COARSE WOODY DEBRIS DYNAMICS IN BLACK ROCK EXPERIMENTAL FOREST OF THE HUDSON HIGHLANDS

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ABSTRACT:

Coarse woody debris (CWD) consists of both standing dead trees (snags) and material that has fallen to the ground (downed woody debris; large branches and stems). CWD is added to ecosystems by numerous mechanisms, including wind, fire, insect attack, pathogens, competition, and geomorphology. During decomposition, logs and other forms of CWD (defined as wood pieces larger than 10cm in diameter and more than one meter in length) reduce erosion and affect soil development, store nutrients and water, provide a source of energy and nutrient flow, serve as seedbeds, and provide habitat for decomposers and heterotrophs. I inventoried and classified CWD amongst four dominant species (*Quercus rubra, Quercus prinus, Acer rubrum* and *Acer saccharinum*) at Black Rock Forest, a *Quercus*-dominated secondary forest in the Hudson highlands of New York State. I used field techniques of ranked decomposition class based on observational criteria and laboratory techniques using a CHN elemental composition analyzer and sequential fiber digestion method for fibrous material. The aim of this study was to 1) provide baseline values for CWD volume, biomass and carbon; 2) determine the overall class distribution of CWD; 3) to compare CWD amounts to other forest sites; and 4) profile the rate of mass loss from wood decomposition. Information gathered in this study provides an empirical basis for management guidelines at Black Rock Forest and clarifies the role of CWD in temperate forest ecosystem function.

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INTRODUCTION:

Coarse woody debris (CWD) is the least studied component of forest biomass, however it is an essential element of temperate forest ecosystems. CWD consists of both standing dead trees (snags) and material that has fallen to the ground (downed woody debris; large branches and stems). CWD is added to ecosystems by numerous mechanisms, including wind, fire, insect attack, pathogens and competition. Dead trees are associated with many key functions in forest ecosystems and because they may persist for centuries (McFee 1966, Triska 1980), their influence is as long lasting as that of living trees. During decomposition, logs and other forms of CWD (defined as wood pieces larger than 10cm in diameter and more than one meter in length) reduce erosion and affect soil development, store nutrients and water, provide a source of energy and nutrient flow, serve as seedbeds, and provide habitat for decomposers and heterotrophs (Franklin et al. 1981, Harmon et al. 1986). In addition, CWD has the potential to store a large amount of carbon in forest ecosystem. The role of CWD in storing carbon is often overlooked, with only plants (Woodwell et al. 1978) or soil carbon (Post et al. 1982, Schlesinger 1977) typically being considered in carbon budgets. Relatively little is known about the rates of formation, accumulation, and decay of CWD, or the factors controlling these processes, despite the relevance of this information to forest ecosystems and the global carbon cycle.

The relatively recent interest in the role of CWD in forested ecosystems started in the western United States and emphasized old-growth forests (Harmon et al. 1986). More recently, research on CWD has expanded to include eastern forests (Pyle 1998, Ducey 1999), although CWD dynamics in the northeast oak forests are still poorly understood (Gore and Patterson 1986, Tyrrell and Crow 1994, McGee 2000). The dynamics of CWD must be considered during forest management if managers wish to provide a continual source of standing and fallen CWD for a variety of functions, such as carbon storage, wildlife habitat and soil development. Although management guidelines have been developed for cavity-using wildlife in managed eastern forests (DeGraaf 1985, Tubbs et al. 1987), only generalized guidelines are available for other ecosystem functions of CWD in eastern forests (Hagan 1999). Guidelines provide lower threshold limits on a per hectare basis for the number snags and CWD logs need for cavity nesting wildlife. The Intergovernmental Panel on Climate Change has identified the accounting and research of CWD dynamics in the world's forest as a major line of division between basic (Tier 1) and intensive (Tiers 2 &3) management practices in combating climate change (IPCC 1996, 2001). Indeed, even the historic range of variability in CWD abundance is difficult to estimate as a result of the long period of land clearing for agriculture and timber harvest and other disturbances in the region. Estimates of variability are further complicated by our lack of understanding of mortality factors that were present a century ago, but are no longer present (Ellsworth 2003), and factors that are present now that were not in the past (Jenkins et al. 2000). For example, factors such as chestnut blight, gypsy moth infestations and climate change are likely influencing the number and volume of CWD within NE forests.

DISTRIBUTIONS OF CWD

Research on CWD decomposition has traditionally employed separate approaches for snags and downed woody debris (DWD). Studies of snag dynamics have tended to focus on fall rates and the factors affecting them (e.g., Cline et al. 1980, Lee 1998, Huggard 1999, Garber et al. 2005); some also have quantified rates of snag breakage (Landram et al. 2002) or progression through a series of decay classes (Raphael 1987, Morrison 1993). These analyses treat snags as discrete units whose condition can be expressed as a function of time standing. In contrast, most studies of decomposition of DWD have been based on Olson's (1963) model of plant litter decomposition, which uses an exponential decay function to describe density change over time. Extending this concept to decaying wood, many researchers have modeled the dynamics of DWD in terms of gradual loss of density (e.g., Lambert et al. 1980, Harmon et al. 1987). Some studies have also used the exponential decay model to represent the loss of volume through fragmentation (Lambert et al. 1980). Their approach tracks the amount of coarse woody debris within individual decay classes, and can be linked with habitat studies that have long used decay classes as a measure of the changing quality of CWD (Maser et al. 1979).

Where CWD carbon content has been directly studied, it has been observed that excluding CWD has substantially and systematically underestimated detrital carbon stores (Harmon and Hua 1991, Gore and Patterson 1986). CWD in *Quercus*-dominated sites have been observed to represent 4-9% of the total detritus with volumes 20-120m^3 ha^{-1} and containing 15-25 Mg C ha^{-1} (Harmon 1986, Yan 1990, Lang and Freeman 1978, Wilson and McComb 2005). Observations of carbon in CWD stores for Black Rock forest range from 5-33 Mg ha^{-1} (Schuster 2006). Aims 1 and 2 of this study will address the quantity of CWD and amount of carbon contained within CWD for a secondary growth *Quercus*-dominated forest. I will then compare carbon estimates for CWD on the North Slope sites to CWD amounts and total carbon estimates on long-term plots for Black Rock (Schuster 2006) and finally to other measured amounts of CWD for *Quercus* dominant forest communities. This study improves upon estimates of carbon inputs from tree mortality rates and surface stores and provides new category-specific measurements of these elements through CWD distributions for snags and DWD. My objective in carrying out these analyses of snag and DWD dynamics is to quantify the progression of CWD pieces through a series of decay classes from tree death until the late stages of log decomposition. Intensive management practices require accurate measurements of this essential forest element for various aspects of management practices and simulations to be used in future research.

In this study we will study the distribution of CWD in the *Quercus*-dominated secondary forest of Black Rock Research Forest in the Hudson Highlands of New York. Our objective is to inventory and classify CWD to 1) determine the overall size and decay class distribution of CWD amongst four dominant species (*Quercus rubra, Quercus prinus, Acer saccharinum* and *Acer rubrum*): 2) to measure changes in density in decaying CWD: 3) to profile the implications and relationships of CWD numbers and volumes to a variety of ecosystem functions. Information gathered in this study will provide an empirical basis for management guidelines and adds further clarity to temperate forest ecosystem function.

THESIS STATEMENT:

- How does tree species abundance within a forest vary the amounts of CWD in Black Rock Forest (in m^3 ha^{-1} and Mg C ha^{-1}) across plots and CWD types?

Null Hypothesis: CWD amounts for four dominant species exhibit no significant variation.

- How are the decay classes of CWD distributed?

Null Hypothesis: The distribution of CWD through decay classes is uniform.

- If CWD abundance varies by species, how does this affect the amount and distribution of carbon within a forest ecosystem (carbon Mg/ha distribution through decay class)?

Null Hypothesis: Carbon concentrations do not vary amongst plots or by species.

- How do CWD amounts (in m^3 ha^{-1} and Mg C ha^{-1}) for four dominant species (*Quercus rubra, Quercus prinus, Acer sacchrum* and *Acer rubrum*) in Black Rock Forest compare to other similarly composed forests in the region?

Null Hypothesis: CWD amounts for Black Rock Forest are within the range of variation observed at other sites.

