (Pyle and Brown 1998). Using this approach, the decay stage of each log was also recorded (Table 2).

Several novel sampling approaches have been developed for CWD in recent years, including Diameter Relascope Samping (DRS) (Bebber and Thomas 2003), Transect Relascope Sampling (TRS) (Ståhl 1998), Point Relascope Sampling (PRS) (Gove et al. 1999), and Perpendicular Distance Sampling (PDS) (Williams and Gove 2003). Of these, simulation studies suggest that PDS is the most statistically efficient for measuring CWD volume because the inclusion probability is proportionate to piece volume rather than length, as with LIS and most other methods. Sampling effort and bias are minimized, as well, because only borderline logs must be measured (Williams and Gove 2003). Yet, few field studies have examined the applicability of the method in the field, with the only published studies using simulation approaches (Williams and Gove 2003, Williams et al. 2005). Using this method in the managed landscape, logs were included if 1) a perpendicular angle (90°) could be constructed between the long axis of the log and the sample point and 2) the distance of the log from the sample point was less than the limiting distance relative to diameter. As with LIS, only CWD with an average diameter $\geq$ 7.5 cm and $\leq$ 45° from horizontal was included; metal tree calipers were used to take two diameter measurements; and CWD species and decay class were recorded. Accurate measurement of the distance to the nearest centimeter from the point of perpendicularity for each log to the sample point was achieved using a Haglof DME 201 ultrasonic distance measuring device. Additional modifications to the protocol included corrections for slope and log curvature and the sampling of multi-stemmed logs individually, as detailed in Williams et al. (2005).

Various sampling areas of each approach were used to evaluate their effects on statistical efficiency, and hence, the ability of a method to detect changes in CWD volume. The LIS method was sub-sampled by transect length (20 m intervals), while keeping the transect centered on the sample point, to allow comparison between methods. Two common volume factors ($K_{PDS}$ 250 volume factor = 20 $m^3ha^{-1}$ and $K_{PDS}$500 volume factor = 10$m^3ha^{-1}$) were performed for the PDS sampling approach. Kpds factors are analogous to basal area factors (BAF) in horizontal point sample, where the factor defines the inclusion probability for a given individual based on diameter.

In order to examine the relationship between sampling cost and precision attained for the two methods, we sought to evaluate costs based on the time required by a practitioner proficient in the method. Therefore, seventy samples points were inventoried using both methods and a two-person field crew—alternating methods between users at each sample point—prior to recording sampling costs. At the subsequent sample points, the start time, time at which each piece was sampled, and end time were recorded for the 100-meter LIS method (n=38) and the 500 $K_{PDS}$ factor (n=35)—the two levels exhibiting the largest sample area for the methods. Sampling time was based on a one-person field crew where the methods were alternated between users at each sample point. Other studies have performed more detailed analysis of costs, recording variables such as time spent walking, measuring, recording, and traveling (between samples, site entry, and exit times) (e.g., Hazard and Pickford 1983, Nemec and Davis 2002). These variables were not recorded in the study due to their dependence on landscape, crew size, and other uncontrollable factors. Fixing the parameters measured on each piece of CWD allowed a more accurate comparison of sampling costs between methods. .

### *2.2.2. Site Attributes*

Across both landscapes, environmental variables used in large-scale inventories were recorded to allow further analysis and more accurate estimates of required sampling effort. Pertinent factors included tree species composition, canopy closure, ecological stage, and site productivity (Tables 4 to 7). The two dominant and co-dominant canopy species were also recorded to classify stands as northern hardwood or spruce-fir forest types. Evidence of past clearcutting and partial harvesting was noted, and the time since each treatment estimated by tree growth and stump decay. Post-harvest residual CWD contribution has been shown to be negligible after 40 years in northern forests (Harmon et al. 1986). Based on harvest practices in the last 20 years, stands were arbitrarily classified as clearcut, partially harvested, or no management to account for our limited ability to discern time since harvests beyond this range. Site productivity was ordinally classified from 1 (highest productivity) to 5 (lowest productivity). Classification was based on decision tree analysis using the following established indicators for Maine: herbaceous cover, overstory species composition, and soil drainage, texture, and depth (Briggs 1994). Reclassification of values to high (1-2.5), medium (3-3.5), and low (4-5) productivity was later performed to provide a more balanced design and enhance analysis.

## *2.3. Statistical Analysis*

### *2.3.1. Comparison of CWD Methods*

For a given landscape and method, CWD volume per hectare was first estimated at the sample level. CWD volume was calculated for LIS at different transect lengths using Van Wagner's (1968) equation:

$$v_i = \frac{\pi^2}{8 \times L} \sum_{j=1}^{m_i} d_{ij}^{\ 2} \qquad [1]$$

Where $v_i$ = estimated CWD volume ($m^3ha^{-1}$) for sample *i*
L = transect length (m)
$d_{ij}$ = average diameter (cm) of log *j* in sample *i*
$m_i$ = number of logs intersected in sample *i* meeting requirements

This approach assumes that CWD pieces are randomly oriented, cylinders lying horizontal on the forest floor. Large deviations from horizontal are necessary for a significant bias in the estimate (Van Wagner 1968). Error was reduced by restricting CWD to pieces $\leq$ 45° from horizontal and measuring both diameter perpendicular to the long axis of the log and perpendicular to horizontal for tilted pieces. Correction factors for tilt have been proposed (Brown and Roussopoulos 1974); however, the error induced in this assumption was likely minimal and is consistent with FIA protocol. An additional assumption in the estimator is that CWD pieces are on average intersected at their mid-point. CWD orientation was not measured in the field, but visual observation suggested that substantial bias was only present at one site in the managed landscape, which was removed from the analyses. Multiplying the number of tallied "in" logs by the appropriate volume factor—10 $m^3ha^{-1}$ and 20 $m^3ha^{-1}$ for 500 $K_{PDS}$ and 250 $K_{PDS,}$ respectively—provided sample volume estimates for PDS. For both LIS and PDS, the average volume, variance, and standard error for a landscape were calculated using standard statistical approaches for random sampling. Although a common approach, a tendency to overestimate the variance is inherent when applied to a systematic design (Marshall et al. 2000).

Comparisons were made between methods regarding statistical efficiency. Mean volume estimates at each sample were compared using two-tailed, one-sample paired Student's t-tests. Mean volume estimates by method were analyzed using Welch's two-sample t-tests assuming unequal variance. Equality of variance was assessed using Bartlett's test in R statistical environment. Potential systematic errors in PDS volume calculations between users were also explored using Wilcoxon rank sum tests with correction for continuity in R. The coefficient of variation (CV) for each transect length and landscape was used to compare the effects of increasing transect length on precision.

For the two methods, multiple linear regression was used to determine CWD density (no. of pieces measured) and user effects on sampling effort. Two-tailed, one-sample Student's t-tests assuming equal variance were used to compare the sampling effort at each sample. Overall difference in the mean sampling time between methods was analyzed using a Welch's two-sample t-test assuming unequal variance. To evaluate the cost-effectiveness of the two methods, relative efficiency (E) was calculated as:

$$E = \frac{t_1 * s_{X1}^2}{t_2 * s_{X2}^2} \qquad [2]$$

Where $t_1$ = mean sampling time for 500 $K_{PDS}$
$s_{X1}^2$ = sampling variance for 500 $K_{PDS}$ volume estimate
$t_2$ = mean sampling time for 100 m LIS
$s_{X2}^2$ = sampling variance for 100 m LIS volume estimate

Relative efficiency is the time required to achieve any specified confidence limit width using the 500$K_{PDS}$ method, expressed as a fraction of the time required to achieve the same confidence limit width using the 100 meter LIS method (Brissette et al. 2003, Jordan et al. 2004). A relative efficiency greater than 1.0 indicates that the LIS method is more efficient; $E < 1.0$ suggests that PDS is more efficient; and an estimate of approximately 1.0 suggests equivalence. Relative efficiency provides comparison of the methods while recognizing that PDS and LIS both provide estimates of CWD volume at a given point, not a measure of accuracy, and as such, the comparison incorporates the sampling errors of each method.

Monitoring approaches for detecting change in CWD attributes are most efficiently designed by re-sampling permanently established sample points (Marshall et al. 2003). In addition to marking each sample point, the ends of, or additionally locations at set intervals along, transects should be permanently established (Marshall et al. 2003). To develop monitoring recommendations, power analysis for two-tailed, one-sample t-test were performed in R statistical environment. The standard deviation from the different LIS transect lengths and landscapes were used to determine the sample size required on average to detect a given change in CWD volume—given predefined alpha and power levels. Though post-hoc power analysis is not recommended for determining the power of a study, a priori power analysis provides an effective means of comparing the sensitivity of methods for detecting change in mean CWD volume across a landscape. For a specified alpha level and standard deviation, either sample size, delta (true difference in means), or power is solved by specifying the other parameters.

