Comparisons of Coarse Woody Debris in Northern Michigan Forests by Sampling Method and Stand Type

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INTRODUCTION

Forest management has increasingly focused on maintaining biodiversity and sustainability. Coarse woody debris (CWD) on the forest floor is a large contributor to biodiversity within Michigan forests. Coarse woody debris influences forest soil nutrient cycling (Fisk et al. 2002, Laiho and Prescott 2004) and provides a suitable seed bed for hemlock regeneration (Ward and McCormick 1982, Goodman and Lancaster 1990, O'Hanlon-Manners and Kotanen 2004). Due to its influence on forest structure at the ground, understory, and overstory levels, CWD is an essential component of mammal, bird, amphibian, arthropod, and microbial habitats (Harmon 1986, Bull et al. 1997, Burris and Haney 2005, Crow et al. 2002). Large-diameter CWD and tip-up mounds created by natural disturbances are a crucial structural component for forest biodiversity and are largely missing from managed landscapes (Goodburn and Lorimer 1998, Tyrell et al. 1998, McGee et al. 1999, Crow et al. 2002).

Measuring levels of CWD is an important step in assessing the sustainability of forest management practices. Several methods of sampling CWD exist, and the Michigan Department of Natural Resources (MDNR) uses one method as part of their forest compartment inventory process (Integrated Forest Monitoring, Assessment, and Prescription [IFMAP] stage two). However, the method used during stage two inventories has not been compared with other sampling methods to determine which protocol provides the most accurate and efficient means of measuring CWD. Some methods have shown different levels of accuracy based on stand type and age and the CWD parameter of interest (Bate et al. 2004). We compared four commonly used methods of measuring CWD to evaluate their utility in future IFMAP stage two inventories.

Although some research has been conducted in northern hardwood forests of the Great Lakes region to examine levels of CWD in old-growth stands (Tyrrell and Crow 1994) and to compare old-growth and managed stands (Goodburn and Lorimer 1998, Hale et al. 1999, McGee et al. 1999), information on CWD remains limited for the region. For example, we found little information on levels of CWD in aspen stands of the Great Lakes region. More study is needed to assess the range of variation of CWD parameters in managed and unmanaged forests of the region, which would aid the evaluation of management practices and decision making with regard to forest and wildlife resources. Hagan and Grove (1999) suggested that to determine how much coarse woody debris is enough in managed forests, several questions need to be answered: 1) What is the natural range of CWD in our forests types? 2) How do managed stands compare with natural regimes of CWD? and 3) Are silvicultural methods diminishing the amounts of CWD over time? To help address these questions, we compared levels of CWD among three forest types in northern Michigan: managed aspen, managed northern hardwood, and unmanaged northern hardwood. We estimated levels of CWD in the three forest types across a range of age classes and management histories.

STUDY AREA

We examined CWD in publicly owned forests of the northern Lower and Upper Peninsulas of Michigan (Figure 1). Study sites were located predominantly on mid- to coarse-textured glacial till, lacustrine sand and gravel, or outwash sand and gravel. We sampled three forest stand types: managed aspen, managed northern hardwood, and unmanaged northern hardwood. We used mesic northern forest element occurrences (EOs) documented by the Michigan Natural Features Inventory (MNFI) for our unmanaged northern hardwood stands. Managed aspen and northern hardwood stands had undergone regular timber management, while unmanaged northern hardwoods showed little or no evidence of cutting within the last 200 yrs

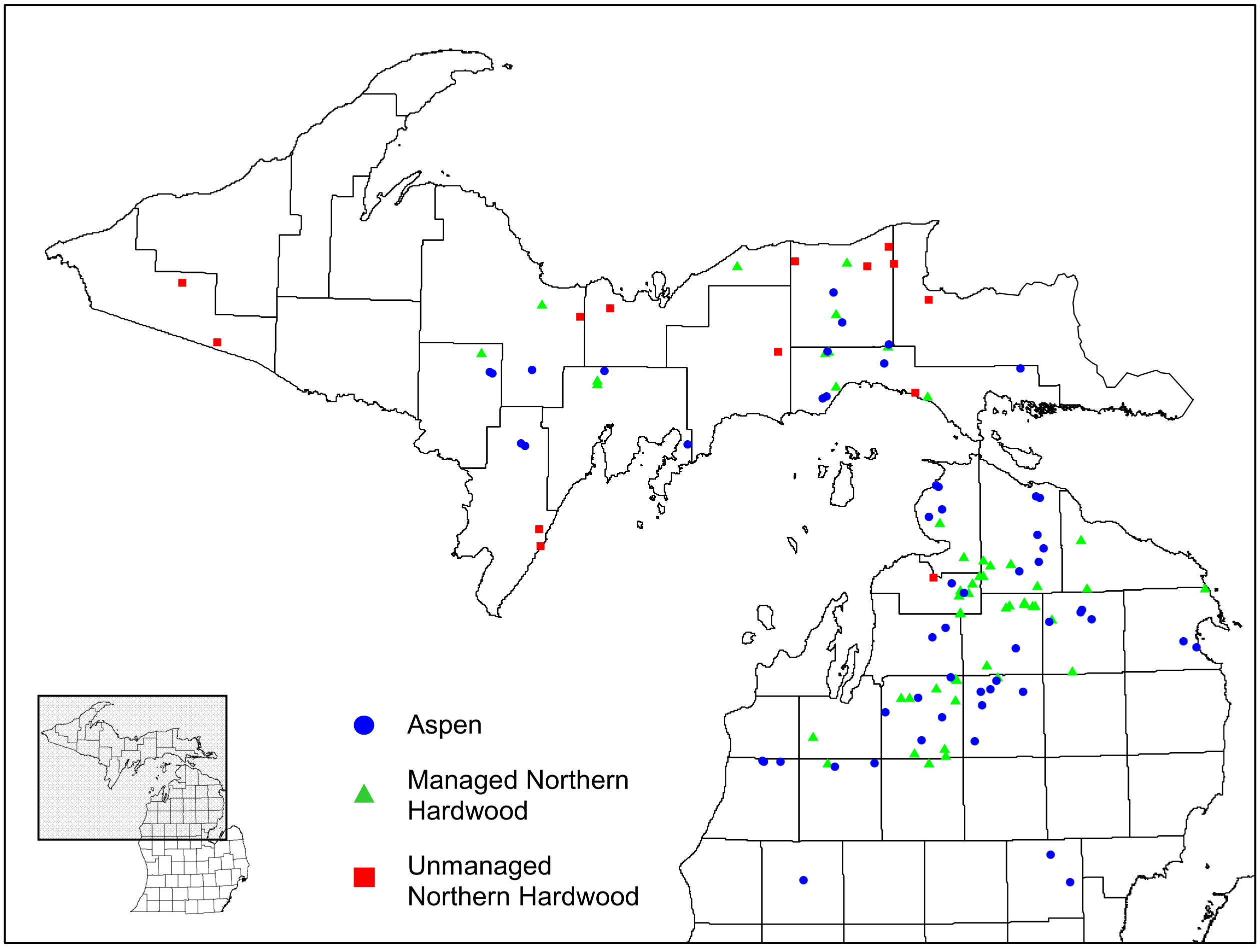

Figure 1. Locations of aspen, managed northern hardwood, and unmanaged northern hardwood stands sampled for coarse woody debris in northern Michigan during 2005-2007.

and were representative of old-growth conditions. Managed aspen and northern hardwood stands were located on State forest land and selected randomly from MDNR Operations Inventory (OI) frozen stand GIS data layers (MDNR 2004, 2005). Aspen stands were randomly selected from four age classes: 20-25, 40-45, 60-65, and 80+ years. Aspen age was determined by the "year of origin" in OI records, which indicated when the stand was last harvested. Randomly selected northern hardwood stands were all uneven aged and had been selectively thinned. Mesic northern forest EOs were selected from high ranking (A, B, or AB) occurrences recorded within the MNFI database and were located on State forest, State park, and federally owned lands. A ranking of A-B indicates that the stand should be of old-growth quality, with natural processes intact and showing minimal signs of silvicultural management.

In 2005, the initial year of the study, we collected data from 20 aspen and 32 managed northern hardwood stands, but unmanaged northern hardwood stands were not sampled. All three forest types were sampled in 2006 and 2007, with an additional 37 aspen, 19 managed northern hardwood, and 14 unmanaged northern hardwood (i.e., mesic northern forest EO) stands. Thus, from 2005 to 2007 we sampled 57 aspen, 51 managed northern hardwood, and 14 unmanaged northern hardwood stands.