METHODS:

STUDY SITE:[1] Black Rock Forest is a 1530-hectare scientific and educational research station located in the Hudson Highlands near Cornwall, NY (41° 24′ N, 74° 01′ W, Figure 1). Mean annual precipitation is 1190 mm and air temperature is strongly seasonal with monthly means ranging from –2.7° C in January to 23.4° C in July (Ross 1958, Turnbull et al. 2001, Engel et al. 2002). The forest soils are medium-textured loams and typically shallow in depth (0.251 m) with granite gneiss bedrock or glacial till parent material (Olsson 1981). The soils are acidic (pH 3.65-4.55), nutrient availability is low, and the site index ranges from poor to average (Lorimer 1981). Typical of much of the eastern deciduous forest following repeated logging and fires, forest regeneration has typically occurred through sprouting from hardwood stumps (Tryon 1939). *Quercus rubra* (Red oak) and *Quercus prinus* (Chestnut oak) are the dominant tree species accounting for 66% of the forest's basal area (Friday 1985). The understory includes many plants in the Ericaceae (e.g., *Kalmia, Vaccinium* spp*.).* The study area is located on the northern slope of Black Rock Mountain. The roughly 50 hectare area features a contiguous mature oak forest about 100-120 years old, typical of forests in the surrounding 2 million acre New York-New Jersey Highlands Province. Soils are all classified as Hollis slope soils, aspect is uniformly north, and slopes average 15% (range: 8 – 25%).

[1] Study site description provided in part by Bill Schuster, Black Rock Forest, and Kevin Griffin, LDEO.

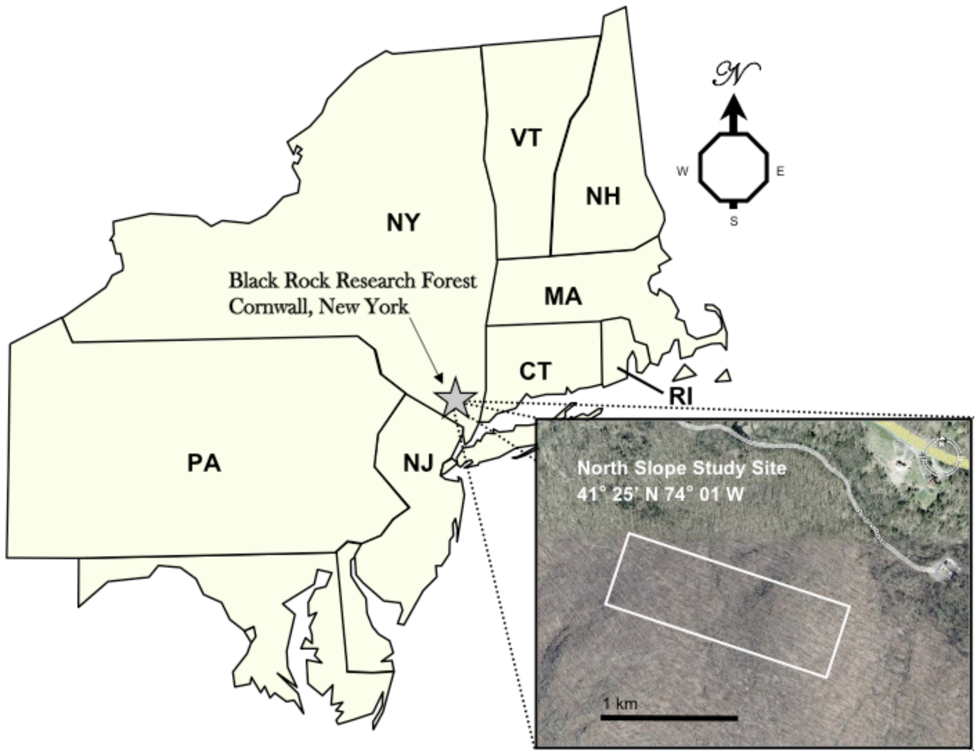

Figure 1: Study Site - Black Rock Research Forest study site and geographic location (Google Earth)

The site was clear-cut in the late 1800s and since has been managed as one unit, planned for eventual timber harvest (Tryon 1939). Thinning operations for firewood were made in 1932 and again around 1960. Long term plots in the forest initiated in the 1930s provide data on forest biomass aggradations. This has included significant losses due to canopy tree mortality since 1999. An important finding has been the dramatic increase in Quercus rubra biomass compared to other species, indicating this species has been the major benefactor subsequent to reductions of American chestnut (*Castanea dentata*) caused by chestnut blight.

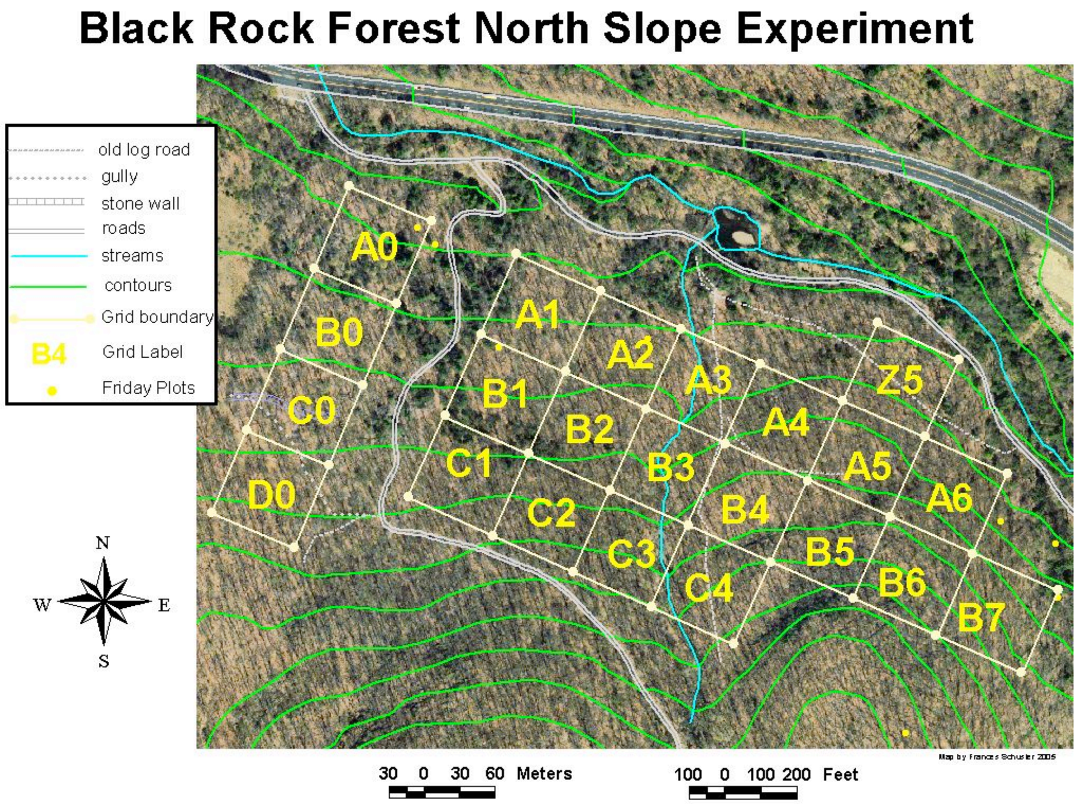

Figure 2: Study Site Plot Organization - Plots were divided and assigned names. A1-Z5 naming conventions correspond to specific plots and are used throughout the study and in the tables and figures presented in this text. Diagram courtsey of Bill Schuster.

The study site was divided into eighteen 0.56 ha forest plots (75 m x 75 m; labeled A1-Z5, Figure 2). The plots have a mean tree density of 515 trees greater than 2.5 cm diameter at breast height each plot measures 75 meters on a side. These plots were further subdivided into 9 subplots measuring 25 X 25 meter (Figure 3). The center subplot of the 3 x 3 arrangement was used in this study. The 25 x 25 m plot size is comparable to those used in other studies.