### *2.3.2. Site Effects on CWD volume*

For a given landscape, the site attributes of interest were productivity, species composition, ecological stage, and harvest history. To minimize variance due to sampling methods, analysis of the effects of each factor on CWD volume was performed using the LIS method with the largest sample area: 100 m LIS and 50 m LIS for the managed and old growth landscapes, respectively. Appropriate statistical analysis approaches were chosen to assess the affects of each attribute based on the distribution of volume estimates across factors, examined using exploratory statistics (e.g., boxplots, qq plots, Bartlett’s analysis for homogeneity of variance, and Shapiro-Wilk’s test of normality). Where appropriate, estimates were transformed to enable parametric approaches. Conversely, nonparametric procedures were used where parametric assumptions were violated. Differences between means for factors were detected using the least significant difference (LSD) approach. Though this technique does not control the experiment-wise error rate, it is more sensitive at detecting true differences given that power is preserved. The unbalanced nature of the data and the lack of control/blocking prevented further statistical analyses, and thus, may have limited the power of our analyses.

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### *2.3.3. Comparison of CWD Attributes by Landscape*

Sampling methods were modified between the managed and the old growth landscapes to adequately address project objectives. As previously discussed, more samples were collected in the managed landscape than the old growth in order to capture the higher anticipated spatial variance in CWD volume. For similar reasons, only 50 meter LIS transects were used at all sample points in the old growth landscape. Field crew travel costs were also prohibitively high, necessitating the reduction in sample size (n=50). To minimize sampling affects on the comparison of CWD attributes, the data set from the managed landscape was randomly subset to replicate the sampling approach in the old growth landscape (LIS length and sample size and spacing). Comparisons between landscapes representing different management histories were then performed for mean coarse woody debris volume, and the distribution of this volume across diameter and decay classes.

## 3. Results:

### *3.1. Comparison of CWD Methods*

Across the managed landscape, there was not a significant difference between the average sampling costs required for the two CWD methods, with a mean sampling time of 23.2 minutes for 100-meter LIS and 25.4 minutes per sample for the 500 $K_{PDS}$ method (Welch's $p$ = 0.45). LIS and PDS also exhibited similar time costs at the sample level (p = 0.46, df = 34), and the required sampling time was not user-dependent for either method. However, sampling costs for LIS ($r^2$=0.47) were more strongly related to the number of pieces sampled than for PDS ($r^2$=0.12) (Figure 1). Despite the apparent equivalence in costs, the required time per sample was much more variable for PDS ($s_t$= 14.8 minutes) than for LIS ($s_t$= 7.9 minutes) (Bartlett's $p < 0.001$). The low correlation between sampling cost and the number of pieces sampled using the PDS method was largely due to the extensive search radius required at most sample points. Across stand types, visual obstruction from dense understory brush and/or regeneration prevented initial tallies of "in" logs from the sample point and necessitated the use of a standardized search approach. Determining the point of perpendicularity was rapid for small logs at close distances but doing so for large logs at further distances was problematic. As anticipated, the frequency of logs tallied using the 500$K_{PDS}$ factor decreased with increasing distance from the sample point; however, logs greater than 20 meters from the sample point were not uncommon, with the furthest recorded at approximately 40 meters (Fig. 2). Given the large search radii required at most sample points, often there was not a clear sense of progression or confidence of completion for the user.

Comparing mean volume estimates at each sample, there was not a significant difference between the 250 $K_{PDS}$ factor and all LIS transect lengths. However, the 500$K_{PDS}$ factor significantly underestimated volume compared to LIS transect lengths of 40, 60, 80, and 100 meters, while a significant difference from 20 meter transects was not detected. Generally, PDS appeared to underestimate CWD volume relative to LIS (Table 7). A significant difference across methods was not observed in estimating mean CWD volume for the managed landscape (Table 8, Fig. 2). Although not controlling for environmental factors such as stand type and ecological stage, an overall systematic bias between users in PDS volume estimates for both factors was not suggested (250$K_{PDS}$: $W$=1251.5, $p$ = 0.83; 500$K_{PDS}$: $W$=1295.5, $p$=0.60, Mann-Whitney tests).

Sample variance was high for both methods at all levels but was reduced by increasing the sample area—increasing LIS transect length or decreasing the $K_{PDS}$ volume factor (increasing inclusion probability) (Table 8). Overall, PDS performed poorly, capturing variance (CV) only slightly better than 20 meter LIS transects. Although the methods exacted similar sampling costs at the sample and landscape levels, disparity between the approaches was best discerned by the relative efficiency, where PDS (500 $K_{PDS}$) was substantially less cost-effective than LIS (100m) ($E$ = 1.69).

For the LIS method, similar trends were observed with increasing transect length in the two landscapes: sample variance decreased with increasing transect length (Table 9). The rate of decrease in CV was greatest across short transect lengths in both sites—10m-30m and 10m-20m in the managed and old growth landscapes, respectively (Fig. 4). For each respective transect length, the CV was lower for the old growth than the managed landscape (Fig. 4). Increasing transect length decreased CV more rapidly in the old growth than in the managed landscape (Figure 4). The relative statistical efficiency gained by increasing LIS transect length was marginal between 80m to 100m in the managed landscape; however, CV continued to decline with increasing transect length to 50 meters in the old growth (Fig. 4). Increasing the transect length further decreased the range of volume estimates and reduced the number of 0 $m^3ha^{-1}$ estimates—which were not observed with transects 40 meters or greater in the managed site and 20 meters or greater in the old growth site (Tables 8 and 9).

Based on the observed standard deviations by LIS sample area, power analysis revealed substantial tradeoffs between sample area, sample effort, and sensitivity to change for CWD volume in a given landscape (Fig. 5 and 6). The minimum sample size required on average to detect a specified change in the mean CWD volume can be reduced by either decreasing the probability of failing to reject a false null hypothesis (power) or increasing the probability of falsely rejecting the null hypothesis when it is indeed true (alpha). The statistical constraints of an inventory have a substantial impact on the minimal required sample effort for each landscape. An important trend is that selection of the appropriate LIS transect length largely depends on the true difference in mean CWD volume that a land manager desires to detect at and with what precision. When small changes in CWD volume must be detected, efficiencies are gained by using longer transect lengths. In such scenarios, 20 meter transects appear impractical in the managed landscape, as do 10 meter transects in both landscapes. However, the difference in the required sample size between longer and shorter transect lengths becomes less apparent as restrictions are relaxed as to how large of a change in CWD volume must be detected. Though these trends hold in the old growth landscape, it is further apparent that detecting changes in CWD volume with high statistical power in such forests will require substantially more effort than in the managed landscape.

### *3.2. Effects of Site Attributes on CWD Volume*

Examining site attribute effects on CWD volume, our study generally failed to detect a significant and consistent pattern across attributes and/or landscapes. One-way ANOVA analysis of site productivity effects in the managed landscape were not significant ($F= 1.83$, $p = 0.17$). In the old growth landscape, however, there was a significant difference in the median CWD volume across productivity classes (Kruskal-Wallis rank sum test $H = 14.76$, $p < 0.001$). Pair-wise comparisons using Wilcoxon rank sum tests did not indicate a significant difference in median CWD volume between medium and high productivity sites ($W$=127, $p$=0.61); although, low productivity sites were characterized by a significantly higher median volume of CWD than medium ($W$=261, $p$<0.001) and high ($W$=194, $p$=0.003) productivity sites. A significant difference in the mean CWD volume for northern hardwood (*Mean* ± *SE:* 52.61±4.55 $m^3$/ha) and spruce-fir (45.43±3.20 $m^3$/ha) forests was not observed in the managed landscape (Welch's two sample t-test $p = 0.20$, $df = 93.67$). It was assumed that stand type differences would be more apparent in the old growth landscape, where the confounding effects of management were removed, yet this assumption was not met (Student's two sample t-test $p$=0.211, $df$=41). As with productivity and forest type, the median CWD volume was not significantly different across ecological stages in the managed landscape ($H$=0.86, $p$=0.65).

The silviculture used in harvesting practices can greatly influence residual CWD volume (Hansen et al. 1991, Franklin et al. 2002). Broadly classifying silvicultural treatments, the number of sample points was approximately balanced between stands partially harvested (n = 33) and clearcut (n = 31) in the last twenty-years. The distribution of volume estimates exhibited dissimilarity by harvest type, with partially harvested stands exhibiting much greater spread (Kolmogorov Smirnov $D = 0.35$, $p = 0.03$). Overall, partially harvested stands

(*Mean±SE:* 59.54±5.75 $m^3$/ha) had a significantly greater mean CWD volume than clearcut stands (48.87± 5.48 $m^3$/ha) (Welch two-sample t-test $p = 0.05$, $df = 62$).