METHODS

Field Sampling

We defined coarse woody debris (CWD) as a log or downed tree of at least 10 cm in diameter, 1 m in length, and with at least two points of ground contact or a minimum of 50 cm of ground contact anywhere along its length. Pieces originating from the same fallen tree were counted separately if they were more than 30 cm apart. Branches or boles of the same tree that met the size criteria were considered individual pieces of CWD. Logs lying at angles ≤ 45 degrees from the ground surface were considered CWD, while logs lying at angles >45 degrees were classified as snags. Stumps with diameters of at least 10 cm at the base (excluding buttress) and heights between 1 m and 1.8 m were considered CWD, while those greater than 1.8 m were considered snags.

Two sampling methods, line intercept (De Vries 1973) and strip plot (Husch et al. 1972), were employed. Bate et al. (2004) found that the line-intercept and strip-plot methods can perform differently depending on stand characteristics. We implemented each method using two approaches to locate sample transects or strip-plots: 1) at systematically placed locations along a predetermined circuit route that meandered through a stand (circuit sampling), and 2) at random locations on transects that ran perpendicular to a base-line transect (random sampling). Given two methods (line intercept and strip plot) and two sampling approaches (circuit and random), we applied four methods in the field: 1) circuit line-intercept (CLI), 2) circuit strip-plot (CSP), 3) random line-intercept (RLI), and 4) random strip-plot (RSP) (Appendix A). Using the four methods, we were able to compare the IFMAP stage 2 method (circuit line-intercept) currently used by State foresters to three other methods. We assumed that the RSP method would provide the best parameter estimates, because it employed both random sampling and the strip-plot design. The random sampling approach ensured that any portion of a stand had equal probability of being sampled, while the circuit design excluded portions of stands from the sample universe. Bate et al. (2004) found strip-plot sampling to perform better than line-intercept methods when considering multiple CWD variables in stands with logs of varying size and shape, although the two methods differed in precision and efficiency depending on the abundance of CWD.

Circuit sampling points were placed systematically at equidistant intervals, beginning with a random starting point, along a pre-determined route drawn within the stand. The number of sampling points per stand depended on the size of the stand, but no more than 14 plots were allowed per stand. Random sampling points were laid out along parallel transects equidistantly spaced at a random interval along a baseline transect. Sampling points were located at random distances from the starting points of each transect. The same quantity of sampling points was used for both the random and circuit methods in a given stand.

At each line-intercept sample station, we used a measuring tape to make a straight 20 m (one chain, or 66 ft) transect. We tallied pieces of CWD that intersected a plane stretching from ground to sky along each transect. When a piece intersected the transect, we measured the following: large end diameter (LED), ignoring the buttress of the log/stump; small end diameter (SED); diameter where the intercept line crosses the log (intersect diameter); and total length. We measured total length from the large end to the small end or where the diameter reached 1 cm.

We situated strip plots at the same sample stations used for line-intercept methods. Strip plots were 4.3 m (14 ft) wide, 20 m in length, and centered along the same transect lines used for the line-intercept methods. We measured a piece of CWD if at least 50 cm of the log was located within the plot, and we recorded whether or not the midpoint of the log was located within the plot to calculate density. We collected the same measurements described above for line-intercept sampling, plus the diameters of CWD at plot intercepts for pieces that crossed plot boundaries, and the length of each CWD piece within the plot. Length within plot and total length were the same if the entire piece fell within plot boundaries.

Diameter was measured by holding a measuring tape above the log at a position perpendicular to the length. If logs were not round, as in the case of extensive decay, then the diameter was estimated from the widest portion visible. Every piece of CWD was assigned a decay class rank from I (recent or least decomposed, leaves present, round in shape, bark intact, wood structure sound, current year twigs present) to V (very decayed, leaves absent, branches absent, bark detached or absent, wood not solid, and oval or collapsed in form) according to Tyrell and Crow (1994). See Appendix A for further description of decay classes.

We identified snags to be sampled differently for line-intercept and strip-plot methods. We conducted a 10-factor prism sweep at the beginning of each transect to locate snags during line-intercept sampling. During strip-plot sampling, we measured any snag that had their center or pith located within the plot. We measured the DBH and estimated the approximate height for all snags determined to be within the prism sweeps or plot boundaries. Snag height was estimated visually and we assigned each snag a rank of 1-5, with each number representing a 5-m height increment.

We used prism sweeps conducted at circuit line-intercept sample stations to characterize the dominant overstory composition of the three forest stand types. The species of each tree considered within each prism sweep was recorded. We used these data to estimate the frequency of occurrence for dominant overstory species and total living basal area by stand type.

Parameter Estimates

We estimated the density, total length, and volume of CWD following the calculations used by Bate et al. (2004). We estimated density for the line-intercept methods following De Vries (1973):

$$\text{Density (logs per ha)} = (5\pi \times 10^3 / L) \sum^{n} (1 / l_i)$$

where L is the transect length (20 m), n the number of CWD pieces intersected, and l the length (m) of the ith log intersected. To estimate density for the strip-plot methods, we took the total number of logs having a midpoint within the plot and converted to logs per ha.

We calculated total length of CWD for line-intercept methods using the following equation from De Vries (1973):

$$\text{Total length (m)} = n\pi \times 10^4 / 2L$$

For strip-plot methods, we estimated total length by first summing the total length (m) of all portions of CWD pieces that fell within the plot and then converting to total length per ha.

We estimated CWD volume for line-intercept methods following De Vries (1973):

$$\text{Volume (m}^3\text{/ha)} = (\pi^2 / 8L) \sum^{n} d_i^2$$

where *d* is the diameter (cm) of each log. During strip-plot sampling, we treated each CWD piece or portion of a piece as a cylinder or frustum to calculate volume. The volumes of all the logs that fell within a plot were summed and then converted to m^3/ha.

Because prism sweeps do not produce unbiased density or mean diameter at breast height (DBH) estimates, snag density and average DBH were only estimated using data from strip-plot sampling. We estimated snag density using the same method described above for CWD density. Mean DBH was estimated by averaging the DBHs of all snags that fell within each plot. We estimated snag basal area for line-intercept methods using data from 10-factor prism sweeps. The number of snags falling within in each sweep was multiplied by 10 to produce an estimate of basal area in ft^2/acre, which was then converted to m^3/ha. We used the same process to estimate total live basal area for the three forest stand types. For strip-plot samples, we estimated snag basal area using the following equation:

$$\text{Snag basal area (m}^2\text{/ha)} = \sum^{n} \pi \, (d_i / 200)^2$$

where *d* is the DBH of the *i*th snag.

Statistical Analyses

We used mixed models (MIXED procedure, SAS Institute 2004) to compare estimates of CWD, snag, and basal area parameters among sampling methods, forest stand types, and aspen age classes. Mixed models are an effective means of analyzing multilevel data structures that allow the inclusion of both fixed and random effects (Wagner et al. 2006). All plot- and transect-level data were averaged by site (i.e., forest stand) prior to analysis. We provided the results of several preliminary analyses in Appendix B (Tables B-1 and B-2).

Method and Stand Type Comparisons: We used a mixed model containing method (CSP, CLI, RSP, and RLI), forest stand type (aspen, managed northern hardwood, and unmanaged northern hardwood), and method*stand type interaction as fixed effects, and sample site (i.e., forest stand) as a random effect, to compare CWD and snag variables among the method and stand type categories. We compared the following dependent variables: density, length, and volume of CWD; snag density, DBH, and basal area; and total basal area of living trees. We conducted preliminary analyses using two data sets: one using data from 2005 to 2007, and the second using data from 2006 and 2007. Although the results were generally similar between the three- and two-year data sets (Table B-1, Appendix B), we only report results from the two-year data set in this report, because we did not use the RSP method or sample unmanaged northern hardwood stands during the 2005 pilot season. When variables had residuals that were not normally distributed, we used square-root and log (natural) data transformations (Zar 1996). We square-root transformed CWD density and length and snag density and DBH, and log transformed CWD volume and snag basal area. Comparisons of least squares means between pairs of fixed effects categories (i.e., methods and stand types) were conducted using the PDIFF option of the LSMEANS statement (SAS Institute 2004).