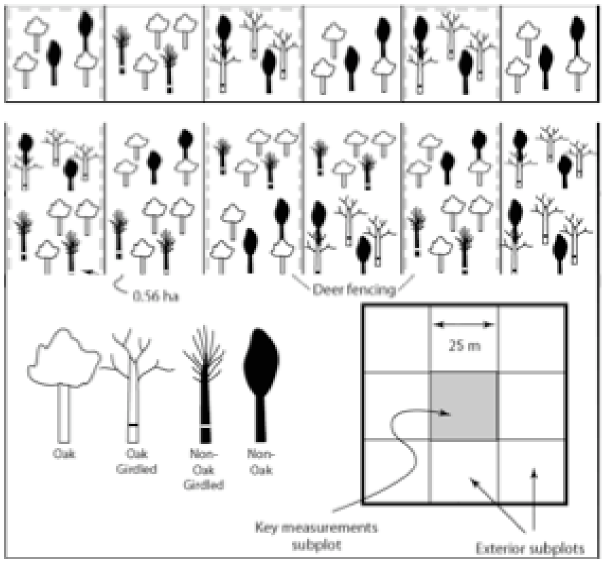

Figure 3: Subplot Divisions - Plots were divided into nine subplots in a 3 x 3 arrangement. Subplots are square, measuring 25 meters a side. Diagram courtesy of Bill Schuster.

EXPERIMENTAL DESIGN:

DATA COLLECTION: FIELD METHODS

Within each center subplot, a 1 meter-wide sweep of the forest floor was conducted. Twenty-five sweeps were performed in total to completely cover each center subplot. Thoroughly canvassing the entire forest floor for snags and DWD was determined to be the best method for complete census of woody material, as the dense litter layer can hide or obscure some material. When either a snag or DWD was encountered, it was measured and flagged to prevent double-inclusion.

This study only includes DWD >10cm diameter and >1.5 m length and snags >10cm diameter at breast height and >1.5m height. Within each subplot DWD was identified to species and measured for length, large diameter radius, small diameter radius and decay class according to visual criteria established by Sollins (1982). To assess the decay stage, CWD were examined for seven variables according to former studies (Sollins 1982; McCarthy and Bailey 1994; Pyle 1999): state of bark (intact or not), classes of bark cover (100, 99–50, 50–1, 0%), change in color in heartwood and sapwood (not changed or changed), hardness of heartwood and sapwood (hard or soft), with or without cracks, classes of deformation (intact, deformed, unable to support its own weight, hard to define), presence or absence of moss cover. The variables were thus ordinal categorical parameters (1, 2, 3, etc.) where higher numbers indicated more advanced decay status. Snags were identified to species and measured for height, diameter at breast height (DBH; 1.3 m), small diameter radius[2], and decay class according to criteria established by Hayden et al. (1995). Table 1 summaries decay class conditions with descriptions for both snags and DWD.

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[2] Assumed to be 10cm unless otherwise measurable.

Table 1: Decay Class Descriptions - Each decay class is based on observation criteria for the conditions of DWD and logs. Hayden (1995) and Sollins (1982) descriptions are used respectively for snag and DWD material.

Decay Class	Description
Snag[1]	
I	Tree is recently dead. Top is intact. Most fine branching still present. Bark is intact.
II	Top is intact. Most of the fine branches have dropped. More than 50% of the coarse branches are left. Bark may begin to loosen
III	Top is intact. Fewer than 50% of the coarse branches are left. Bark may or may not have sloughed off.
IV	Top is broken. No coarse branches remain. Bark may or may not have sloughed off. Height at least 6m.
V	Top repeatedly broken. No coarse branches remain. Bark may or may not have sloughed off. Height less than 6 m.
DWD[2]	
I	Wood is hard. All bark is still intact.
II	Wood is hard. Bark has begun to fall off.
III	Wood is soft and has some give when kicked. Usually no bark remaining.
IV	Wood is substantially decayed and pieces easily slough off. Inner heartwood may be soft but is intact. Moss usually present on the outer surface.
V	Wood is decayed throughout. Texture is powdery and resembles soil.

Snag and DWD volumes were calculated for each piece using the following equation for a frustrum cone:

VOLUME = $1/3\,\pi\, l\,(r^2 + R^2 + rR)$

- Where R is the large radius, r is the small radius and l is the length (for snags height replaces length). The end diameters for snags are calculated with a 10cm diameter.

The total DWD volumes were summed per each subplot, per tree species and per decay class. These volumes were then converted to per-hectare estimates.

DATA COLLECTION: LAB METHODS

For each decay class a series of samples was collected for compositional assays. Samples are either cross sections or cores, depending on which technique provided a sufficient sample to characterize the decay class and be used in later analysis (typically between 10-50 grams). Coring was the preferred sample collection method, however later decay classes (i.e., IV and V) proved difficult to collect given their advanced state of deterioration. In these cases, cross-sections or bulk samples were taken. Cross-sections are made by cutting logs through perpendicular to the length (these samples are commonly called “cookies”). Samples were collected from tagged, known CWD observed during field collection. When and where species and decay classes were under-represented for sample collection in the study plots, material from surrounding forest floor was used. Samples were collected to achieve five samples per decay class per species for a total of 100 samples (4 tree species x 5 decay class x 5 samples of each).

Core samples were trimmed to 15cm lengths and then weighed. Core diameters were estimated using the bore diameter of the tree corer used to gather all samples. Volume was calculated by using the volume of a cylinder.[4] Cross-section samples were standardized to fixed volumes, typically 1cm width x 1cm height x 15cm length. Mass over volume was used to derive the density of wood for tree species.[5] Only sapwood and heartwood material were used in density measurements; decay classes III, IV and V had scarce to no bark present, limiting the accuracy of density measurements; as such, they were excluded from this portion of the study. All density measurements are displayed in g/cm^3. Bulk density averages for each decay class were used to convert volume to dry mass using the following equation.

EQUATION: CWD MASS PER PLOT = $\Sigma V_I D_I$

- Where v_i is the volume of the ith decay stage per plot, d_i bulk density of ith decay stage, and where average (±1 SD) bulk densities for *Quercus rubra* were $d_1 = 0.56 \pm 0.08$ g/cm^3, $d_2 = 0.50 \pm 0.06$ g/cm^3, $d_3 = 0.44 \pm 0.10$ g/cm^3, $d_4 = 0.22 \pm 0.06$ g/cm^3 and $d_5 = 0.14 \pm 0.06$ g/cm^3 (average bulk densities were different for *Quercus prinus*, *Acer rubrum* and *Acer saccharinum*)

Carbon calculations utilize Harmon’s (1986) study which show carbon estimates to be 0.496% of the mass no matter what stage of decay the material may be in. As such, the carbon amounts for each decay class are calculated from the material mass numbers as devised in the equation above.

ANALYTICAL METHODS: DECAY RATE MODELING

EQUATION:

$X = X_0 e^{-kt}$

- Where X is for present wood density, X_0 is initial wood density, k is decomposition constant, t is time.

[4] Equation for volume of a cylinder: $\pi r^2 * h$ (pi*radius^2*height).

[5] Equation for density: $d = m/V$; density g/cm^3

Olson's (1963) decay models were used to plot density loss across decay class, the assumption being that decay is proportional to the amount of material remaining. Utilizing these models in the study requires the ability to track the input and sequence of CWD from death to fall (for snags) and decomposition state of DWD upon input to the forest floor. While the time component in the above equation is not known at the time of this writing, this study's CWD analysis represents density loss through decay stages using a line-of-best fit through means and standard deviations.

One-way analysis of variance (ANOVA) was used to test the hypothesis for volume (m^3 ha^{-1}), mass (Mg ha^{-1}), elemental C (Mg/ha) content of the CWD, separately amongst plot, species and decay class distribution. Calculations and analysis were performed in Microsoft Excel©, JMP Statistical Software© and Synergy Software Kaleidagraph©. All lab work was conducted under the supervision of Kevin Griffin at his lab at the Lamont Doherty Earth Observatory in Palisades, New York.

RESULTS:

The study site was chosen in part due to its rather homogenous assemblage per plot of the four dominant species. Per plot CWD volume (m^3 ha^{-1}) was highly variable, with no uniform pattern attributable to lower elevations sites (A1-A6) or higher elevation sites (C1-C4) (Figure 4). Plot A4 had substantially more CWD than any other plot. Within this plot several trees had recently fallen. These CWD inputs were the result of increased erosion of soils from the bases of the trees. This occurrence is seen as a naturally occurring input of CWD to the forest system, and as such these trees and their resulting volumes were left in the per plot totals.