### *3.3. Comparison of CWD Attributes by Landscape*

Confounding variables likely limited our ability to interpret factors correlated with CWD volume within landscapes; however, examining CWD attributes at larger spatial scales more clearly revealed the possible implications of management. With lower than half the mean volume of CWD, the managed landscape (*Mean±SE* 48.31±4.69) had substantially less downed wood than the old growth (112.66±8.13 $m^3$/ha) (Welch's two sample $p < 0.001$, $df$=78.38). As previously noted, the spatial distribution of CWD volume was much more variable in the managed landscape (CV = 68%) than in the old growth (CV = 51%). The distribution of this volume across size-classes differed between the two landscapes (Fig. 8). The mean volume of CWD in the two smaller size classes was greater for the old growth (both $p<0.001$). Although, the managed landscape had a greater proportion of its volume in the smallest size class (8-20 cm), the old growth site had a greater proportion of CWD volume in 20-40 cm logs. There was not an apparent difference in the volume of CWD in 40-60 cm logs ($p = 0.28$). Logs over 60 cm made up a greater proportion of CWD volume in the old growth, but logs over 50 cm were not observed in the managed landscape. The distribution of CWD volume by decay class was suggested similar trends between the landscapes (Figure 9). More CWD was in lower decay stages (1-2) in the managed landscape than in the old growth. Generally, CWD in later decay stages was rare in both systems.

## 4. Discussion:

### *4.1. Monitoring Recommendations for CWD in Northeastern Forests*

In selecting the appropriate methods for structuring large-scale forest inventory and monitoring approaches for CWD, multiple factors should be addressed—many of which are project specific (e.g., budgetary constraints). Probably universal is the need to maximize the statistical efficiency attained for a given cost by selecting the appropriate sampling method, sampling area (ie. line length, $K_{PDS}$ factor), and sample size, all of which invoke tradeoffs. Various studies have examined costs (e.g., Hazard and Pickford 1983) and cost-effectiveness of LIS and alternative CWD sampling techniques (Bailey 1970, Howard and Ward 1972, Martin 1976, Delisle et al. 1988, Ståhl and Lamas 1998, Nemec and Davis 2002, Bebber and Thomas 2003, Brissette et al. 2003, Jordan et al. 2004). However, these comparisons are confined to the stand level, and to our knowledge, none review the cost-effectiveness of PDS and LIS for large-scale inventories and through field based assessment. Williams and Gove (2003) propose that PDS should be the most cost-effective of the methods, requiring one-half to one-sixth the time to achieve equivalent precision with LIS, citing preliminary field trials in the northeastern, U.S. Supporting this claim, field studies using Point Relascope Sampling (PRS)—a complementary plot-less approach having CWD selection probability proportional to length squared—indicated that variable radius sampling approaches exact less time cost and are more cost-effective than LIS (Brissette et al. 2003, Jordan et al. 2004).

Many of these comparisons are invalidated by unrealistic assumptions not met in our study nor likely to be met in managed landscapes in the Northeast. Brissette et al. (2003) assumed that the number of CWD pieces sampled for PRS and LIS was directly and equivalently related to sampling time and further used a hybrid sampling approach with four 20-m LIS transects arranged in a cross. Jordan et al. (2004) implemented a single LIS transect of 40.25 meters with random orientation—an inefficient approach warranting caution (Hazard and Pickford 1986). More so, simulation studies by Williams and Gove (2003) and Bebber and Thomas (2003) standardized sample effort across methods by equalizing the number of CWD pieces sampled—an assumption lacking merit in field applications. Caution must be used in comparing our results with such studies where different methods and effort (e.g., sample area, spacing, arrangement, CWD size-restrictions) were evaluated at higher spatial resolution (within stands vs. across stands) and in different geographic regions with varying management histories. When sighting conditions are poor and where a large search radius is required, a high potential for non-detection bias has been recognized with search-based approaches (Ringvall and Ståhl 1999, Bebber and Thomas 2003, Williams and Gove 2003, Jordan et al. 2004). In the managed landscape, site limitations due to dense understory vegetation, high stocking levels, and/or large volumes of downed wood across a range of size classes imposed greater sampling costs for PDS than expected.

With large-scale inventories, cost evaluation must extend beyond sampling time. For instance, the increased discrepancy between LIS and PDS volume estimates with increasing PDS factor (theoretical search radius) may have been due to a consistent non-selection bias across users. The absence of significant differences in the volume estimates and sample costs for both methods according to user, however, suggests that such systematic biases were unlikely. Theoretically, PDS demands much lower sampling costs because only borderline logs must be measured. Under the field conditions observed in our study, such assumptions were invalid. Rarely were logs easily distinguished as “in” due to the previously mentioned constraints. The lack of a clear sense of progression and survey completion with PDS may result in decreased crew morale and enhanced fatigue, propagating further user errors. Surveys based solely on ocular estimation of “in” logs and measurement of borderline logs with PDS may introduce significant user biases—a non-issue in our study given the individual measurement of each CWD piece. Although surveyor bias may also occur with the LIS method, systematic error is atypical, despite some random measurement error, due to the more restricted protocol (Ringvall and Ståhl 1999). Under the field conditions experienced in our study, LIS provided a clearer sense of progression and confidence in the survey method. LIS appeared more robust to measurement error and simpler to understand and perform. Though beyond the scope of this study, re-measurement of a subset of samples by each user using the same method would have better revealed potential surveyor bias. Large-scale inventories should recognize and account for surveyor based measurement errors.

The adaptability of LIS to meet specific land management needs further supports the selection of this method. Whereas one-factor of PDS may only be used to estimate volume and may not be extended to other CWD attributes, small adjustments to LIS sampling protocol, such as estimating piece length, allow calculation of total and average CWD length, density, surface area, projected area, diameter, and biomass (Marshall 2000, Marshall et al. 2003). Overall, PDS was the least cost-effective sampling approach. From our analysis, it cannot be recommended over LIS for large scale surveys of managed forests in the northeast, implementing a similar sampling design and field equipment as in this study.

In using LIS for large scale inventories, land managers must determine an appropriate transect length to capture the spatial variance of CWD. Previous studies suggest that LIS requires substantial effort (total line length) to achieve high precision (Pickford and Hazard 1978); however, the sampling effort required differs vastly based on the characteristics of CWD in the region and the statistical constraints of the inventory. Site specific factors that influence the efficiency of different transect lengths include the spatial distribution, frequency, total volume, size class distribution, and shape of CWD (Warren and Olsen 1964, De Vries 1973, Pickford and Hazard 1978, Marshall 2002, Nemec and Davis 2002, Woldendorp 2004). Accordingly, shorter transect lengths and fewer samples are required where the spatial distribution of CWD is more homogeneous and found at higher frequencies, greater volumes, across fewer size-classes, and exhibits less taper.

Precision of volume estimates for a landscape may be increased either by increasing the transect length—thus decreasing the standard deviation—or expanding the sample size to decrease the standard error of the mean. This relationship breaks down at its extremes (Pickford and Hazard 1978, Woldendorp 2004), and consequently, extremely short transects ($\leq$ 10 m) are not recommended. Other studies have also observed the greatest decrease in CV with increasing the length of shorter transects and a likewise reduction in the range of CWD volume estimates (Woldendorp 2004). The lower CV for a given transect length in the old growth landscape was attributed to higher CWD volumes and the decreased spatial heterogeneity of this volume. Given the seemingly asymptotic trend in CV with transect lengths greater than 80 meters in the managed landscape, this transect length is likely sufficient to capture the spatial variance of CWD. With no such trend observed in the old growth landscape, transect lengths longer than 50 meters may be more statistically efficient where there are comparable volumes of CWD.

The decision of an appropriate transect length is project specific and largely directed by budgetary constraints. Costs will dictate variables such as the number of samples that can be collected in a given amount of time using a field crew of a certain size. Given the lack of financial return from downed CWD, the most cost-effective sampling strategy for CWD volume would be to integrate supplemental protocol into existing commercial inventories for standing trees (e.g., Waddell 2001, Marshall et al. 2004). Most large-scale inventories, as such, use a systematic random sampling design without stratification similar to that assumed in our project. The extreme spatial variability of CWD requires a substantial sampling effort to monitor changes in CWD volume with high precision. As such, land managers in the northeast need an idea of the level monitoring performance they can anticipate for an allotted sampling effort. Specifically, tradeoffs exist between the sensitivity of an approach (LIS length and sample size) in detecting an actual change in CWD volume (power) versus the probability of indicating a significant change when none is present (alpha). Aware of these tradeoffs upfront, land managers may consult the appropriate graphs for the landscape most similar to their management scenario and determine the minimum effort required on average to detect a specific change in CWD volume. Though these calculations provide a generalized estimate of the sample effort required, they elucidate valuable practicalities regarding the statistical efficiency of the different LIS approaches for monitoring changes in CWD volume across a landscape. Where highly-sensitive methods are required to detect small changes in mean CWD volume, efficiencies are gained by using longer transects. Conversely, where detection of only larger changes in mean CWD volume is necessary, the efficiency gained by using longer transects diminishes.