Aspen Age-class Comparisons: We compared CWD and snag variables among four age classes of aspen forest stands using a mixed model that consisted of age class (20-, 40-, 60-, and 80-year) as a fixed effect and site as a random effect. We conducted the analysis using data from all three years and the CSP and CLI methods, because aspen was sampled every year and both sampling methods occurred in every stand.

RESULTS

Method Comparisons

Coarse woody debris density estimates varied by sampling method (F=4.95, df=175, p=0.0025). Mean CWD density estimated using the CSP method was greater than the other three methods, which were all similar (Table 1). Average CWD length estimates differed by sampling method (F=3.82, df=175, p=0.0110). Pair-wise comparisons of mean length estimates indicated that the CSP and CLI methods were similar, CLI and RSP methods did not differ, and the RSP and RLI methods were similar. Estimates of mean CWD volume were similar among the four sampling methods (F=1.93, df=175, p=0.1270). Snag density (F=2.05, df=54, p=0.1581) and DBH (F=0.71, df=34, p=0.4058) did not differ between the circuit or random strip-plot methods (Table 1). Mean snag basal area was similar among the four sampling methods (F=0.16, df=175, p=0.9237). The method*stand type interaction effect was not significant for any of the variables analyzed (see Table B-1, Appendix B). Although we did not measure the time spent conducting each method, field workers reported that CLI sampling took the least time of the four methods to implement in the field.

Table 1. Least squares mean and lower and upper 95% confidence limit (LCL and UCL) estimates for coarse woody debris, snag, and basal area parameters by sampling methodology from forest stands in northern Michigan during 2006-2007. Bolded p-values indicate significant differences among sampling methods ($p<0.05$). Means followed by the same letter were not significantly different ($p>0.05$).

	Circuit Strip Plot (n=70)			Circuit Line Intercept (n=70)			Random Strip Plot (n=57)			Random Line Intercept (n=57)			
Variable	Mean	LCL	UCL	Mean	LCL	UCL	Mean	LCL	UCL	Mean	LCL	UCL	P value
Coarse Woody Debris													
Density (logs/ha)	153.9 A	129.5	180.4	122.4 B	100.7	146.2	125.9 B	101.9	152.5	109.4 B	87.1	134.3	**0.0025**
Length (m/ha)	884.0 A	747.0	1032.6	810.9 AB	679.8	953.4	748.2 BC	613.5	896.3	687.0 C	558.2	829.1	**0.0110**
Volume (m^3/ha)	21.3	16.7	27.1	20.9	16.4	26.5	18.7	14.3	24.4	16.4	12.5	21.3	0.1270
Snag													
Density (snags/ha)[1]	33.0	24.2	43.2	---	---	---	25.0	16.4	35.4	---	---	---	0.1581
DBH (cm)[1]	24.3	21.9	26.7	---	---	---	25.8	22.9	28.8	---	---	---	0.4058
Basal Area (m^2/ha)	1.7	1.3	2.1	1.6	1.2	2.0	1.6	1.2	2.1	1.5	1.2	2.0	0.9237

[1] Estimates produced using CSP and RSP methods only.

Stand Type Comparisons

Prism sweeps indicated that aspen stands were dominated by trembling aspen (*Populus tremuloides*) and/or bigtooth aspen (*Populus grandidentata*) clones that had regenerated from stump sprout and root suckers following past harvests (Figure 2). Sugar maple (*Acer saccharum*) was the second most common species observed in aspen stands. Red maple (*Acer rubrum*), balsam fir (*Abies balamea*), and white birch (*Betula papyrifera*) were also regularly observed in aspen stands, but each species made up <10% of the trees sampled. Sugar maple was the dominant tree species in both managed and unmanaged northern hardwood stands (Figure 2). Although red maple, American basswood (*Tilia americana*), American beech (*Fagus grandifolia*), aspen, and eastern hemlock (*Tsuga canadensis*) were also observed in managed northern hardwoods, they each represented <10% of the trees sampled. Other species recorded sporadically in managed northern hardwood stands included balsam fir, white birch, and yellow birch (*Betula alleghaniensis*). When compared to managed northern hardwood stands, unmanaged northern hardwoods were characterized by lower frequencies of sugar maple, red maple, American basswood, and aspen, and greater frequencies of eastern hemlock, American beech, yellow birch, and northern white cedar (*Thuja occidentalis*) (Figure 2).

Most CWD and snag variables differed by stand type, and in pair-wise comparisons, managed aspen and northern hardwood stand types were typically similar, but differed from the unmanaged northern hardwood type (Table 2). Coarse woody debris density estimates varied among the stand types (F=3.40, df=67, p=0.0391). Density estimates for managed aspen and northern hardwood were similar and lower than mean density for unmanaged northern hardwoods. Average length of CWD differed by stand type (F=8.49, df=67, p=0.0005), and mean length for unmanaged northern hardwoods was about two times greater than estimates

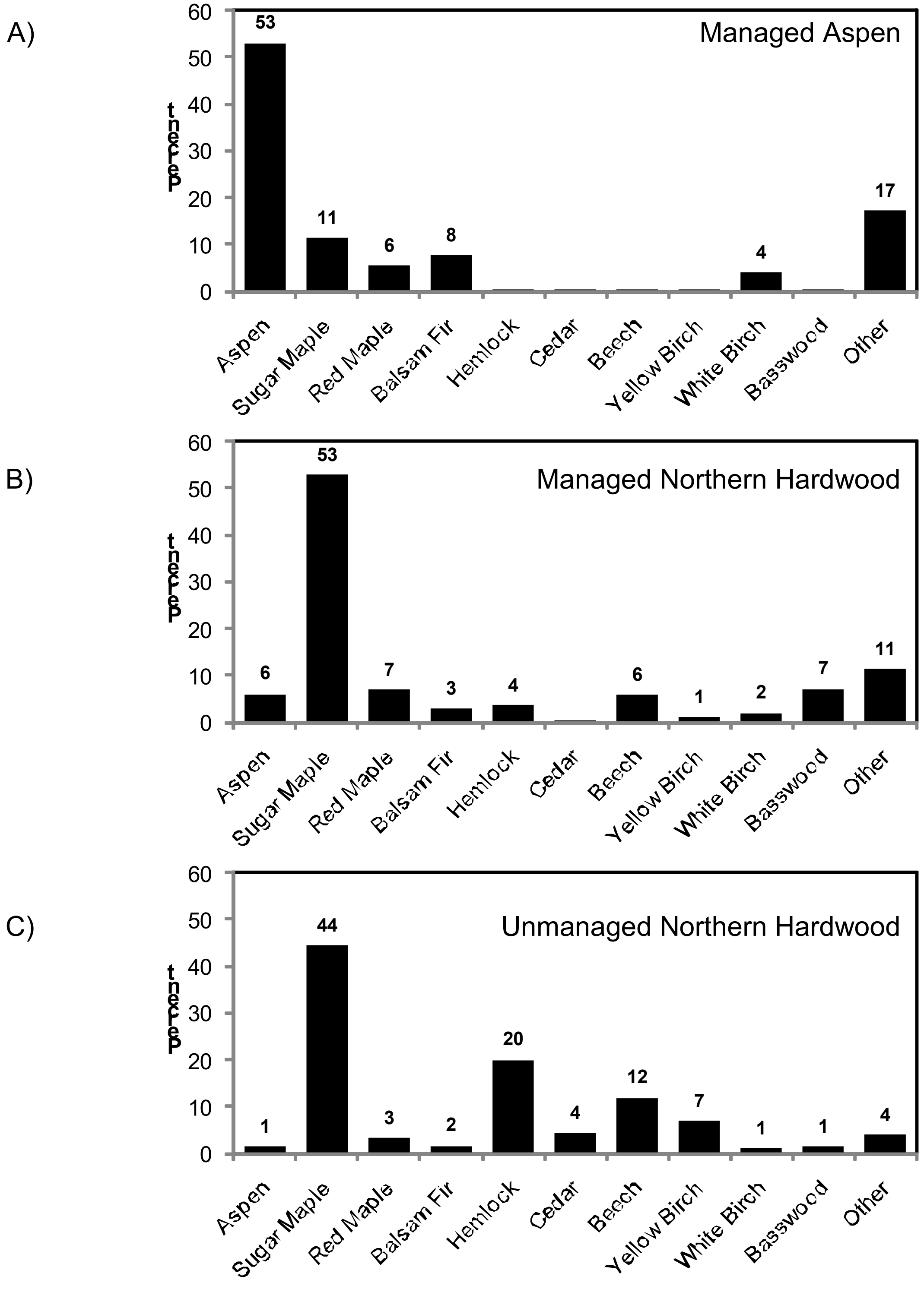

Figure 2. Composition of dominant overstory tree species in A) managed aspen, B) managed northern hardwood, and C) unmanaged northern hardwood stands sampled in Michigan during 2006-2007. Percentages are based on mean frequency of occurrence during basal area sweeps conducted at CLI transects. Species in the "other" category each represented ≤3% of all trees sampled.