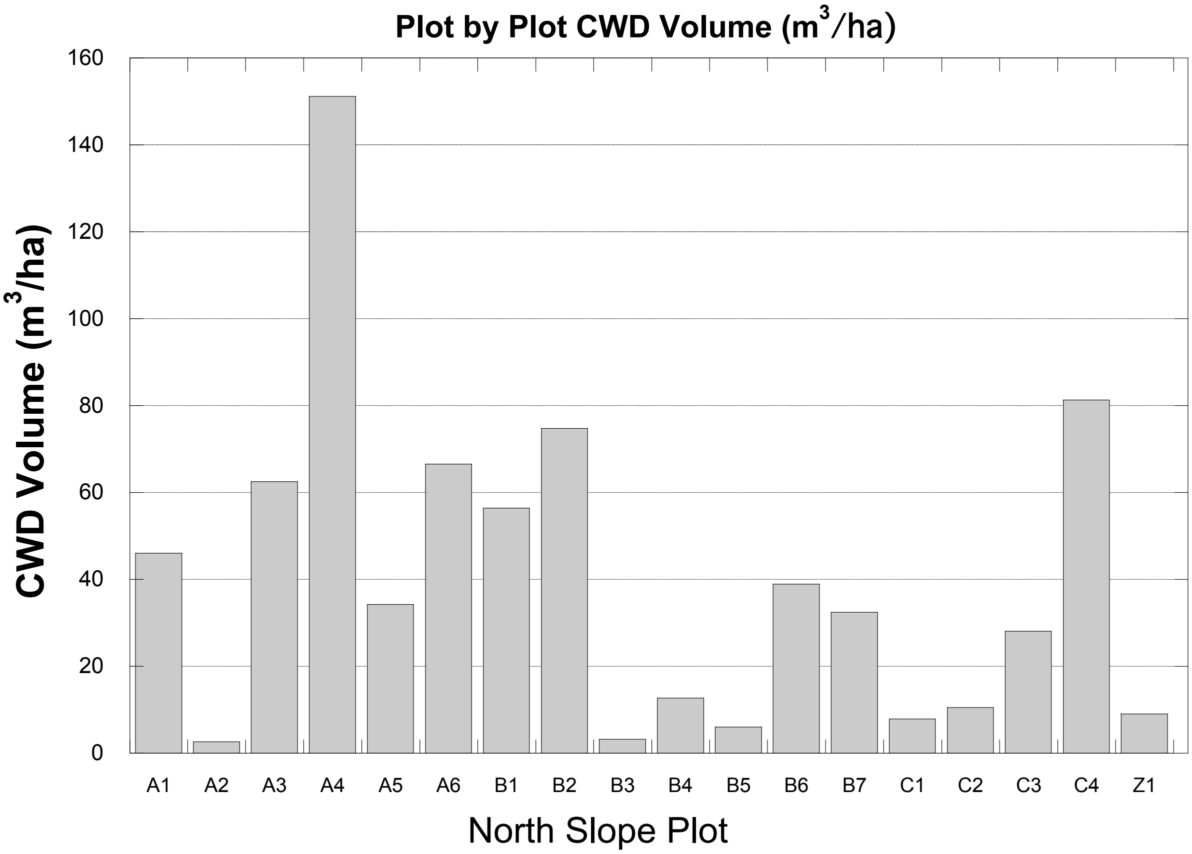

Figure 4: Plot-by-Plot CWD Volume – CWD volume per hectare amounts are compared between subplots. Mean CWD for the eighteen plots was 40.3 ± 38.0 m^3 ha^{-1}. Mean per hectare CWD volume for the North Slope of Black Rock Forest is at the lower end of the spectrum for forest communities in the Northeast (Table 2). Both Carbonneau and McGee studies note the effect of beach bark disease on mean CWD volumes and recommended lower than observed volumes.

(n = 263)

Table 2: Study Site Comparisons - Total CWD volumes ± 1SD for this study are compared for similar forest communities of North East. Studies have been divided by stand age.

Study	State	Forest Type	Volume (m^3/ha ± SD)
Old Growth (100yrs+)			
Carbonneau (1986)	NH	northern hardwoods	166±42
McGee (1999)	NY	northern hardwoods	139±22
Goodburn and Lorimer (1998)	WI/MI	northern hardwoods	102±6
Hardt and Swank (1997)	NC	sugar maple	86
Harmon (1986)	TN	beech-birch	82
Lang and Forman (1978)	NJ	oak	47
This Study	NY	mixed oak	40±37

Goebel and Hix (1996)	OH	mixed oak	30±31
Maturing (70-100yrs)			
McGee (1999)	NY	northern hardwoods (89-103yr)	61±16
McCarthy and Bailey	MD	mixed mesophytic (65-89yr)	42
Goebel and Hix (1996)	OH	mixed oak (90-109yr)	22±20

Total CWD volume for individual tree species was also variable between species (Table 3). Sixty-eight observations of *Quercus rubra* were made representing 35% of the total volume per hectare; this is substantially more than for other species studied. No observations were made of *Quercus prinus*, *Acer saccharinum* or *Acer rubrum* in decay class I. Volume observations were made for *Quercus rubra* and *Quercus prinus* in decay class V, however these were less than then significant digits so are displayed as zero values. Few observations were made for *Acer saccharinum* or *Acer rubrum* in decay class V and are similarly below displayable values.

Total CWD biomass was calculated to be 17.9 ± 16.8 Mg/ha and highly variable. *Q. rubra* accounts for more than half of the CWD biomass in Black Rock Forest. *Q. prinus*, *A. saccharinum* and *A. rubrum* CWD biomass levels were lower, however within expected ranges based on the number and size of the observations in this study. Carbon Biomass was 8.9 ± 8.3 Mg/ha and highly variable as well. *Q. rubra* accounts for more than half of the CWD Carbon biomass in Black Rock Forest. *Q. prinus*, *A. saccharinum* and *A. rubrum* CWD biomass levels were lower, however within expected ranges based on the number and size of the observations in this study.

Within each species, decay class III accounts for most volume, biomass and carbon.

Table 3: CWD Volume, Biomass and Carbon Amounts – Total forest CWD amounts are broken out by the four study species and by decay class. Biomass amounts and carbon totals are shown for study species and for decay classes. Values are shown ± SD

Species/Total/Element		Number of records	Mean diameter (cm)	Volume (m3/ha)	Biomass (Mg/ha)	Biomass Carbon (Mg/ha)
Total forest CWD*		**263 (18 plots)**	**17.4**	**40.3 ± 38.0**	**17.9 ± 16.8**	**8.9 ± 8.3**
Red Oak						
	Specie totals	**118**	**17.7 ± 8.8**	**21.2 ± 1.3**	**9.4 ± 0.1**	**4.7 ± 0.1**
	Decay Class					
	I	7	25.8 ± 12.7	2.9 ± 0.4	1.6 ± 0.0	0.8 ± 0.0
	II	13	19.5 ± 9.2	2.3 ± 0.3	1.2 ± 0.0	0.6 ± 0.0
	III	68	17.2 ± 8.5	14.2 ± 0.5	6.2 ± 0.0	3.1 ± 0.0
	IV	21	16.3 ± 8.2	1.4 ± 0.1	0.3 ± 0.0	0.2 ± 0.0
	V	9	16.6 ± 6.1	0.4 ± 0.0	0.1 ± 0.1	0.0 ± 0.0
Chestnut Oak						
	Specie totals	**52**	**18.1 ± 8.4**	**9.7 ± 1.2**	**3.9 ± 0.1**	**1.9 ± 0.1**
	Decay Class					
	I	0	0	0	0	0
	II	6	10.5 ± 0.7	2.5 ± 0.7	1.4 ± 0.0	0.7 ± 0.0
	III	30	17.4 ± 0.4	6.3 ± 0.4	2.2 ± 0.0	1.1 ± 0.3
	IV	11	17.9 ± 0.1	0.7 ± 0.1	0.2 ± 0.0	0.1 ± 0.0
	V	5	19.3 ± 0.1	0.30 ± 0.1	0.1 ± 0.0	0.0 ± 0.0
Red Maple						
	Specie totals	**34**	**14.2 ± 2.0**	**2.0 ± 0.0**	**0.6 ± 0.1**	**0.3 ± 0.0**
	Decay Class					
	I	0	0	0	0	0
	II	7	12.6 ± 2.4	0.2 ± 0.0	0.1 ± 0.0	0.0 ± 0.0
	III	20	15.0 ± 8.0	1.6 ± 0.5	0.5 ± 0.1	0.3 ± 0.0
	IV	6	17.8 ± 9.4	0.1 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	V	1	11.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Sugar Maple						
	Specie totals	**39**	**17.2 ± 9.4**	**6.8 ± 0.5**	**2.8 ± 0.1**	**1.4 ± 0.0**
	Decay Class					
	I	0	0	0	0	0
	II	3	11.3 ± 1.5	0.1 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	III	30	17.7 ± 9.8	6.4 ± 0.4	2.7 ± 0.1	1.3 ± 0.0
	IV	5	18.7 ± 10.2	0.2 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	V	1	15.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0