### *4.2. Effects of Site Attributes on CWD Volume and Management Implications*

Reduction in variance and an increase in the power of an inventory to detect change is usually attained through stratification by factors such as productivity, forest type, harvest history, and ecological stage. However, consistent relationships to allow such stratification were not observed in the managed and old growth landscapes. The volume of CWD is a function of complex input and output process interactions at various spatial and temporal scales (Harmon et al. 1986), which make such stratification difficult. For instance, site productivity affects species composition, growth rates and size potential, disturbance processes, stand stocking levels, and the rate at which stands enter stem exclusion—all of which interactively influence CWD input and output rates (Harmon et al. 1986, Sturtevant et al. 1997). Several studies have demonstrated greater tree mortality, CWD volume, and frequency of large downed logs with increasing site productivity (Volk and Fahey 1994, Sturtevant et al. 1997, Spetich et al. 1999). Conversely, a consistent trend between productivity and CWD volume was not detected in our study, even when controlling for other factors. In the old-growth stand, however, CWD volume was greater in low productivity sites. As classified, low productivity sites were characterized by very poorly drained soils, which may result in increased windthrow mortality—a dominant natural disturbance process in these forests (McCune et al. 1988, Seymour et al. 2002, Lorimer and White 2003). Extending residence time, slow decay due to local abiotic conditions and the cooler regional climate likely facilitates CWD accumulation. In the managed site, complex interactions between factors, both recorded and not, likely concealed productivity effects. Alternatively, the site productivity classification system used may have been insensitive to significant differences in productivity, or productivity may influence CWD input at larger geographic scales where differences are greater (Spetich et al. 1999). Similar confounding factors may have obscured the effects of forest type. Spruce-fir forests typically exhibit higher CWD volumes than northern hardwood stands, with the relationship generally maintained for coniferous and deciduous forest types within the same region due to faster decay rates in the latter forests (Harmon et al. 1986); however, no such trend was observed in either landscape.

Space-for-time substitution in chronosequence studies has provided an abundance of information on how CWD volume changes with stand development. Across forest types and following both natural and harvest disturbance, a general “U-shaped” temporal pattern has been observed for CWD volume with stand age (Bormann and Likens 1979, Gore and Patterson 1986, Spies and Cline 1988, McCarthy and Bailey 1994, Petranka et al. 1994, Stevens 1997, Clark et al. 1998, Crooks et al. 1998). Following initial disturbance, stands are characterized by high residual CWD volumes which then decrease overtime. At the stem exclusion stage, CWD volume theoretically reaches a minimum with depletion of the residual but then begins to increase through inputs from the current stand. Contribution from the resident stand continues through competitive exclusion and small-scale disturbance induced mortality, reaching a maximum at the multi-aged stage. Surprisingly, no such trend was observed between CWD volume and ecological stage in the managed landscape, with forests exhibiting similar volumes across ages. However, the availability of CWD during early stages of stand development is largely dependent upon stand history (Spies and Cline 1988). Fraver et al. (2002) suggests that the “U-shaped” temporal trend may not be applicable to selectively harvested stands in the Acadian forests of Northern Maine due to the complex interaction of natural, small-scale disturbances and repeat harvest entries. Numerous studies have also failed to recognize the common “U-shaped” temporal pattern (Carleton and Arnup 1993, Goebel and Hix 1996, Busing 1998, Hardt and Swank 1997, Lee et al. 1997, Flemming and Freedman 1998). Although chronosequence studies may reveal general trends, controlled studies over longer time scales where CWD inputs and outputs are more closely followed (ie., pre-harvest and post-harvest measurements) would better distinguish the effects of harvesting on CWD volume in our study site.

### *4.3. Comparison of CWD Attributes Between the Managed and Old Growth Landscape*

More generally comparing the two landscapes, substantial differences were apparent in CWD volume and the distribution of this volume across size and decay classes, bringing into question the effects of forest management. Although our study did not examine paired chronosequences of forest development for managed and natural stands, many such studies have suggested that managed forests exhibit lower accumulation of CWD across all stages of stand development (Flemming and Freedman 1998, Duvall and Grisgal 1998, Goodburn and Lorimer 1998). Particularly strong disparities occur in the stand initiation and demographic transition stages (Duvall and Grisgal 1989). CWD inputs from harvests are often much lower than natural disturbances (Sippola et al. 1998), and management activities such as pre-commercial and partial harvest often preclude natural stem mortality from stem exclusion and thus CWD accumulation (Flemming and Freedman 1998). Harvest operations also differ in the amount of residual CWD due to decay rates and standing tree retention: CWD decays much more rapidly after clearcutting and partial harvests leave standing live and damaged trees to contribute to CWD inputs (Bormann and Likens 1979, Hansen 1991). These factors most likely drive the difference in CWD volume observed between these practices in the managed landscape.

The exact difference in CWD volume between managed and old growth stands varies largely dependent on geographic region and forest type: in old growth sites in Indiana, Illinois, Iowa, and Missouri, Spetich et al. (1999) found three-times the volume of downed CWD as in second growth sites; Shifley et al. (1997) observed twice the volume of CWD in old growth than 70- and 90- years old second growth stands in Missouri; and McGee et al. (1999) recorded nearly twice the volume of downed CWD in old growth than in mature-managed and partially harvested northern hardwood stands. Our results correspond closely with those of McGee et al. (1999) in that the mean volume of CWD in the old growth landscape was more than twice that in the managed. Further, the mean volume of CWD in the old-growth landscape approximated McGee et al.'s (1999) estimated average of 110 $m^3$/ha for old growth, northern hardwood stands.

In addition to total CWD volume, forest management further effects the distribution of this volume across diameter classes, with a reduction in the number of large-diameter logs and large logs in advanced decay stages (Andersson and Hytteborn 1991, Hansen et al. 1991, Guby and Dobbertin 1996, Freedman et al. 1996, Fridman and Walheim 2000). Although rare in both sites, large logs (>50 cm) were absent from the managed landscape. Whereas Gore and Patterson (1986) did not observe downed CWD > 38 cm in uneven-aged managed northern hardwood stands of New Hampshire; the managed landscape, the managed landscape had nearly the same volume of logs 40-60 cm as in the old growth. Retention of large trees and snags is essential for biodiversity and ensuring their future contribution to the CWD pool (Hansen et al. 1991). The paucity of large logs (>60 cm) in the managed landscape suggests that current retention of such structural features may be insufficient to emulate old-growth CWD conditions. However, the high proportion of volume in 40-60 cm logs in the managed landscape indicates that current harvesting practices are retaining large logs that contribute to future stands. The implications for biodiversity will be largely affected by species assemblages and threshold values. Further research is warranted on the topic in the Northeast.

Whereas natural disturbances contribute dead wood across size-classes, harvests result primarily in an input of small diameter CWD (Fraver et al. 2002). Supporting this trend, the managed landscape had a larger proportion of CWD volume in smaller diameter classes (8-20 cm) compared; however, the old growth landscape had a greater proportion of volume in intermediately sized (20-40cm) down wood. Shifley et al. (1997) similarly observed a lower proportion of volume in logs over 20 cm in managed than in old growth stands. The distribution of CWD volume across diameter classes affects the ecological functions that CWD sustains and thus forest biodiversity. Larger logs typically exhibit greater structural diversity, such as more frequent and larger cavities which provide microsites used by a diversity of animals for denning and shelter (Harmon et al. 1986). Some small mammal species preferentially inhabit logs of different diameters (Hayes and Cross 1987), and many bryophyte speices are large-log specialists. The greater distribution of CWD volume across size classes in the old growth stand likely provides a diversity of microsites for species; whereas, conversely the declining distribution of CWD volume with log size in the managed landscape may not provide adequate structural diversity for many wood-dependent species.

Another factor affecting the functional value of dead wood for forest biodiversity is the distribution of CWD volume across decay classes. As dead wood structurally changes through decay, so does its functional role as habitat for different species. A successional transition of bryophyte (Andersson and Hytteborn 1991; Rambo and Muir 1998), fungi, and invertebrate communities has been observed or suggested with wood decay states (Crites and Dale 1998). CWD decay state further affects which vertebrate species use logs and in what manner (Thomas 1979). Therefore, the greatest diversity is supported through distribution of CWD volume across decay classes. As such, the higher proportion of log volume in early decay stages may diminish the ecological value of CWD in the managed landscape relative to the old growth site. The larger proportion of volume in the most decayed state for the managed landscape was likely due to the correlation between size and decay—smaller logs in the managed landscape decay more rapidly. Various other factors, such as how decay is distributed across size classes, species, forest types, and forest connectivity, influence the functional role of CWD. Therefore, these attributes provide a generalized perspective of how landscapes may differ due to management practices.