Table 2. Least squares mean and lower and upper 95% confidence limit (LCL and UCL) estimates for coarse woody debris, snag, and basal area parameters from managed and unmanaged forest stands in northern Michigan during 2006-2007. Bolded p-values indicate significant differences among forest types ($p<0.05$). Means followed by the same letter were not significantly different ($p>0.05$).

	Managed Forest Types						Unmanaged			
	Aspen (n=37)			Northern Hardwood (n=19)			Northern Hardwood (n=14)			
Parameter	Mean	LCL	UCL	Mean	LCL	UCL	Mean	LCL	UCL	P value
Coarse Woody Debris										
Density (logs/ha)	105.6 A	84.3	129.3	111.7 A	81.7	146.5	169.4 B	125.2	220.3	**0.0391**
Length (m/ha)	588.5 A	464.2	727.6	615.4 A	441.6	818.0	1208.3 B	916.2	1540.8	**0.0005**
Volume (m^3/ha)	8.7 A	6.5	11.4	11.8 A	8.0	17.2	65.8 B	43.0	100.6	**<0.0001**
Snag										
Density (snags/ha)[1]	26.9	18.5	36.8	28.2	16.5	42.8	31.7	16.8	51.1	0.8797
DBH (cm)[1]	18.3 A	16.2	20.6	21.4 A	18.3	24.7	37.1 B	32.5	42.1	**<0.0001**
Basal Area (m^2/ha)	1.0 A	0.7	1.2	1.1 A	0.7	1.5	3.3 B	2.4	4.4	**<0.0001**
Live Tree										
Basal Area (m^2/ha)[2]	15.3 A	13.4	17.1	21.3 B	18.7	23.8	26.6 C	23.6	29.6	**<0.0001**

[1] Estimates produced using CSP and RSP methods only.

[2] Estimates produced using CLI method only.

for managed forest types. Mean volume of CWD varied by stand type (F=, df=67, p<0.0001), with estimates for managed aspen and northern hardwood types being similar and approximately six times lower than average volume in unmanaged northern hardwoods (Table 2). While snag density was similar among the three forest types (F=0.13, df=67, p=0.8797), snag DBH (F=30.00, df=60, p<0.0001) and basal area (F=19.29, df=67, p<0.0001) differed. Average snag

DBH was similar between managed aspen and northern hardwood stands, but mean snag DBH in unmanaged northern hardwoods was approximately 70-100% greater than that of the managed types. Mean snag basal area of unmanaged northern hardwoods was about three times greater than estimates for the managed forest types. Average estimates of total live tree basal area also differed among the three stand types (F=22.37, df=66, p<0.0001), with the greatest mean in unmanaged northern hardwoods and lowest in managed aspen (Table 2).

Aspen Age-class Comparisons

Mean CWD density (F=3.22, df=50, p=0.0302), length (F=4.08, df=50, p=0.0114), and volume (F=4.90, df=50, p=0.0046) of aspen stands varied by age class (Table 3). In pair-wise comparisons of mean CWD densities, the 20- and 40-year classes were similar and there was no difference among the 40-, 60-, and 80-year age classes. Average CWD length in 20-year aspen stands was lower than the other age classes, while length estimates from the 40-, 60-, and 80-year were similar. Mean CWD volumes in the 40-, 60-, and 80-year age classes were similar and greater than the 20-year mean estimate. Snag density (F=3.21, df=32, p=0.0361) and basal area (F=5.03, df=50, p=0.0040) differed among the four age classes. Average snag density was similar between the 20- and 80-year age classes and among the 40-, 60-, and 80-year classes, while estimates for the 40- and 60-year classes were greater than the 20-year mean (Table 3). Snag basal area estimates for the 40-, 60-, and 80-year age classes were similar and greater than the 20-year average.

Table 3. Least squares mean and lower and upper 95% confidence limit (LCL and UCL) estimates for coarse woody debris, snag, and basal area parameters by age class from managed aspen forest stands in northern Michigan during 2005-2007. Except where noted, data were collected using the CSP and CLI methods. Bolded p-values indicate significant differences among age classes ($p<0.05$). Means followed by the same letter were not significantly different ($p>0.05$).

	20-year (n=12)			40-year (n=14)			60-year (n=13)			80-year (n=11)			
Variable	Mean	LCL	UCL	Mean	LCL	UCL	Mean	LCL	UCL	Mean	LCL	UCL	P value
Coarse Woody Debris													
Density (logs/ha)	43.5 A	14.9	87.1	101.1 AB	56.7	158.3	111.5 B	63.0	173.7	157.7 B	94.2	237.3	**0.0302**
Length (m/ha)	205.5 A	67.6	418.0	528.7 B	300.6	820.7	661.5 B	394.1	997.7	825.7 B	499.8	1233.0	**0.0114**
Volume (m^3/ha)	2.8 A	1.2	5.5	8.2 B	4.58	14.25	10.17 B	5.63	17.82	14.47 B	7.78	26.28	**0.0046**
Snag													
Density (snags/ha)[1]	10.5 A	2.2	24.5	42.4 B	24.5	65.2	37.9 B	20.2	60.9	31.0 AB	14.0	54.5	**0.0361**
DBH (cm)[1]	15.3	7.6	23.0	16.1	13.6	18.6	18.4	14.0	22.7	18.5	14.1	22.8	NA[2]
Basal Area (m^2/ha)	0.3 A	-0.3	0.9	1.4 B	0.8	1.9	1.7 B	1.1	2.3	1.7 B	1.1	2.3	**0.0040**
Live Tree													
Basal Area (m^2/ha)[3]	10.8	6.2	15.4	15.5	12.8	18.2	17.6	12.5	22.8	16.9	13.3	20.5	NA

[1] Estimates produced using CSP and RSP methods.

[2] Indicates the SAS model did not converge.

[3] Estimates produced using CLI method only.

DISCUSSION

Methods Comparisons

The primary goal of our study was to compare the CWD sampling methodology currently used by the MDNR (CLI) with RSP methodology, which we assumed would be most likely to produce unbiased estimates of several CWD variables. We also included two variants of these methods (CSP and RLI) in our comparisons. The CLI methodology produced similar estimates to RSP sampling for the three CWD variables we measured: density, length, and volume. Although density and length estimates differed among the four methods, CLI and RSP sampling were similar in pair-wise comparisons. We did not measure the time required to implement each method, but CLI sampling was substantially easier to set up and conduct in the field and appeared to be the most time efficient. Because we did not conduct complete inventories of CWD in the study stands, we do not know which sampling methods produced CWD estimates similar to the true means. If we assume that RSP was most likely to produce estimates similar to population means, then it appears that CSP sampling may have overestimated CWD density and length. The method*stand type interaction effect was not significant in any of our models, which indicates that all four methods produced comparable results across the three stand types. If the goal of sampling is to compare levels of CWD across the stand types we investigated in northern Michigan, then it appears all of the methods we used would produce similar results.

In their comparisons of strip-plot and line-intercept sampling, Bate et al. (2004) found that best method depended on the CWD variables of interest, size of the CWD of interest, stand or harvest history, CWD abundance, and desired precision and efficiency. Bate et al. (2004) found precision and efficiency were similar for strip-plot and line-intercept sampling in unharvested stands for all variables except CWD density, for which strip-plots were better. In harvested stands, Bate et al. (2004) found strip-plots to perform better in efficiency and precision than the line-intercept method for CWD density and volume. We did not measure wildlife use of CWD in our study, but Bate et al. (2004) found their strip-plot sampling to better estimate wildlife use (i.e., visual evidence of use by woodpeckers, squirrels, and bears) than a line-intercept method.

When estimates of snag density and DBH are needed, CSP sampling, which is easier to set up and implement in the field than the RSP method, produced similar results to RSP sampling. Thompson (2002) noted that systematic sample designs that include random starts, such as our circuit sampling methods, produce unbiased parameter estimates. If snag density and DBH are deemed important variables to resource managers, plot sampling for snags could be incorporated into the current CLI method. We found no difference in snag basal area among the four methods, which indicates that the prism sweeps used during line-intercept sampling provided similar results to the estimates produced via more labor-intensive strip-plot methods.