* Includes snags and other species not listed below

Mean species volumes ± 1SE are compared for the four dominate species of the North Slope (Figure 5). *Quercus rubra* mean volume per plot were significantly higher than *Quercus* prinus, *Acer rubrum* and *Acer saccharinum* (ANOVA: $F_{3,68} = 5.2$, p = 0.002). Tukey's Test shows similarity between groups using an A-B categorization. *Q. rubra* is similar to *Q. prinus* in variation of mean volume per plot, however is distinct from *A. saccharinum* and *A. rubrum*. Both *A. saccharinum* and *A. rubrum* mean volumes per plot were similar.

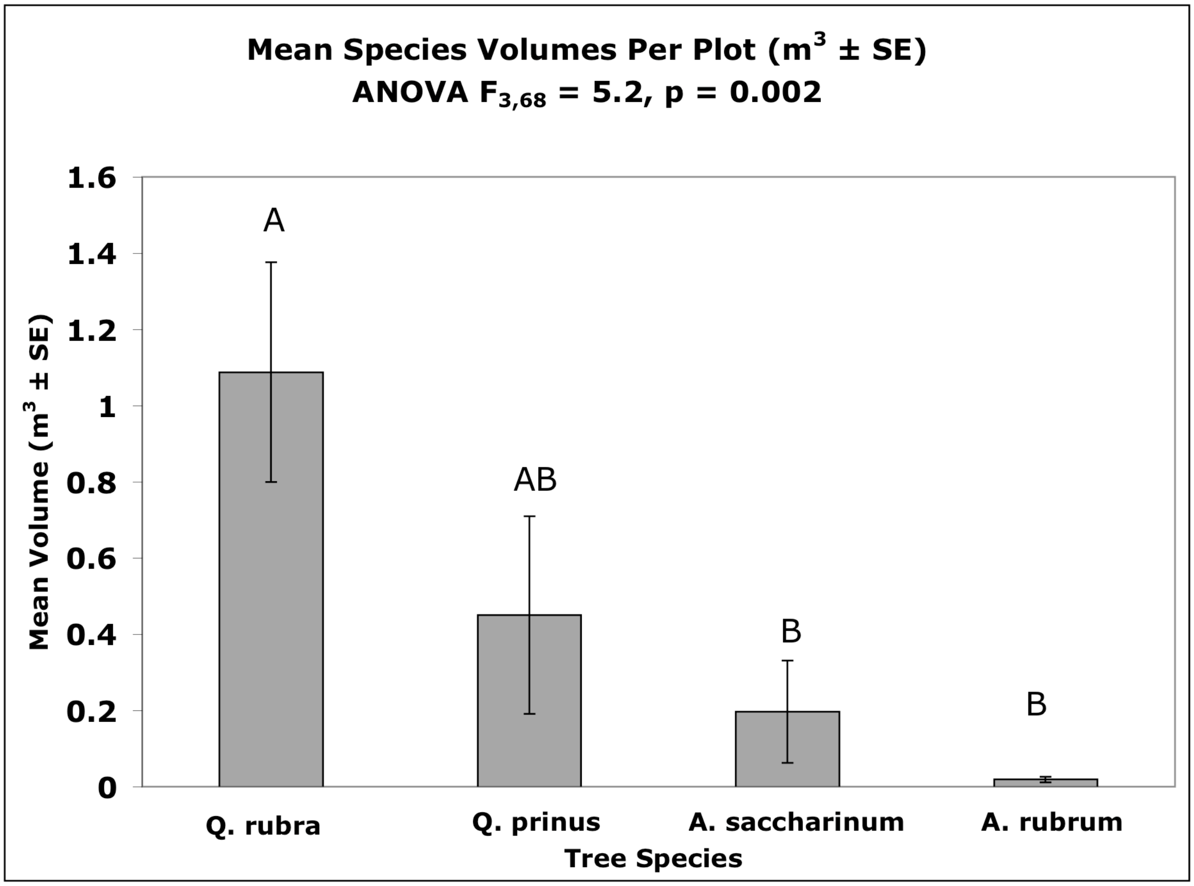

Figure 5: Comparison of CWD Between Species - The four study species are compared in an ANOVA with Tukey's Test. Values are mean volumes per plot ± SE. A-B classifications note similarity between groups.

The distribution of CWD decay classes was non-uniform (Figure 6). Decay class III is represented more than all other decay classes. Decay classes I and II are the least represented of the distribution. Decay classes IV and V were observed with some frequency, but were much less than decay class III. The chi square value for CWD distribution was 82.6, $p < 0.0001$ when compared to a uniform model of distribution.

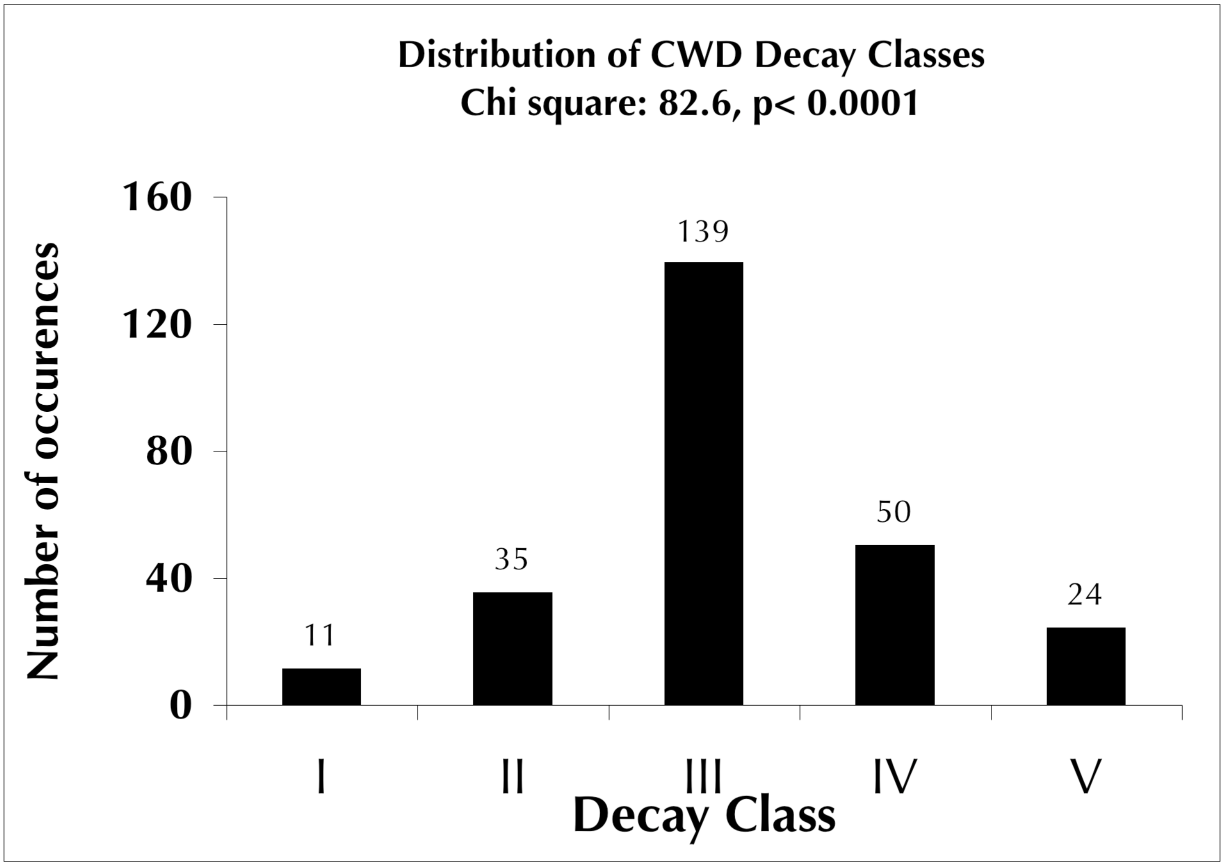

Figure 6: CWD Decay Class Distributions - Decay class distributions for all species are compared based on total number of occurrences within the study. Chi square values are shown

In comparing the difference between species in mean log volume, no significant variation was found (Figure 7). The mean size of logs for *Q. rubra* was similar to those of *Q. prinus, A. saccharinum* and *A. rubrum*. All mean log volumes were highly variable with *Q. rubra* demonstrating the greatest variation.