### *4.4. Considerations in Applying and Extending Project Results*

Although these results provide general recommendations of how land managers might effectively monitor changes in CWD volume in northeastern forests and furthermore reveal insights into how CWD attributes vary between a managed and old growth landscape, several caveats must be acknowledged. Concerning the LIS method, orientation bias, in which logs are not randomly oriented, has been recognized as inducing significant bias in volume estimates (Warren and Olsen 1964, van Wagner 1968, De Vries 1979, Hazard and Pickford 1986). Consequently, various arrangements of transects have been used and suggested to be more efficient—such as running two lines in random directions (van Wagner 1968, Howard and Ward 1972), three or five transects radiating from a central point (e.g., Waddell 2002, Nemec and Davis 2002), and an equilateral triangle (e.g., Delisle et al. 1988). Despite their wide use, the bias and variance properties of such hybrid methods have only recently been examined (Affleck et al. 2005, Barbesi 2007). When CWD pieces are randomly oriented, there is no advantage in using one arrangement over the other (Bell et al. 1996, Nemec and Davis 2002, Woldendorp et al. 2004). Furthermore, such approaches may exact greater sampling costs, and a single line would, in most cases, better capture the spatial variance of CWD (Marshall 2002). Though significant departures from random orientation were not observed in the field, non-random orientation may be difficult to detect. It must then be acknowledged that the fixed orientation of LIS transects in our study may have induced increased variance in volume estimates, not negating the methods comparisons but with potential implications for the power analysis.

The LIS approach used assumes that logs are intersected at their midpoint on average. This assumption may have introduced inaccuracy in our comparison of volume distribution across size-classes. Though beyond the scope of our study given that land mangers would generally only be interested in CWD volume, more accurate estimates could have been attained by measuring additional variables, such as piece length, midpoint, small and large end diameters. The analyses presented are limited to static observations and must be interpreted as such. General trends are presented regarding the distribution of volume across size- and decay-classes due to the inherent variability in these attributes and the difficulty of attaining precise estimates (Shifley et al. 1994). CWD volume is affected by a complex of factors that impact temporal and spatial patterns through input and output processes. Though both sites exhibited similar forest types and abiotic conditions, with management history the most prominent difference, the limited temporal scale of the study and the inability to account, nigh control for, all variables must be recognized. Further research is needed surrounding the biotic and abiotic interactions—and the relavent spatial scales of these processes—that affect the biodiversity support function of CWD in the Northeast.

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**Table 1.** Classification system for CWD decay from Hunter (1990), as adapted by Maser et al. 1979 and Thomas et al. 1979 from Fogel et al. 1973.

| Decay Classes | Key Characteristics |
|---|---|
| 1 | Bark firmly attached, exposed wood has fresh color (not weathered), wood beneath bark is solid, small twigs and branches intact, log elevated on support point/branches. |
| 2 | Bark flaking, not firmly attached, bare wood has weathered appearance, kicking the log may knock off bark but wood is solid, small twigs mostly absent, larger branches mostly intact, log elevated but may sag slightly. |
| 3 | Bark mostly absent, surface of bare wood will flake off or shred when kicked, log is firm but some areas of the wood are soft when pressed with a foot, large branches mostly absent, log sagging considerably, much of it is on the ground. |
| 4 | Log no longer solid and intact piece, log will crush or break into large pieces when kicked, log shape becoming oval or flattened, wood is very soft when pressed with finger, powder wood may be present, nearly all of log on the ground. |
| 5 | Log oval or flat, enerally powder wood, log very soft, can be easily broken using your fingers, entire log is on the ground. |
| 6 | Decomposed log forms a ridge on forest floor, is uaully fully covered with moss, organic material, seedlings, etc., digging into ridge reveals remnants of powder wood beneath organic matter and soil. |

**Table 2.** Large tree and snag decay classes from Hunter (1990), as adapted by Maser et al. 1979 and Thomas et al. 1979 from Fogel et al. 1973.

| Decay Classes | Key Characteristics |
|---|---|
| 1 | Alive and healthy. |
| 2 | Tree in decline. |
| 3 | Tree dead, bark intect, small twigs and branches intact, wood solid. |
| 4 | Tree dead, bark flaking, small twigs absent, large branches intact, wood solid. |
| 5 | Bark mostly absent, nearly all branches absent, wood still fairly solid. |
| 6 | Wood becoming soft in places, very top of tree has separated from bole, some flaking of the bole will result from kicking tree. |
| 7 | Bole considerably decomposed, mid-portion of the tree has collapsed, kicking bole may result in large chunks falling from bole, wood generally soft. |

**Table 3.** Cover type classification codes based on tree species composition.

| Code | Species Group |
|---|---|
| IH | Intolerant Hardwood (*Prunus* spp., *Alnus* spp., *Betula papyrifera*, *Populus* spp.) |
| TH | Tolerant Hardwood (*Acer* spp., *Quercus* spp., *Fagus grandifolia*, Fraxinus spp., Betula alleghaniensis) |
| S | Softwood (*Abies balsamea*, *Picea* spp., *Pinus* spp., *Tsuga canadensis*, Thuja occidentalis, Larix larcinia) |
| HS | Mixed canopy predominately (50-75%) hardwood |
| SH | Mixed canopy predominately (50-75%) softwood |

**Table 4.** Canopy height classification.

| Height Code | Height Size Class |
|---|---|
| 0 | < 2 meters (0-5 ft.) tall, recent clearcuts or old fields |
| 1 | 2-6 meters (>5-20 ft.) tall, advanced regenerating clearcuts and old fields |
| 2 | 7-12 meters (>20-40 ft.) tall and majority of canopy trees < 11.5 cm (4.5 in.) DBH |
| 3 | 12-19 meters (>40-60 ft.) tall and majority of canopy trees 11.5-24 cm (4.5-9.5 in.) DBH |
| 4 | > 19 m (> 60 ft.) tall and majority of canopy trees > 24 cm (9.5 in.) DBH |

**Table 5.** Canopy closure classification.

| Canopy Code | Canopy Closure |
|---|---|
| A | Closed (> 75% closure) |
| B | Slightly Open (>50-75% closure) |
| C | Moderately Open (>25-50% closure) |
| D | Open (<25% closure) |

**Table 6.** Classification of stand ecological stage adapted from Oliver and Larson (1990).

| Ecological Stage | Description |
|---|---|
| Stand Initiation | Follows major disturbance (fire, complete windthrow, clearcutting, seed-tree cut, etc.) |
| Stem Exclusion | Stage when the canopy is dense enough to keep new saplings from entering the canopy and self-thinning is a dominant ecological process. When canopy trees die, their spaceis filled by adjacent trees. |
| Demographic Transition | When the stand makes a transition from a single cohort of canopy trees to multiple age classes of canopy trees. Canopy trees are large enough that when they die they create gaps which are filled with new seedlings. |
| Multi-Aged | When multiple age-classes of trees are present. Original age-class has disappeared. |

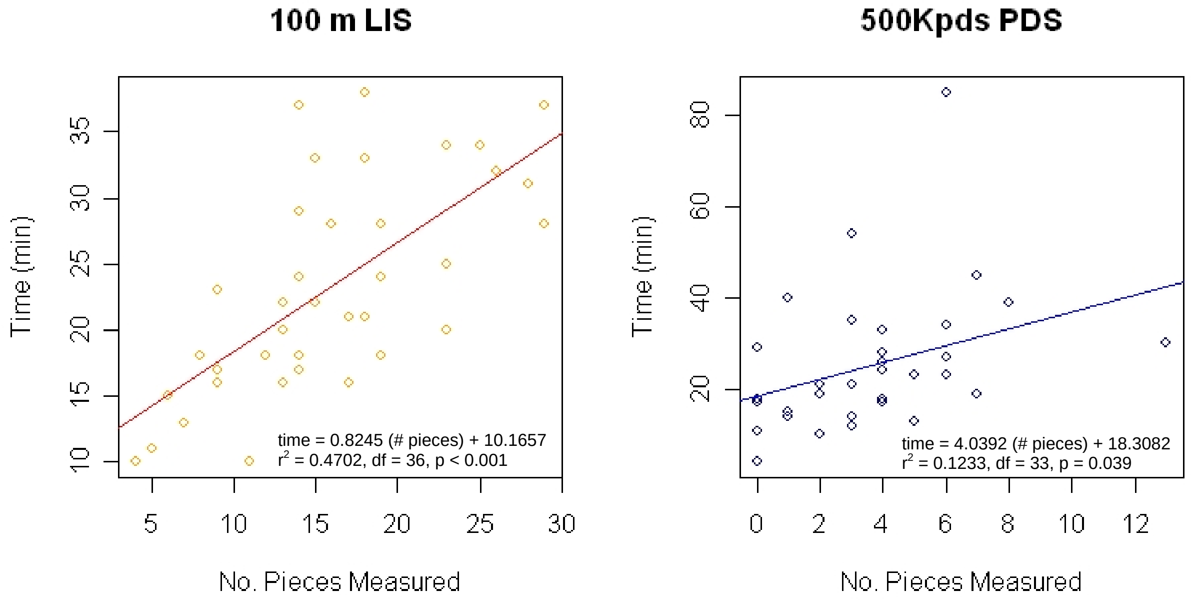

**Figure 1.** Simple linear regression of the effects of the number of CWD pieces measured on the sampling effort required for LIS and PDS.