Stand Type Comparisons

We observed greater mean CWD density, length, and volume, and snag basal area and DBH in unmanaged northern hardwood stands compared to managed northern hardwood and aspen forest in Michigan, which is consistent with the findings of similar studies (Goodburn and Lorimer 1998, Hale et al. 1999, Webster and Jenkins 2005). Researchers have also documented similar patterns in European forests (Siitonen et al. 2000, Debeljak 2006). Debeljak (2006) found that management of Slovenian forests dominated by silver fir (*Abies alba*) and beech (*Fagus sylvatica*) led to the reduction and homogenization of CWD when compared to virgin stands. Greater levels of CWD in old-growth compared to managed forests could be a function of greater stand ages, increased tree diameters, and forest composition. Total volume of CWD and volume of hemlock CWD increased linearly with stand age in old-growth hemlock-hardwood forests of northern Wisconsin and Michigan (Tyrrell and Crow 1994). Hemlock is known to have a slower rate of decay, so would likely remain on the forest floor longer than most hardwood species (Harmon et al. 1986). Managed northern hardwood and aspen stands that we investigated were missing large, 50 to 70 cm DBH (i.e., 200-300 year old) trees that frequently occurred in unmanaged northern hardwood stands. We also found that 20% of the trees recorded during basal area sweeps in unmanaged hardwoods were large-diameter hemlock, compared to 4% in managed northern hardwood stands. Eastern hemlock is a long-lived (500 years) conifer with greater CWD residence time than hardwoods species, so differences in hemlock abundance between managed and unmanaged stands will influence both present and future forest structure. Differences in forest structure between managed and unmanaged stands are likely affecting wildlife use, because CWD and snag variables, such as size, location, and density are important factors in determining wildlife use (DeGraaf and Shigo 1985, Bull et al. 1997). Howe and Mossman (1996) found that several bird species were associated with eastern hemlock forests in northern Wisconsin and western Upper Michigan, and that uneven-aged managed stands containing hemlock supported greater bird densities than even-aged managed northern hardwood stands.

We found mean CWD density for unmanaged northern hardwoods to be similar to previous studies (Tyrrell et al. 1998), while our volume estimate varied from those reported by other researchers in the Great Lakes region and northeastern United States (Tyrrell and Crow 1994, Goodburn and Lorimer 1998, Tyrrell et al. 1998, Hale et al. 1999). We estimated mean CWD density for unmanaged northern hardwoods at 169 logs/ha, which was within the range of densities reported in Tyrrell et al. (1998) for old-growth northern hardwoods (99-481 logs/ha) and slightly below the range for old-growth conifer-northern hardwoods (200-288 logs/ha). We estimated total CWD volume at 66 m^3/ha for unmanaged northern hardwoods, which was lower than estimates reported by Tyrrell et al. (1998) (range 121-213 m^3/ha), Goodburn and Lorimer (1998) (mean 102 m^3/ha), and McGee et al. (1999) (mean 136.7 m^3/ha) for old-growth northern hardwoods. Hale et al. (1999) estimated mean volume at 55 m^3/ha for old-growth maple-basswood forest. Our mean volume (66 m^3/ha) was intermediate between the estimates of Tyrrell and Crow (1994) (mean 54 m^3/ha) and Goodburn and Lorimer (1998) (mean 93.9 m^3/ha) for old-growth hemlock-hardwoods. However, Tyrrell and Crow (1994) only characterized logs with ≥20 cm diameters, while we used a 10 cm diameter threshold similar to other studies (Goodburn and Lorimer 1998, Hale et al. 1999). Differences between our volume estimate and those of previous studies could be related to varying methods used to sample and estimate CWD volume or differing stand characteristics, such as species composition, stand age, site history, and climate. Our estimates of snag density and basal area for unmanaged northern hardwoods were within the range of values summarized in Tyrrell et al. (1998) for old-growth northern hardwoods and conifer-northern hardwood forests. We observed similar mean snag density, DBH, and basal area to those reported by Goodburn and Lorimer (1998) for old-growth northern hardwoods.

We recorded lower CWD density and volume estimates for managed hardwood forests than those of other studies (Goodburn and Lorimer 1998, Hale et al. 1999, McGee et al. 1999). A variety of factors could account for these differences, including differing stand selection processes (e.g., random versus selected), sample sizes, stand ages, management histories, regional climates, and sampling methodologies. We observed similar mean snag density in managed northern hardwoods to those of comparable managed forest types in the Great Lakes region (Goodburn and Lorimer 1998, Hale et al. 1999), while estimated snag density from managed northern hardwoods in New York were greater than ours (McGee et al. 1999). Our mean snag DBH estimate for managed northern hardwood stands was intermediate between estimates reported by Goodburn and Lorimer (1998) for even-aged and selectively cut northern hardwood stands. We observed a mean snag basal area for managed northern hardwoods that was similar to McGee et al. (1999), while estimates in Goodburn and Lorimer (1998) were greater than ours.

Aspen Age-class Comparisons

Our sampling of aspen stands within four age classes indicated that CWD and snag variables varied with stand age. Although CWD variables tended to increase with increasing age, estimates of density, length, and volume were statistically similar among the 40-, 60-, and 80-year age classes. Differences in CWD parameters generally occurred between the 20-year age class and all other age classes. Low amounts of CWD in the youngest age group (20 yrs) suggests that residue from final harvest in aspen has limited residency time in these stands. Aspen stores large amounts of nutrients in perennial tissue (Pastor and Bockheim 1984), which influences the rapid decay of material deposited. Our results also suggest that CWD may have built up enough by the 40-year age class to be similar to later age classes. We found similar patterns in snag density and basal area among the age classes. We observed high variability in CWD and snag parameters, as suggested by broad confidence limits, so more sampling is needed to refine estimates and further elucidate relationships between CWD and snag variables and stand age.

Future Research

Our data set presents opportunities for additional analyses to further characterize CWD in northern Michigan forests, including comparisons between managed and unmanaged forests of 1) percent cover of CWD, 2) CWD variables by decay class, 3) CWD variables by size class, 4) total snag volume, and 5) snag variables by size class. We did not estimate percent cover of CWD, but other studies measured this variable due to its likely importance to wildlife (e.g., Tallmon and Mills 1994, Carey and Johnson 1995, Bate et al. 2004). Comparisons of CWD percent cover by sampling method and stand type would be valuable to determine if the four sampling methods performed similarly in estimating percent cover, and to further characterize CWD in managed and unmanaged forests in Michigan.

Previous researchers have measured CWD parameters by decay class, because of the importance of decay class to wildlife use and forest structure (e.g., Tallmon and Mills 1994, Tyrrell and Crow 1994, Goodburn and Lorimer 1998, Hale et al. 1999, Webster and Jenkins 2005). Decayed logs and stumps are known to provide important sites for eastern hemlock regeneration, which may be due to desirable environmental conditions (Goodman and Lancaster 1990), protection from adult hemlock allelopathy (Ward and McCormick 1982), or refuge from fungal pathogens (O'Hanlon-Manners and Kotanen 2004). We recorded the decay class of each CWD piece according to Tyrrell and Crow (1994) and plan to compare CWD variables between managed and unmanaged stands by each of the five decay classes.

We intend to categorize our data into size classes and compare CWD parameter estimates between managed and unmanaged stands, which would provide better characterization of potential wildlife habitat in northern Michigan forests. Bull et al. (1997) stated that wildlife use of CWD generally correlates with size, and that variables such as size, distribution, and density are more important with regard to wildlife than measures of weight and volume. Small mammals, amphibians, reptiles use smaller logs for travel corridors, escape cover, and shelter (Bull et al. 1997), while larger diameter logs support use by larger vertebrates, such as marten, fisher, bobcat, and black bear (DeGraaf and Shigo 1985, Ruggiero et al. 1994).

In addition to snag density and basal area, researchers have measured snag height and volume, and estimated snag variables by size class (e.g., Goodburn and Lorimer 1998). Wildlife management guidelines stress the importance of large-diameter snags for cavity nesting birds and larger-bodied mammals (DeGraaf and Shigo 1985, Tubbs et al. 1987). When conducting plot sampling, we measured the DBH and approximate height of snags, which would permit estimation of mean snag height, total snag volume, and volume by size class.