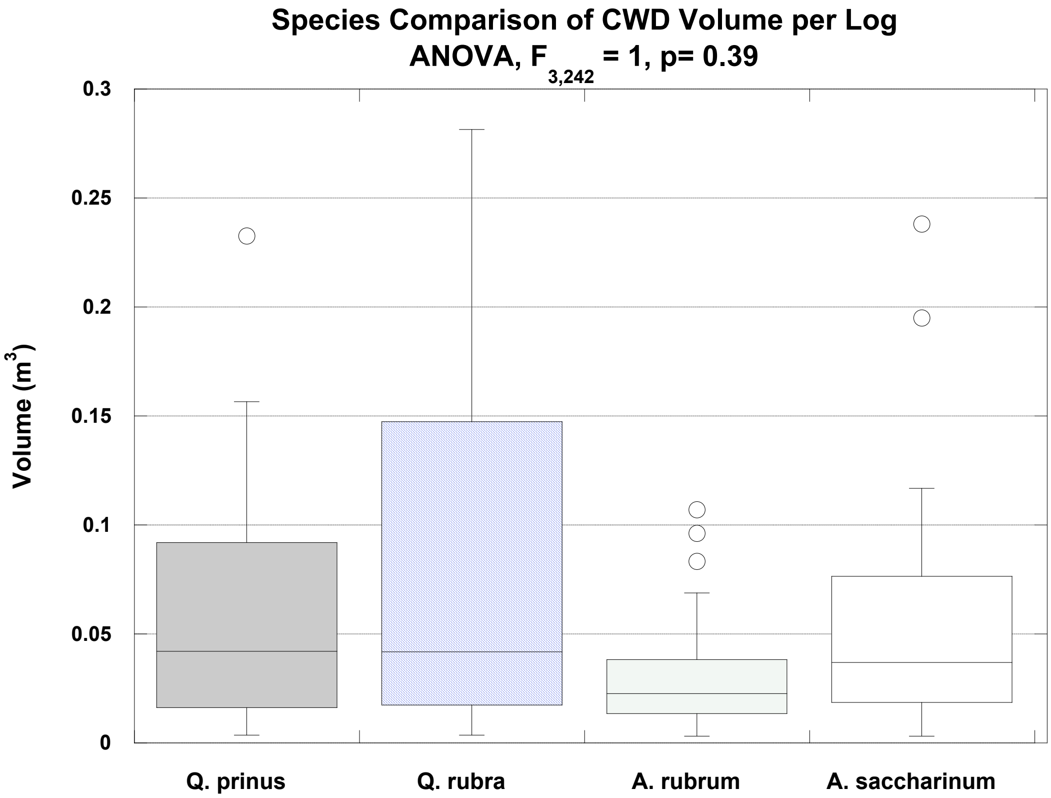

Figure 7: Mean Log CWD Volume - The four study species mean CWD volumes ± SD. ANOVA analysis results are shown.

Density profiles for the four study species show a similar rate of decay (Figure 8). Second-degree polynomial lines are fitted to the data. *Q. rubra* line-of-best fit displays the most complex shape while *Q. prinus*, *A. saccharinum* and *A. rubrum* are near linear in shape. Decay class II and III density was highly variable for all species.

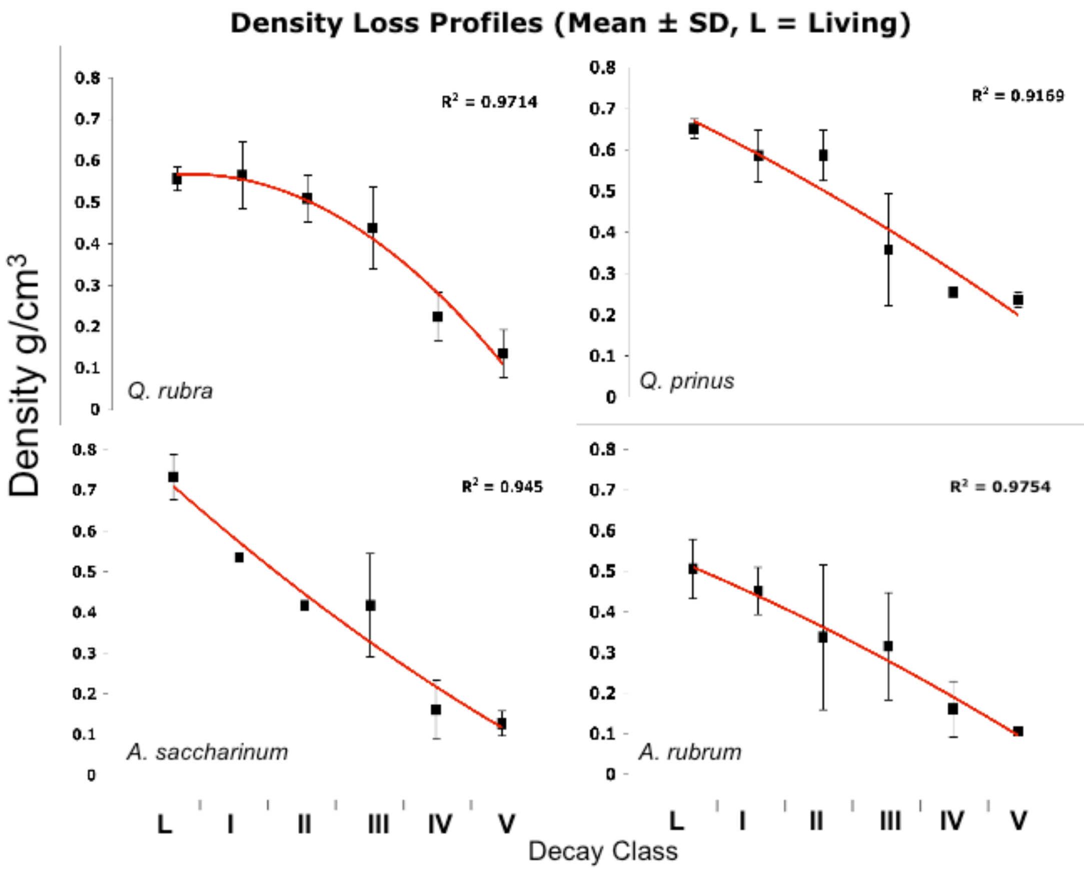

Figure 8: Density Profiles - Density profiles are compiled for each of the four dominant species of the North Slope. Markers are mean density - for each decay class including living. Second-degree polynomial lines-of-best-fit are fitted to the data with r^2 values.

In breaking out the study's DWD and snag observations into diameter classes, we see notable differences in the number of occurrences and volumes per hectare. The per hectare number of DWD occurrences for diameter class 10-20 cm was 157.3, five times the next largest category of 20-30 cm. However, abundance in this category only attributes to 10.5 m^3 ha^{-1}. Conversely, 11.6 snag per hectare in the 30-50 cm category accounts for 16.5 m^3 ha^{-1} of the volume on the North Slope of Black Rock Forest.

Table 4: Diameter Class for DWD and Snags - Per hectare DWD and snag observations are categorized for four diameter classes.