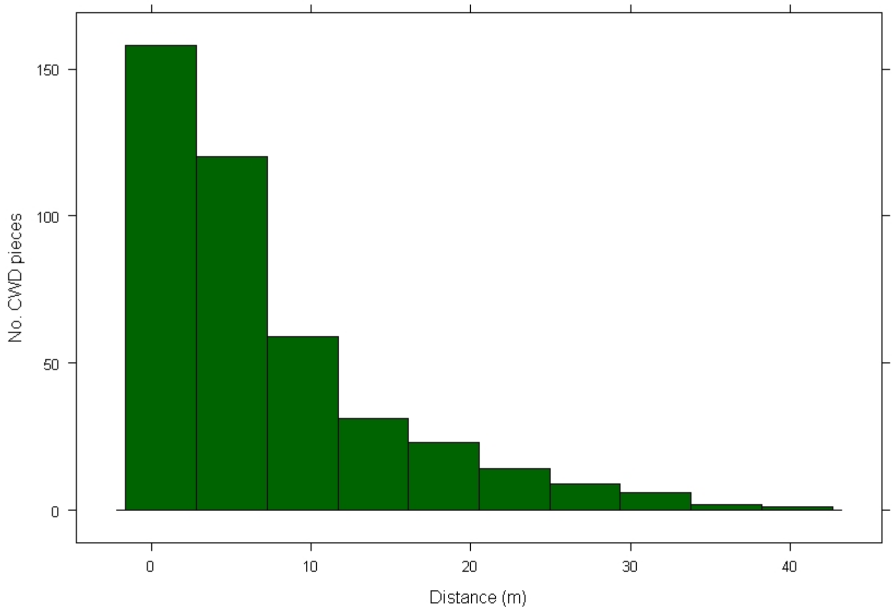

**Figure 2.** Number of CWD pieces measured in relation to their distance using the PDS method (500 $K_{PDS}$ factor) in the managed landscape.

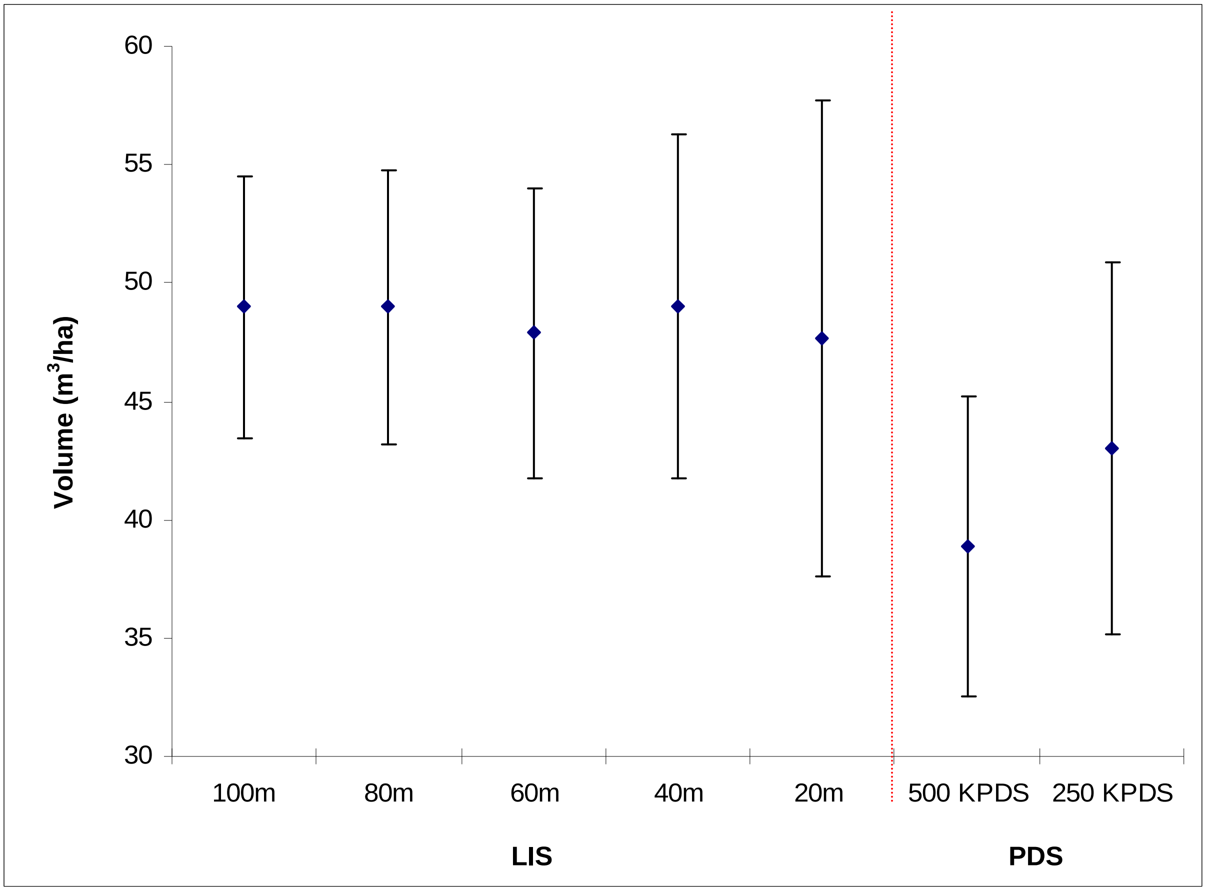

**Figure 3.** Mean CWD volume estimates (m$^3$/ha) with 95% CI by method for the managed landscape.

**Table 7.** Mean difference ($x_{LIS}$-$x_{PDS}$) per sample in CWD volume estimates (m$^3$/ha) for the managed landscape using LIS and PDS with contrasting sample areas (two-sided, one-sample Student's t-tests).

| **PDS Method** | **LIS Method**<br>100m | 80m | 60m | 40m | 20m |
|---|---|---|---|---|---|
| 250 $K_{PDS}$ | 6.00 | 5.99 | 4.89 | 5.59 | 4.66 |
| 500 $K_{PDS}$ | 10.11** | 10.10** | 9.00** | 9.70** | 8.77 |

**p-value < 0.01

**Table 8.** Summary statistics for CWD volume estimates ($m^3/ha$) in the managed landscape using LIS transects of different length and two PDS volume factors (n=107).

| | LIS | | | | | PDS | |
|---|---|---|---|---|---|---|---|
| | **100m** | **80m** | **60m** | **40m** | **20m** | **500K$_{PDS}$** | **250K$_{PDS}$** |
| **Mean** | 48.99 | 48.98 | 47.88 | 49.04 | 47.65 | 38.88 | 42.99 |
| **Minimum** | 2.15 | 2.69 | 1.86 | 1.97 | 0.00 | 0.00 | 0.00 |
| **Maximum** | 122.55 | 138.02 | 138.97 | 189.15 | 285.08 | 170.00 | 220.00 |
| **STDEV** | 28.79 | 30.30 | 31.96 | 38.00 | 52.46 | 32.89 | 41.01 |
| **SE** | 2.78 | 2.93 | 3.09 | 3.67 | 5.07 | 3.18 | 3.96 |
| **CV (%)** | 58.77 | 61.87 | 66.75 | 77.50 | 110.09 | 84.60 | 95.38 |

**Table 9.** Summary statistics for CWD volume estimates ($m^3/ha$) in the old growth landscape using LIS transects of different length (n=50).

| | LIS | | | | |
|---|---|---|---|---|---|
| | **50m** | **40m** | **30m** | **20m** | **10m** |
| **Mean** | 112.66 | 108.24 | 111.22 | 109.06 | 97.94 |
| **Minimum** | 15.97 | 16.54 | 19.72 | 4.46 | 0.00 |
| **Maximum** | 271.27 | 287.59 | 359.77 | 346.65 | 507.48 |
| **STDEV** | 57.46 | 63.71 | 74.14 | 84.15 | 110.01 |
| **SE** | 8.13 | 9.01 | 10.49 | 11.90 | 15.56 |
| **CV (%)** | 51.00 | 58.86 | 66.66 | 77.16 | 112.33 |