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APPENDIX A:

COARSE WOODY DEBRIS SAMPLING METHODS

Circuit Transects will be laid out to efficiently cover all areas of the target stand with a minimum of backtracking. A starting point that is clearly identifiable on an aerial photo is selected, and a route through the stand is selected along which transects and plots are established (Figure 1). The number of transects within the stand will depend on stand size. Transects will be one chain (66 feet) in length and separated by a distance of at least one-half chain (33 feet). The number and length of cwd intersecting transects will be recorded. Plots will be determined using a 10 BAF prism at the beginning of each transect. The number, height, diameter, and species of snags in the plot will be recorded.

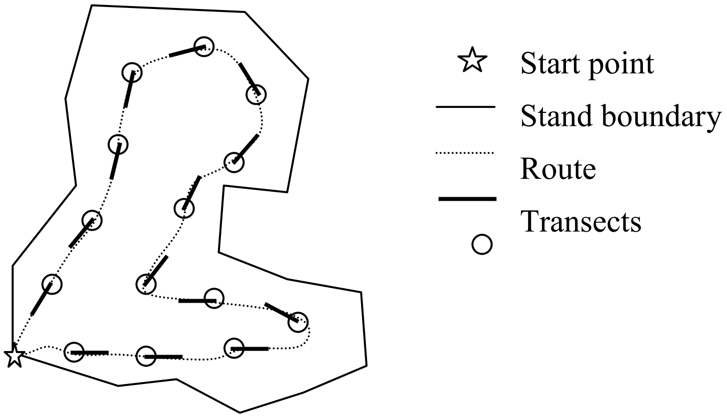

Figure 1. Example of circuit transect layout within a stand

Circuit strip plots will be laid out in the same manner as circuit transects, with the same starting point, and along the same route. Transects will be used as the basis for the central length of strip plots (one chain in length, separated by one-half chain), and strip width will be 14 feet (7' on each side of the transect, Figure 2). The number and length of cwd, as well as snags within the plot within plots will be recorded.

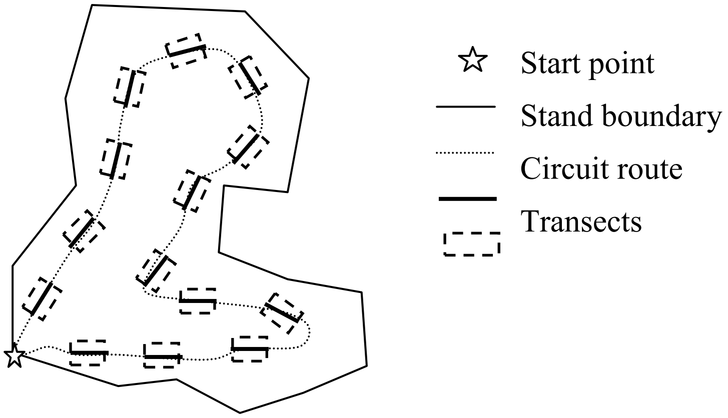

Figure 2. Example of circuit strip plot layout within a stand.

Random transects with plots will be laid out along parallel routes through the stand. A baseline along a known feature will be selected and starting points for routes will be established at a set distance apart. A randomly selected distance will be traversed from the start along the route to locate the first transect. Additional transects will be established a random distance greater than or equal to one-half chain (33') from the end of the previous transect (Figure 3). The number of transects within the stand will be equal to the number of circuit transects established within the stand (dependent on stand size). Transects will be one chain (66 feet) in length. The number and length of cwd intersecting transects will be recorded. Plots will be determined using a 10 BAF prism at the beginning of each transect. The number, height, diameter, and species of snags in the plot will be recorded

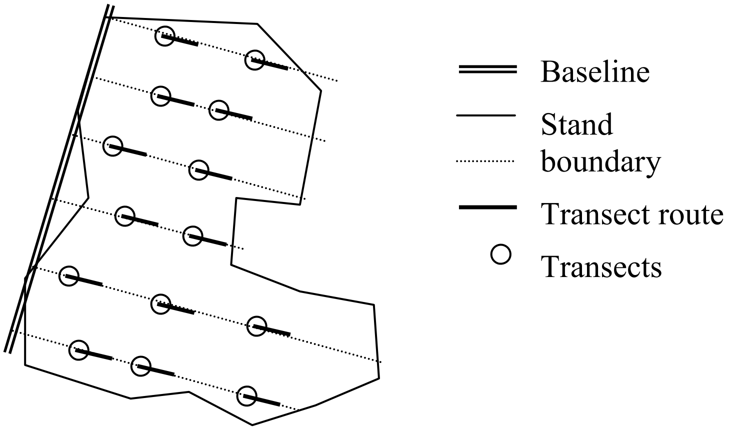

Figure 3. Example of random transect layout within a stand.

CWD Measurements:

Dead and down material measurements will include the number, size, and decay class of coarse woody debris pieces that meet minimum size requirements.

Methods:

1) <u>Gather field sheets and maps:</u> Make sure that you have a complete set of field sheets ant the appropriate maps for the stand. The map will show the number of transects/plots within the stand. Prepare one data sheet for each transect/plot, making sure to note the forest, compartment, and stand number, and the id for the transect/plot.
2) <u>Necessary equipment:</u> With transect maps and field forms prepared, inventory personnel go to field with: pencils, data forms, prisms (BAF 10), dbh tape, measuring tapes, flagging, compass, and GPS.
3) <u>Starting point</u>
   Circuit Transects and Strip Plots: Use map and GPS to find the starting "reference" point of first transect.
   Random Transects: Use map to find the beginning of the baseline and start of the transect route. use the start point coordinates listed on the top of page one to navigate with GPS.
4) <u>Locate sampling sites:</u>
   If the GPS unit is detecting your location with an acceptable amount of error, you can locate the sampling sites using the GPS unit. The start points of all transects/plots should be uploaded in the unit and labeled as they are on the map. The direction of the transects can be determined using the directions indicated on the map (random transects and circuit transects/plots) or using the GO TO function on the GPS unit to determine the direction of the next sample (circuit transects/plots only). If the GPS unit is not working, follow the directions on the map to locate your starting point and pace to the next starting point using the distance and direction indicated on the map.
5) <u>BA Plots for Snags (*Transects only*):</u> Establish plot center at the beginning of each transect (do not conduct BA plots at strip plot locations). Determine a starting direction (direction of travel). Systematically work in a clockwise direction using a 10 Basal Area Factor (BAF) prism to determine the number of "in" snags (Figure 4). Tally the number and species of snags "in" the plot. Have a partner measure the diameter of each snag at breast height (dbh) using a dbh tape and estimate the height of the snag in 5m increments. Record all information on the data sheets.

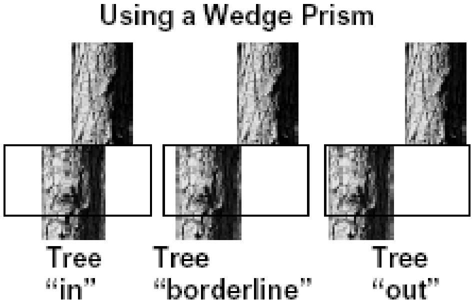

Figure 4. Illustration of how to use a Basal Area (BA) prism to determine the number of snags to tally.

6) CWD Along Transects: Have one partner hold the end of the measuring tape and, in the direction indicated on the map or GPS, measure one chain (66', 20m), making sure the transect is as straight as possible. Using the "GO, NO-GO" gauge, tally qualifying down woody pieces that intersect a planar transect that stretches from ground to sky (e.g. if a qualifying piece crosses the transect above ground, that piece must be tallied). For each intersected qualifying piece measure diameter at the transect intersection, small and large ends, piece length, and assign decay class (Figures 5 and 6).
7) CWD and Snags Within Strip Plots: Complete strip plots immediately after completing circuit transects (do not collect plot data at random locations). Using the pre-measured poles as a guide for determining the plot width, work systematically from one end of the plot to the other, tallying snags within the plot. Using the "GO, NO-GO" gauge within the plot, tally qualifying down woody pieces and measure the total length, length within the plot (may be the same if there are no intersections with plot edge), diameters at plot intersections (if present), large and small end diameters (indicate if outside the plot), and assign a decay class to all qualifying down woody pieces that have at least 0.5m (~20") of length within the plot (Figure 6). Record whether the point of mid-length of a tallied log falls within the plot.