Diameter (cm)	Number of DWD	Number of Snags	Volume (m^3/ha)
10 - 20	**157.3**	13.3	10.5
20 - 30	31.1	6.2	10.0
30- 50	11.6	**11.6**	**16.5**

> 50	0.9	0.9	3.3

DISCUSSION:

The study plots proved to be highly variable. Many of the natural mechanisms of CWD input were observed on the North Slope. Soil erosion, blow downs and competition are some noteworthy examples.

The site was chosen in part because of its homogenous assemblage per plot of the four dominant species. This study found that CWD volumes for *Q. rubra* were significantly higher than for the other species (ANOVA: $F_{3,68} = 5.2$, $p = 0.002$). The evidence rejects our null hypothesis that CWD volumes for the four species are equally abundant. The evidence definitively demonstrates that the dominance of *Q. rubra* in the canopy is reflected in the CWD volumes of the forest floor. In interpreting the analysis of species CWD volume on a per plot basis *Q. rubra* shared some similarity in variation to *Q. prinus* and was unique to *A. saccharinum* and *A. rubrum*.

Decay classes were non-uniform in their distribution, with decay class III occurring substantially more than any other decay class. As such, the evidence reject s the null hypothesis that decay class distribution is uniform, from which it can be concluded that the study captures the unique decay signature by categorization into classes. The over representation of decay class III has two likely reasons: one is that decay class III reflects some historical or natural event, which is echoed or captured in this class; or that the categorizations of decay classes based on visual criteria does not account for a longer residence time of woody material in this class. A follow-up study this will look add a time component to the decay class system and hopefully shed some light on this observation of decay class III over-representation.

Of the 264 CWD observations made in this study the vast majority were *Quercus rubra* and account for ~50% of the volume at this site (Figure 9). Thinning and selective harvesting operations were conducted at several stages in the 20th century to promote the growth of *Quercus rubra*. *Quercus rubra* living biomass is dominant on this site in part for this reason and is also evident in CWD volumes. In looking at the number of observations for *Acer rubrum* it seems that this doesn’t translate into a relative proportion of volume.

When looking at mean log volume size compared between species no significant difference is found. Size does not matter with regards to DWD log volume. Small basal area and yet high stem density species can likely contribute to CWD amounts as can larger stemmed species.

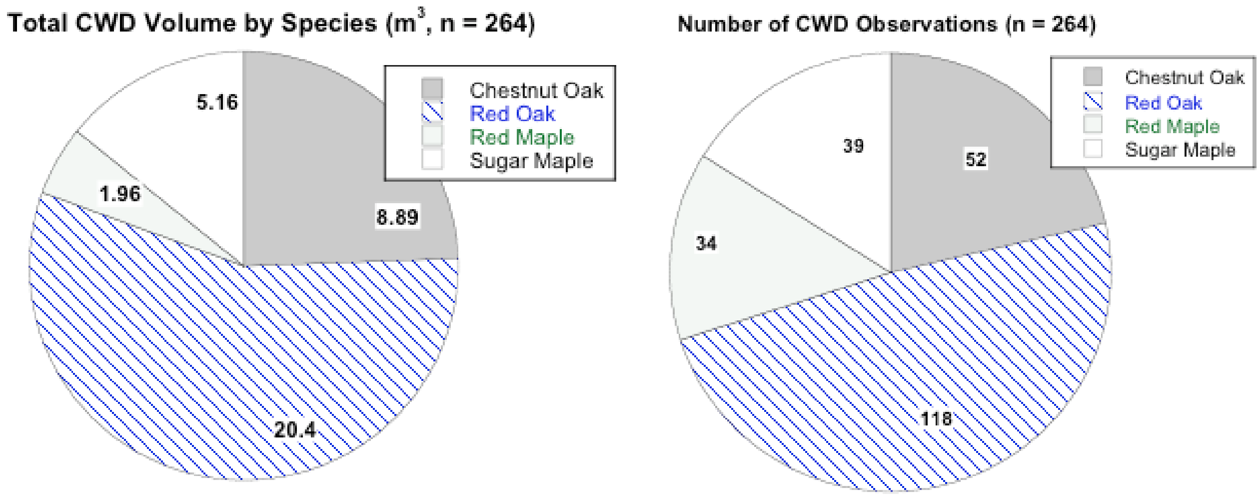

Figure 9: Total Species Volume to Number of Observations Comparison: Total CWD volumes and the number of observations that this volume represents for the study's four dominant species are compared side-by-side

SITE COMPARISONS

An important distinction in understanding the role of CWD is the difference between old growth oak forests and managed secondary growth oak forests. Studies have shown that as a forest matures CWD amounts increase until a steady state is reached (Harmon and Hua 1991, Wilson and McComb 2005). The large variation in volume measurements and carbon content have been explained by differences in forest management and the effects of environmental factors (climate, disturbance regime, decomposition rates, etc.) on CWD deposits as they accumulate towards a natural equilibrium.

The proportion of trees that were snags with diameter >10 cm at Black Rock Forest (65%) was within the upper range for oak forest cited by Tritton and Siccama (1990). This study measured 6.2-13.3 snags ha^{-1} with dbh > 10 cm, but only 0.9-11.6 snags ha^{-1} with dbh > 30 cm. Hunter (1990) summarized snag densities in a variety of forest types and stand ages. Snag densities greater than about 10 cm dbh in eastern forests range from 4 snags ha^{-1} in a Maine deciduous forest to 84 snag ha^{-1} in cove hardwoods in Kentucky. McGee et. al (1999) found 96.3 snags ha^{-1} in a 90-100 year old northern hardwood stand in the stem exclusion phase of stand development. Rubino and McCarthy (2003) found only 26.8 snags ha^{-1} in a central hardwood forest, and 24% of the 0.5 ha plots had no snags. Snag densities for Black Rock Forest are lower than observed in other forest sites.

The mean snag and log volumes 40.3 m^3 ha^{-1} were much lower than others sites reported in the literature. Spies and Frankling (1991) indicated that 93-165 m^3 ha^{-1} could be expected in western coniferous forests of a comparable age. After clear-cutting a hardwood forest in Maryland, CWD initially decreased then gradually increased for >100 years, but was 52 m^3 ha^{-1} at 80 years (McCarthy and Bailey 1994). An old growth forest in Kentucky averaged 66 m^3 ha^{-1}, but was highly variable; CWD per plot varied 0- 239 m^3 ha^{-1} (Muller and Liu 1991). The closest forest in comparison comes from McGee et al. (1999), which measured 41 m^3/ha of CWD logs in a 90-100 year old northern hardwood forest. Rubino and McCarthy (2003) found 2.2-154.8 m^3 ha^{-1} of CWD logs in Ohio, with a mean of 42 m^3 ha^{-1} and oaks having 28.6 m^3 ha^{-1}. Given the high variability of CWD in other studies I expected some plots to have no logs; however, in this study 100% of the plots had logs present. Aims 1 and 2 of this study provide data regarding volume, mass, and CWD decay class distribution in order to make comparisons to other similarly composed forest communities. Forest managers can then assess an appropriate, natural CWD load to reflect the current observations of CWD elsewhere.

The major factor in the low amount of CWD is that Black Rock Forest is primarily in the stem-exclusion phase of stand development, where the high densities of small snags I observed are expected (Vanderwel et al. 2006), and it is the phase of development that typically has the lowest CWD biomass (Gore and Patterson 1986; Spies et al. 1988). Rapid decay rates in this forest (McComb 2003), combined with the small size of dead trees, equates to the low amounts of CWD on the ground.

Decay rates are highly variable among species, plots and between solid and hollow logs (McComb 2003). In general, eastern hardwoods decay more rapidly than western conifers (Harmon 1986; Vanderwel et al. 2006). Several studies have found relatively few logs in the late, highly decayed classes, either because the decay rates are high in late stages of decay or because identification is inhibited by the other material on the forest floor (leading to a bias of under-representation in the latter stages). We could not reliably estimate decay rates because this study represents the first, baseline assessment of woody decay at Black Rock Forest. I found that only 7.2% of the logs were in the two most highly decayed classes.