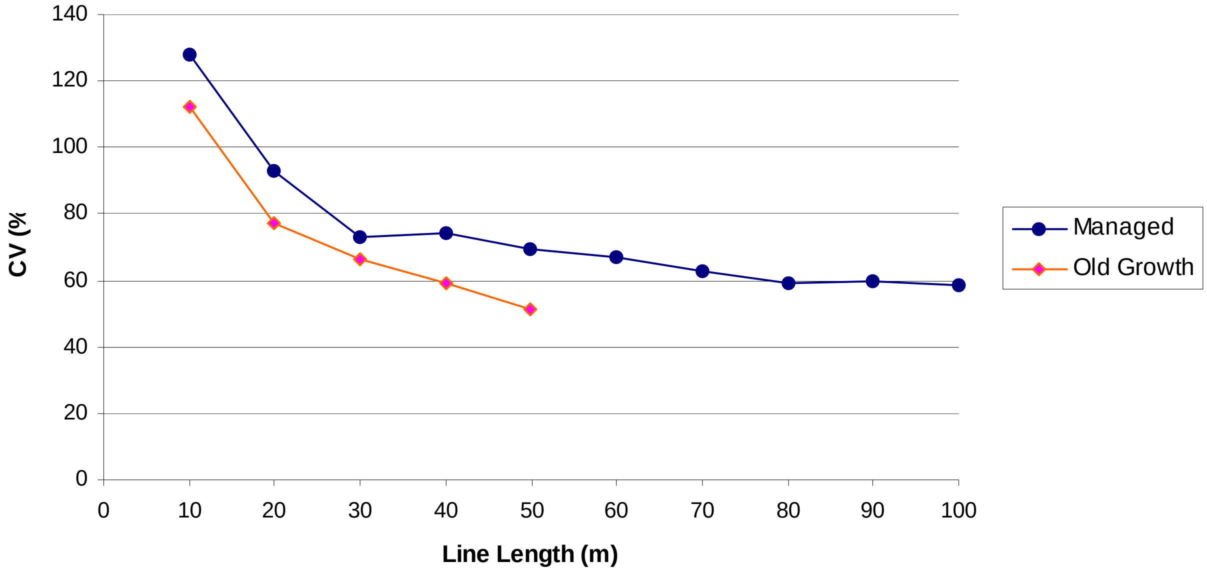

**Figure 4.** Relationship between the coefficient of variation (%) and LIS transect length in the managed (n=107) and old growth (n=50) landscapes.

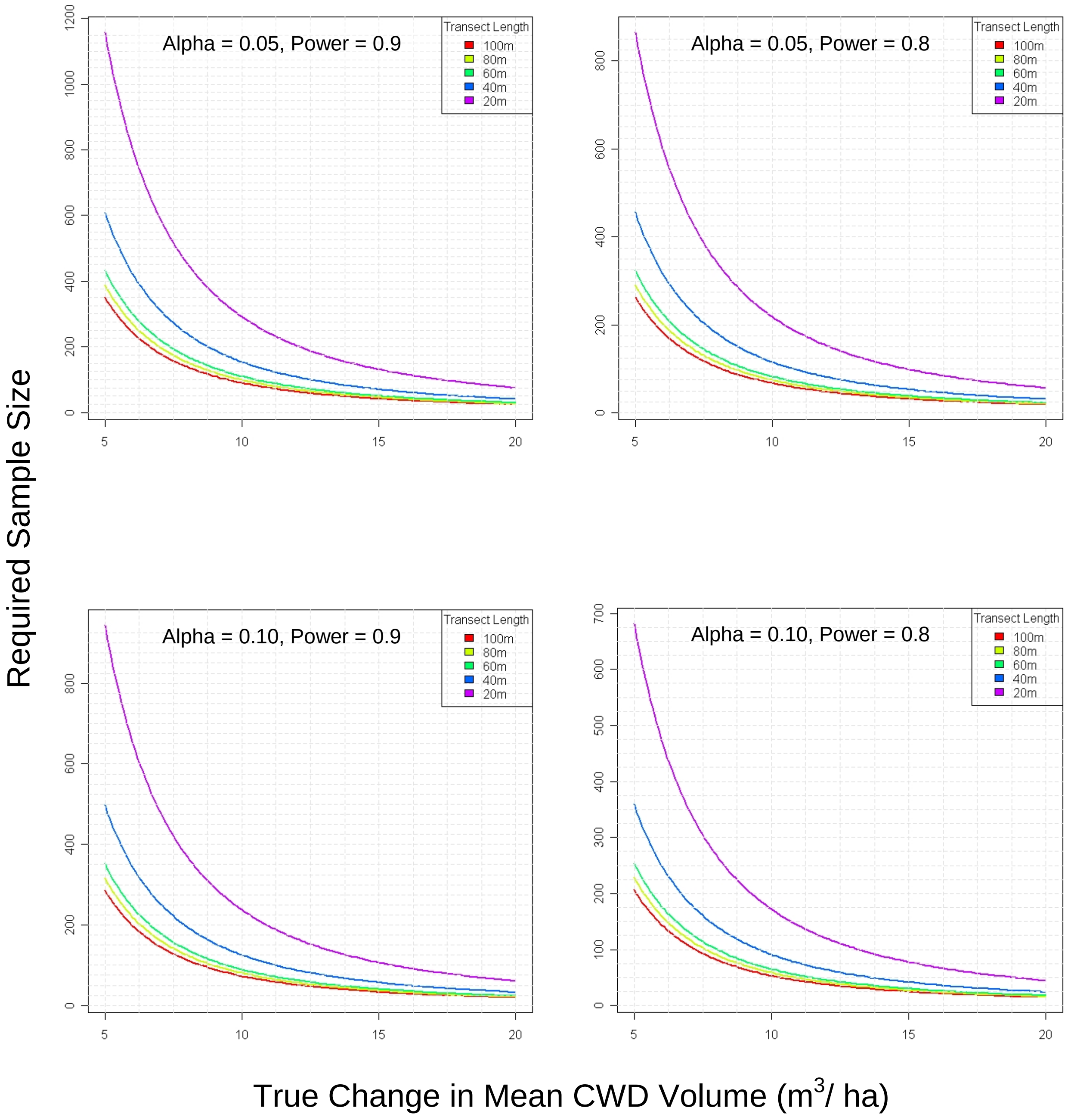

**Figure 5.** Minimum sample size required on average to detect a specified change in mean CWD volume ($m^3$/ha) at a predefined alpha and power level using a specified LIS transect length in the managed landscape.

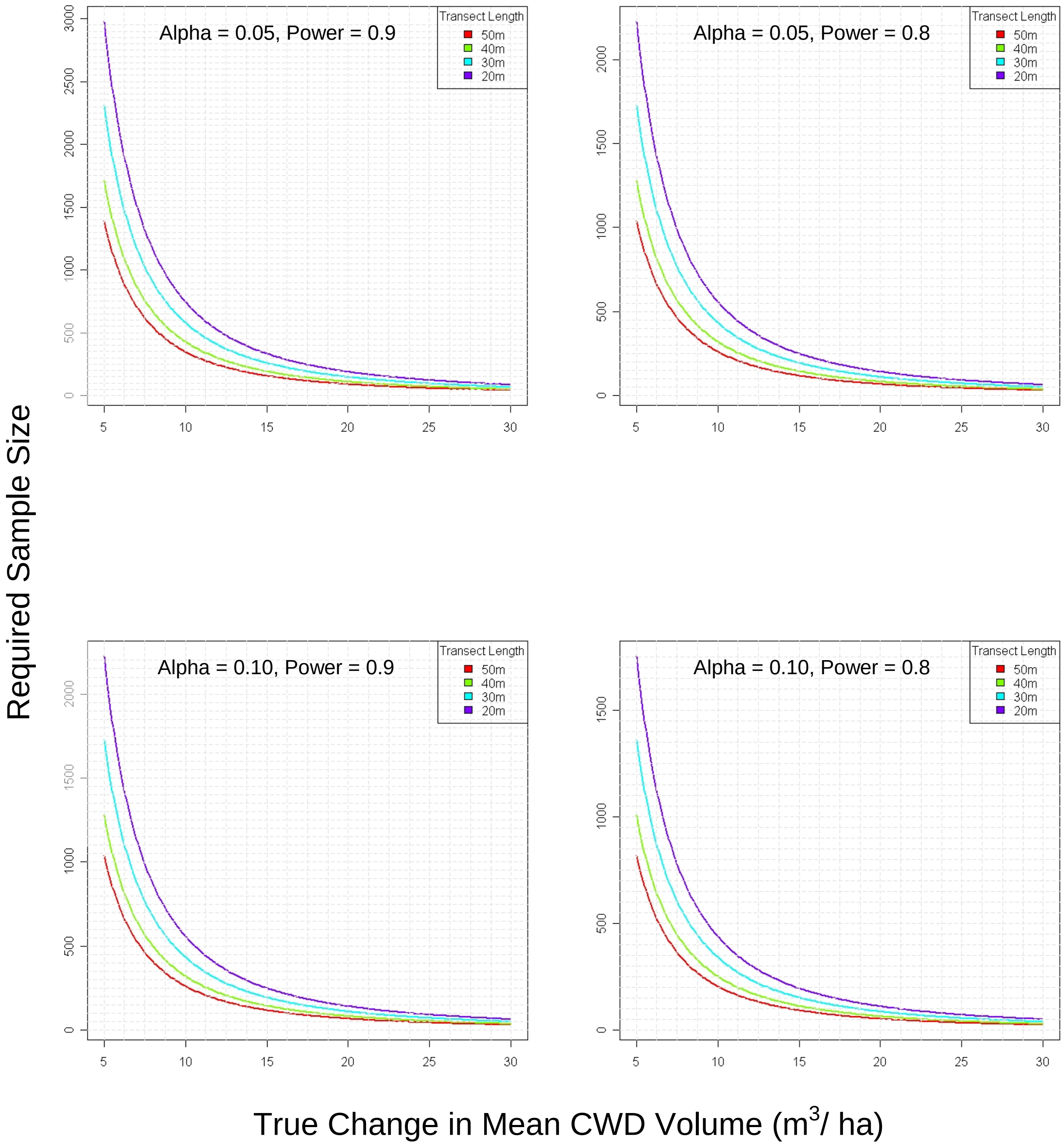

**Figure 6.** Minimum sample size required on average to detect a specified change in mean CWD volume ($m^3$/ha) at a predefined alpha and power level using a specified LIS transect length in the old growth landscape.