Qualifications for tallying a "piece" as CWD:
1) CWD includes logs on the ground or stumps. Logs/downed trees should have at least 2 points of ground contact or at least 1.5' of ground contact anywhere along its length.
2) Logs must be at least 4" (10cm) in diameter. Transects: 4" anywhere along its length. Plots: 4" anywhere along its length within the plot. *(Note: we started this project using 7" as a guide but later changed to 4".)*
3) Stumps must be at least 4" (10cm) in diameter at the base (excluding buttress) and at least 18" tall but no taller than 6 feet ("stumps" taller than 6 feet would meet our definition of a snag.)
4) Broken lengths originating from the same fallen tree: count as same piece only if individual portions are less than 1' apart and meet requirements above for a qualifying piece.

Rules for making measurements:
All measurements are to the nearest 1cm.

Diameter: Measure the diameter by holding a tape above the log, at a position perpendicular to the length. If pieces are not round in cross-section because of missing chunks of wood or "settling" due to decay, measure the diameter in two directions representing the largest and smallest diameters and take an average. If the log is splintered or decomposing at the point where a diameter measurement is needed, measure the diameter at the point where it best represents the log volume. Diameter at small end: record the diameter of the small end to the nearest centimeter at either the actual end of the piece if the end is >3cm, or at the point where the piece tapers down to 3cm. This will serve as the end of the log for length measurements. Diameter at large end: Record the diameter to the nearest centimeter, ignoring buttressed areas (USDA 2004).

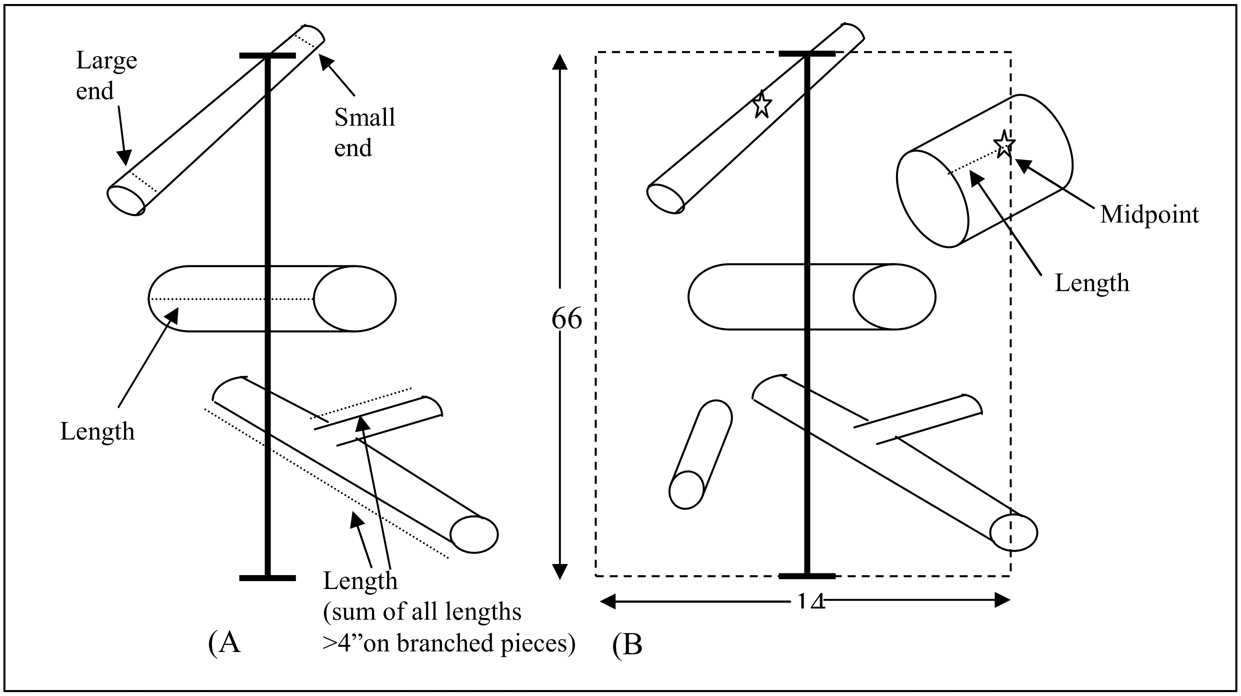

Figure 5. Illustration of coarse woody debris field measurements at transects (A) and strip plots (B). Logs shown in each illustration should be tallied and have measurements and decay class recorded.

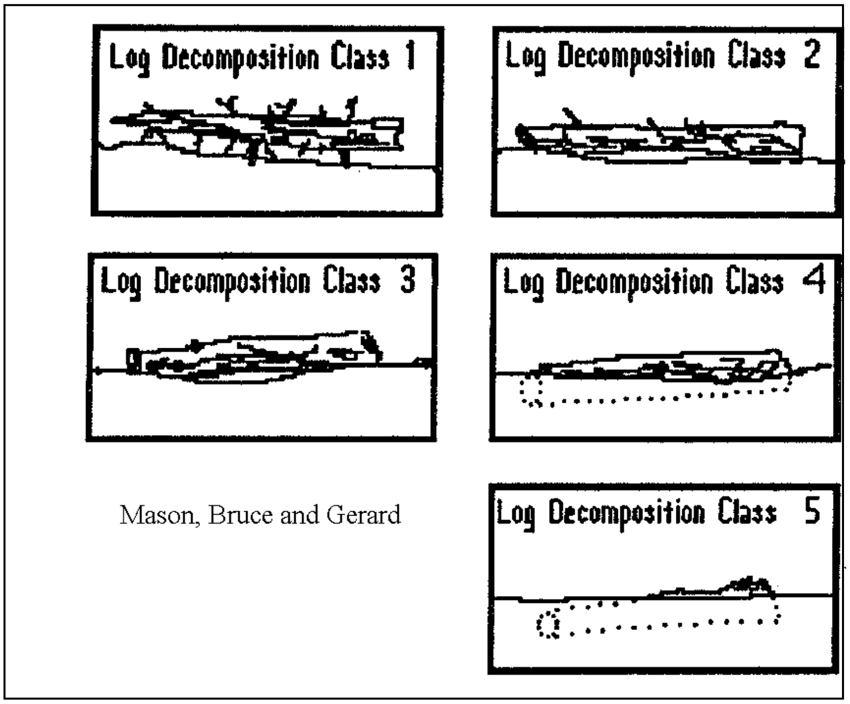

Figure 6. Illustration of log decomposition classes.

USDA Forest Service. 2004. 2.0 Phase 3 Field Guide – Down Woody Materials.

APPENDIX B:

RESULTS OF DATA ANALYSES

Table B-1. Results of preliminary data analyses conducted on coarse woody debris and snag variables in northern Michigan forests. The first analysis was conducted using data from all three years (2005-2007), while the second was done using only data from 2006 and 2007. Data from 2005 were dropped in the second set of analyses, because the RSP method was not used and no unmanaged northern hardwood stands (i.e., mesic northern forest element occurrences) were sampled. Parameter estimates for fixed effects and results of normality tests of residuals are provided for raw and transformed data. Bolded values indicate the final analyses provided in the report narrative.