CWD and Carbon Storage

Schuster (2006) collected data on carbon and other organic material for the Black Rock Forest environment. The focus of that research has largely been on living biomass. Some surface data exists, however this data is less developed systematically according to various processes, mechanisms or species relationships. In previous studies, observations of carbon in CWD stores for Black Rock Forest range from 5-33 Mg ha^{-1} (Schuster 2006). Carbon stores in CWD for the North Slope site of Black Rock Forest were 8.9 ± 8.3 Mg ha^{-1}. This number contextualizes the CWD environment of the North Slope for carbon stores. The North Slope environment receives less than optimal daylight compared to south facing slopes, and as such, has a shorter growing season. Whether this directly impacts CWD volume is not known, however, it is within reason to suggest that CWD volumes could be at the lower end of the ranges for Black Rock Forest as a result.

Observations have shown that over the last 50 years biomass accumulation of *Quercus rubra* has increased in this area in response to increasing regional temperatures (Wallach et. al. 2006). The change this has on competitive dynamics, succession and mortality may be reflected in inputs of CWD. A regression analysis between basal areas for *Q. rubra* and CWD volumes for a per plot basis could demonstrate a relationship between. From such an analysis current and future increases in biomass would be added to the Black Rock CWD pool compounding the storage of carbon on two fronts; living and dead biomass. Given that this forest is in an early stem exclusion stage and CWD carbon stores are low, this forest has a large potential for future storage as this forest ages and climate increases biomass accumulates.

POTENTIAL IMPLICATIONS FOR ECOSYSTEM PROCESSES

Overall, Black Rock Forest appears to have less than the recommended numbers of large snags and CWD to support cavity-nesting wildlife (Tubbs et al. 1987). This low abundance of large snags and CWD could have significant implications for several ecosystem processes, including habitat for animals dependent of dead wood, seedbeds for plant establishment, and storage of carbon. Because of the high variability among plots, only a few plots had enough snags and CWD to meet most guidelines developed to ensure the persistence of populations of cavity-using animals. Evans and Conner (1979), Tubbs et al. (1987), and DeGraaf and Shigo (1985) provided estimates of snag diameters needed to support a suite of cavity nesting birds found in northeastern forests. In general, four size classes seem to encompass the needs of a broad suite of species: dbh >10 cm (e.g., black-capped chickadees, *Poecile atricapillus* L.), dbh > 20 cm (e.g., downy woodpecker, *Piciodes pubsecens* L.; eastern bluebirds, *Sialia sialis* L.), dbh > 30 cm (e.g., American kestrel, *Falco sparverius* L.; northern flicker, *Colaptes auratus* L.; hairy woodpecker, *Piciodes villosus* L.; red-breasted nuthatch, *Sitta canadensis* L.) and dbh >50 cm (e.g., pileated woodpecker, *Dryocopus pileatus* L.; barry owl, *Strix varia* Barton). Based on the diameter and distribution of snags using these size classes, only 0.9-11.6 snags/ha are available within the north slope environs at Black Rock Forest for those species using snags with dbh > 30 cm.

Typically, snags with dbh > 10 cm are considered to be of some value for foraging birds and those with dbh > 20 cm might be used by at least the small cavity nesters. Hunter (1990) concluded that 5-10 large snags ha^{-1} would be sufficient to sustain most vertebrate species dependent of dead wood in a managed stand. New Hampshire guidelines call for > 6 snags ha^{-1} of which 3 are > 30 cm and one > 46 cm (Hagan and Grove 1999). Compared with these guidelines, Black Rock Forest has an adequate number of snags**.**

Rapid decay rates associated with dead wood in these systems further limits the availability of CWD for many organisms. Relatively strong relationships between forest floor vertebrate occurrence and abundance with CWD volume are observed in western and eastern forests (McComb 2003; DeGraaf and Yamasaki 2001). Certain species such as salamanders (e.g., Plethodontidae), small mammals (e.g., *Sorex* spp., *Peromyscus* spp. and *Clethrionomys* spp.) and ruffed grouse (*Bonasa umbellus* L.) use CWD in eastern forests (DeGraaf and Yamasaki 2001), but large logs are rare in these forests. Thus, species that utilize CWD resources in northeastern forests at the present must adapt to the abundance, sparse distribution and rapid turnover rates within these systems.

Until this forest ages or until additional exogenous disturbances occur to kill large trees, many of the functions of dead wood typical of other forest types, such as erosion prevention, seedling establishment and carbon storage (Harmon et al. 1986) may be limited. Several factors combine to influence the amount of CWD at Black Rock Forest. There was no dead-wood legacy following field abandonment at stand establishment: most logs and firewood were extracted after harvest and thinning operations in the mid-20th century. This study observed an irregular distribution of CWD across the landscape and the static rate of decay across tree species. Disease, defoliating insects, ice storms and large-scale blow-down events may change current conditions markedly, but as noted from the pulse of CWD with the decay class III, likely related to thinning treatments, these effects on CWD abundance in the system are long lasting. Clearly, we need additional information to fully understand how dead wood functions in contemporary forests, with frequent exotic insect and disease influences, compared with historic conditions under which many species evolved.

Black Rock Forest is representative of the mostly even-aged forests in southern New England. Two special issues of journals (e.g., Trani et al. 2001; Litvaitis 2003) have stressed the need for creating and maintaining early successional stages for certain wildlife species because short, dense vegetation of that stage is largely missing in the northeastern forests. This study shows that large snags and CWD are also limited habitat elements in these forests. Along with creating early-successional forests, managers may wish to consider retaining trees and snags in early-successional patches, typical of what might have occurred following natural disturbances. In addition, they may wish to maintain the small proportion of older stands in the region while enhancing the development of big trees through thinning, to eventually create large logs and snags of CWD that can be incorporated into all stages of forest succession.

CONCLUSION:

The mean CWD volume per hectare for the North Slope site of Black Rock forest is 40 ± 38 m^3 ha^{-1} and at the lower end of the spectrum for forests of a similar age and type in the Northeast. Similarly, CWD biomass and carbon mass are both at the end of the ranges when compared to Black Rock Forest estimations and other studies conducted in the northeastern United States. This study demonstrates that *Quercus rubra* is the dominant tree species exactly to what is observed in the forest stand. *Quercus rubra* represents a sizable portion of the CWD, deadwood biomass and carbon for this forest. Decay class III dominates the decay class distribution of CWD. Whether decay class III's abundant representation is a product of some historical or natural phenomenon registered in the decay classes, or demonstrates that decay classes based on observational criteria poorly capture the nuances of woody decay is not known at this time. Further investigations using time as second variable may provide a probable answer.

Like most of southern New England, the area was reforested after agricultural abandonment, and there was extensive cutting of the second-growth forest. Thinning and management practices can be a significant source of CWD for numerous ecosystem functions if left to remain in the forest. This study demonstrates that CWD volumes for the Black Rock environment reflect stand traits. Considering in part the various unique components of CWD, snags and DWD, this study shows that CWD numbers are adequate to sustain narrow ecological functions such as cavity nesting sites. However, when considered collectively in serving large ecological roles, such as providing reservoir carbon storage, preventing soil erosion and serving as seedbeds, CWD numbers may be less than optimal in comparison to other NE study sites.

IMPLICATIONS OF RESEARCH:

CWD decay dynamics are an essential but often overlooked aspect of the forest cycle. The increasing awareness of anthropogenic disturbances to the forest ecosystem has lead to cultural and scientific awareness of species interrelations and the functional roles of various forest components. This study has quantified CWD, its distribution through decay classes and the implications these numbers may have to larger ecological processes. The role of atmospheric CO_2 in global climate change has redoubled science's effort to understand the differences and dynamics of global ecosystem carbon budgets. CWD decomposition studies are gaining greater and greater exposure in the northeast, but given the mosaic of different forest communities, climate regimes and management practices, the necessary baseline studies have not been done. Black Rock Forest represents a managed forest with a specific interest in assessing carbon amounts from biomass. In the coming era of carbon accounting, information regarding inventory techniques and verification of carbon amounts will have special importance to managed forests wishing to attain carbon credits/certificates. While the role of CWD in carbon storage is important and a major driver of research into this forest component, studies often neglect to emphasize the role of CWD, per se.

This study has many descriptive scientific elements, however it reflects our current understanding of CWD in the Black Rock Forest setting. Expanding our knowledge of CWD provides an increased scientific appreciation of CWD, and I hope it will also lead to more enlightened management of this important ecological resource. Understanding the behavior and functional importance of CWD is still rudimentary, and it deserves greater scientific attention given the incredible diversity of processes and relationships associated with it.

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