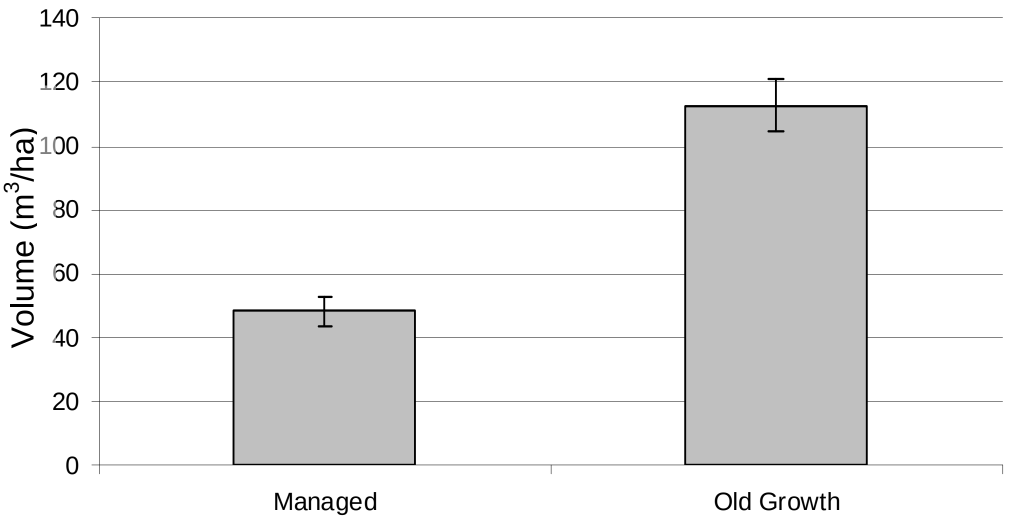

**Figure 7.** Mean (±SE) coarse woody debris volume in the managed and the old growth landscapes.

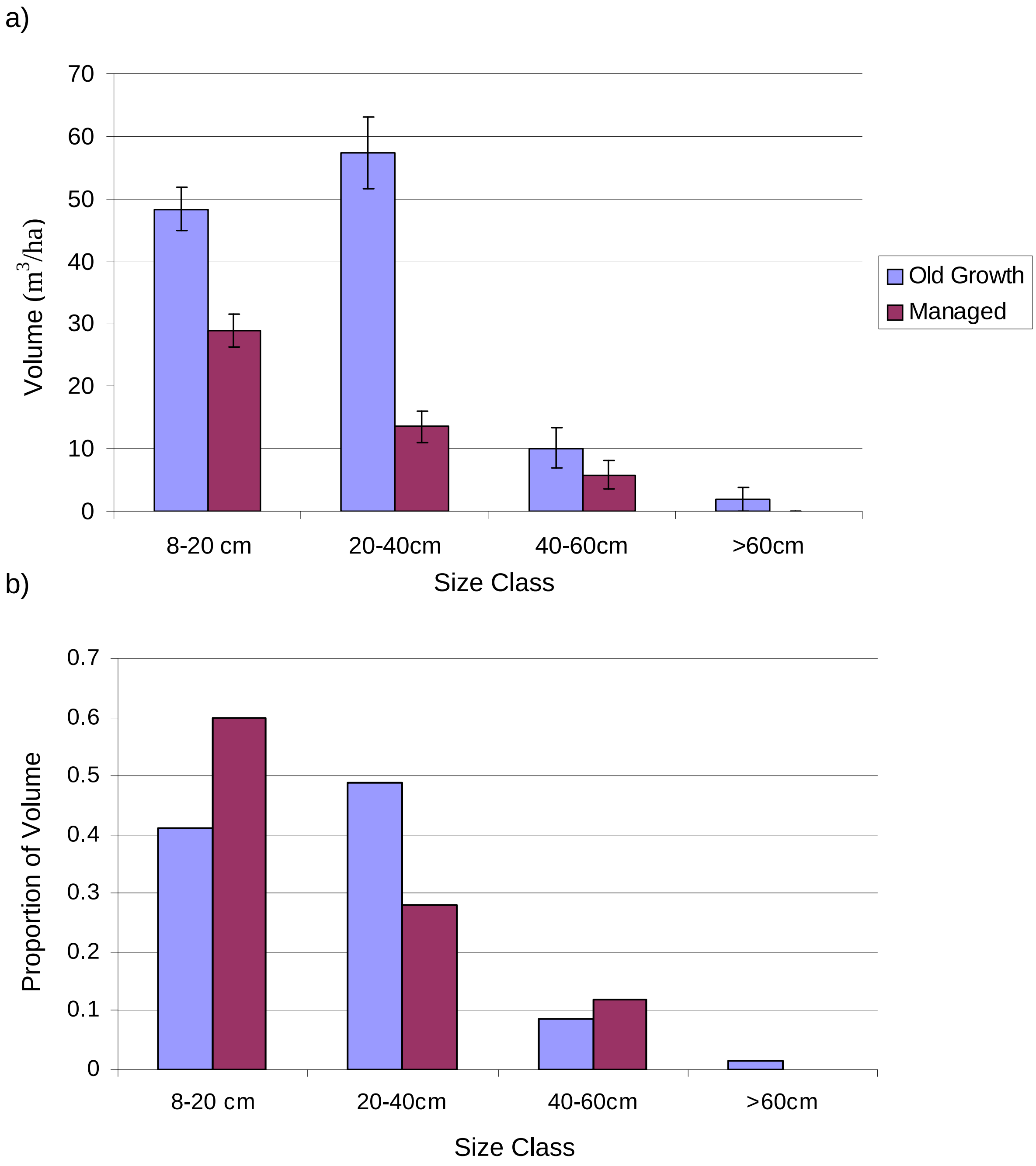

**Figure 8.** Mean (±SE) volume (a) and proportion of volume (b) of CWD across size classes by landscape.

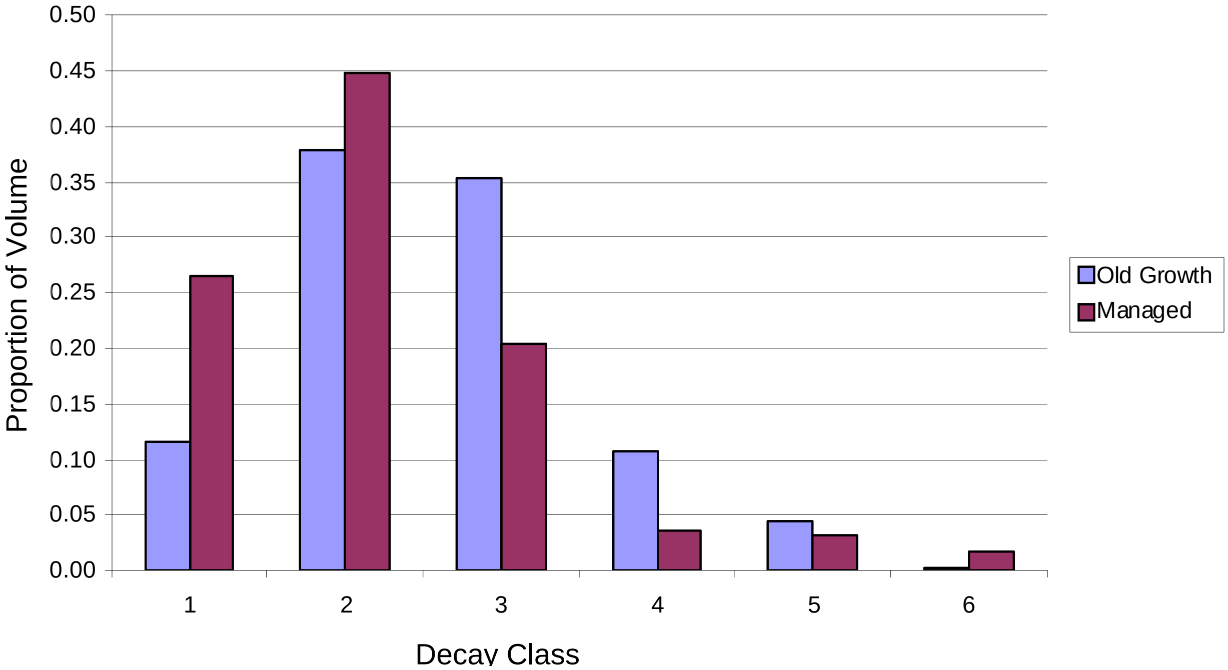

**Figure 9.** Proportion of volume by decay class for the managed and old growth landscapes.