Variable and	Data	Methods Comparisons[2]					Stand Type Comparisons[3]				Method *Stand Type	K-S Test of Residuals	
Transformation ()[1]	Set	CSP	CLI	RSP	RLI	p-value	A	NH-M	NH-UM	p-value	p-value	D Stat.	p-value
Density (none)	3-yr	171.1	142.7	143.5	138.1	0.0103	131.5	141.5	173.5	0.4517	0.0308	0.0938	<0.0100
	2-yr	169.1	138.2	137.6	123.5	0.0019	125.8	125.6	174.8	0.1167	0.0842	0.1015	<0.0100
Density (sqrt)	3-yr	12.1	10.8	11.2	10.8	0.0199	10.2	10.5	13.0	0.1400	0.2370	0.0565	<0.0100
	2-yr	**12.4**	**11.1**	**11.2**	**10.5**	**0.0025**	**10.3**	**10.6**	**13.0**	**0.0391**	**0.2385**	**0.0573**	**0.0417**
Density (log)	3-yr	4.7	4.4	4.6	4.4	0.1285	4.2	4.3	5.1	0.0889	0.7257	0.1356	<0.0100
	2-yr	4.9	4.6	4.8	4.5	0.0258	4.4	4.6	5.1	0.0327	0.3822	0.1486	<0.0100
Length (none)	3-yr	955.3	866.8	804.3	765.3	0.0009	655.2	663.5	1225.0	0.0007	0.0367	0.0839	<0.0100
	2-yr	988.4	899.4	829.2	776.3	0.0031	706.2	683.4	1230.4	0.0005	0.0930	0.0736	<0.0100
Length (sqrt)	3-yr	28.5	27.1	26.3	25.53	0.0189	22.8	23.0	34.7	0.0006	0.4314	0.0608	<0.0100
	2-yr	**29.7**	**28.5**	**27.4**	**26.2**	**0.0110**	**24.3**	**24.8**	**34.8**	**0.0005**	**0.2472**	**0.0480**	**>0.1500**
Length (log)	3-yr	6.4	6.1	6.3	6.1	0.3498	5.7	5.8	7.1	0.0186	0.8580	0.1740	<0.0100
	2-yr	6.6	6.5	6.5	6.3	0.2321	6.0	6.2	7.1	0.0091	0.5348	0.1625	<0.0100
Volume (none)	3-yr	40.7	40.5	31.6	32.8	0.0039	15.1	15.9	78.0	<0.0001	0.0022	0.1818	<0.0100
	2-yr	40.9	40.4	31.5	32.2	0.0172	14.5	16.1	78.2	<0.0001	0.0229	0.1814	<0.0100
Volume (sqrt)	3-yr	5.4	5.4	4.9	4.9	0.0173	3.4	3.6	8.4	<0.0001	0.0301	0.0594	<0.0100
	2-yr	5.5	5.5	5.0	4.9	0.0205	3.4	3.8	8.5	<0.0001	0.0579	0.0525	0.0874
Volume (log)	3-yr	3.0	3.0	2.9	2.8	0.2869	2.2	2.3	4.2	<0.0001	0.7283	0.0401	0.1433
	2-yr	**3.1**	**3.1**	**3.0**	**2.9**	**0.1270**	**2.3**	**2.6**	**4.2**	**<0.0001**	**0.3887**	**0.0301**	**>0.1500**
Snag Density (none)	3-yr	46.5	na	32.2	na	0.0520	38.4	40.5	39.2	0.9718	0.3571	0.1324	<0.0100
	2-yr	43.8	na	31.3	na	0.0780	37.6	35.7	39.5	0.9513	0.2751	0.1212	<0.0100

Table B-1. Continued.

Variable and	Data	Methods Comparisons[2]					Stand Type Comparisons[3]				Method *Stand Type	K-S Test of Residuals	
Transformation ()[1]	Set	CSP	CLI	RSP	RLI	p-value	A	NH-M	NH-UM	p-value	p-value	D Stat.	p-value
Snag Density (sqrt)	3-yr	5.8	na	5.1	na	0.1569	5.2	5.4	5.7	0.8754	0.4843	0.0602	0.1110
	2-yr	**5.8**	**na**	**5.0**	**na**	**0.1581**	**5.2**	**5.3**	**5.7**	**0.8797**	**0.4575**	**0.0694**	**0.1368**
Snag Density (log)	3-yr	3.1	na	2.9	na	0.4272	2.8	2.9	3.3	0.4824	0.6679	0.1521	<0.0100
	2-yr	3.1	na	2.9	na	0.3474	2.8	3.0	3.3	0.5389	0.7092	0.1600	<0.0100
Snag DBH (none)	3-yr	25.4	na	26.8	na	0.4380	18.7	21.1	38.4	<0.0001	0.8335	0.0881	<0.0100
	2-yr	25.9	na	26.8	na	0.6252	18.8	21.9	38.4	<0.0001	0.8383	0.0835	0.0796
Snag DBH (sqrt)	3-yr	4.9	na	5.1	na	0.2221	4.3	4.6	6.1	<0.0001	0.9295	0.0612	>0.1500
	2-yr	**5.0**	**na**	**5.1**	**na**	**0.4058**	**4.3**	**4.7**	**6.1**	**<0.0001**	**0.8640**	**0.0434**	**>0.1500**
Snag DBH (log)	3-yr	3.1	na	3.2	na	0.1270	2.9	3.0	3.6	<0.0001	0.9634	0.0344	>0.1500
	2-yr	3.2	na	3.3	na	0.2887	2.9	3.1	3.6	<0.0001	0.8178	0.0523	>0.1500
Snag Basal Area (none)	3-yr	4.7	1.7	2.2	1.9	0.0006	1.2	1.4	5.2	0.0001	0.0046	0.3108	<0.0100
	2-yr	4.5	1.9	2.2	1.9	0.0529	1.3	1.4	5.2	0.0023	0.0379	0.3373	<0.0100
Snag Basal Area (sqrt)	3-yr	1.7	1.4	1.5	1.4	0.0111	1.2	1.2	2.0	<0.0001	0.0222	0.1170	<0.0100
	2-yr	1.6	1.4	1.5	1.4	0.2141	1.2	1.2	2.0	<0.0001	0.0503	0.1185	<0.0100
Snag Basal Area (log)	3-yr	1.0	0.9	0.9	0.9	0.3979	0.7	0.7	1.5	<0.0001	0.1588	0.0548	<0.0100
	2-yr	**1.0**	**1.0**	**1.0**	**0.9**	**0.9237**	**0.7**	**0.7**	**1.5**	**<0.0001**	**0.2683**	**0.0468**	**>0.1500**
Living Basal Area (none)	2-yr	**na**	**na**	**na**	**na**	**na**	**15.3**	**21.3**	**26.6**	**<0.0001**	**na**	**0.1241**	**0.0101**
Living Basal Area (sqrt)	2-yr	na	na	na	na	na	3.9	4.6	5.2	<0.0001	na	0.1536	<0.0100
Living Basal Area (log)	2-yr	na	na	na	na	na	2.7	3.1	3.3	<0.0001	na	0.1952	<0.0100

[1] Transformations: none = raw data, sqrt = square root, and log = natural log.

[2] Methods: CSP = circuit strip-plot; CLI = circuit line-intercept; RSP = random strip-plot; and RLI = random line-intercept.

[3] Stand Type: A = aspen; NH-M = managed northern hardwood; and NH-UM = unmanaged northern hardwood (element occurrence).

Table B-2. Results of preliminary analyses of coarse woody debris and snag variables within four age classes of aspen forest stands. Data were collected in northern Michigan during 2005-2007 using the circuit strip-plot and line-intercept sampling methods.

	Aspen Age Class (estimates and p-value)					K-S Test of Residuals	
	20-year	40-year	60-year	80-year	p-value	D	p-value
density-none	69.2	114.2	141.0	184.6	0.0495	0.1176	<0.0100
density-sqrt	**6.6**	**10.1**	**10.6**	**12.6**	**0.0302**	**0.0659**	**>0.1500**
density-log	3.0	4.5	4.3	4.9	0.0167	0.1036	<0.0100
length-none	326.5	590.1	834.8	918.5	0.0220	0.1377	<0.0100
length-sqrt	**14.4**	**23.0**	**25.7**	**28.7**	**0.0114**	**0.1099**	**<0.0100**
length-log	4.1	6.1	5.8	6.6	0.0112	0.1861	<0.0100
volume-none	5.7	9.9	16.5	21.9	0.0212	0.1737	<0.0100
volume-sqrt	2.0	3.1	3.7	4.3	0.0086	0.0891	0.0487
volume-log	**1.3**	**2.2**	**2.4**	**2.7**	**0.0046**	**0.0501**	**>0.1500**
snagdens-raw	22.5	50.6	48.8	40.6	0.1765	0.1319	<0.0100
snagdens-sqrt	**3.3**	**6.5**	**6.2**	**5.6**	**0.0361**	**0.0917**	**0.0873**
snagdens-log	1.6	3.5	3.2	3.1	0.0080	0.1569	<0.0100
snagdbh-raw	---[1]	---	---	---	---	---	---
snagdbh-sqrt	---	---	---	---	---	---	---
snagdbh-log	---	---	---	---	---	---	---
snagBA-raw	**0.3**	**1.4**	**1.7**	**1.7**	**0.0040**	**0.0578**	**>0.1500**
livingBA-raw	---	---	---	---	---	---	---
livingBA-sqrt	---	---	---	---	---	---	---
livingBA-log	---	---	---	---	---	---	---

[1] Indicates the model did not converge.