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STRUCTURAL CHARACTERISTICS OF OLD-GROWTH, MATURING, AND PARTIALLY CUT NORTHERN HARDWOOD FORESTS

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Abstract. Live tree diameter distributions, and abundance and quality of standing and downed coarse woody debris (CWD), were compared among three northern hardwood stand types in the Adirondack Mountains of New York, USA: old growth; partially cut, uneven-aged with 40–50 cm maximum residual diameters; and maturing, even-aged, 90–100 yr old, postfire. Downed CWD (stumps ≤1 m tall and logs) volumes in the old-growth, partially cut, and maturing stands were 139, 69, and 61 m^3/ha, respectively. Large (≥50 cm diameter) CWD comprised 17%, 13%, and 4% of the total downed CWD volume in the old-growth, partially cut, and maturing stands respectively. Approximately one-half the large CWD in the partially cut stands was in the form of cut stumps. Standing CWD (stumps >1 m tall and standing dead trees) basal areas averaged 8.6, 1.2, and 4.1 m^2/ha in the old-growth, partially cut, and maturing stands, respectively. Basal area of large (≥50 cm diameter) standing CWD averaged 70%, 0%, and 5% of the total in the old-growth, partially cut, and maturing stands. Both downed and standing CWD loads were influenced by mortality due to beech bark disease. Decay distributions of downed CWD were similar in all stand types. The old-growth stands averaged 55 live trees ≥50 cm dbh/ha, including 14 trees ≥70 cm dbh/ha. The partially cut stands contained 5 trees ≥50 cm dbh/ha, with none >55 cm dbh. The maturing, even-aged, stands averaged 1.3 stems ≥50 cm dbh/ha in the postdisturbance cohort but also had ~8 postfire residuals/ha with diameters up to 70 cm dbh.

Implementing forest ecosystem management guidelines to emulate the structural characteristics of old-growth northern hardwoods should retain at least 16 live trees/ha ≥50 cm dbh including 6 trees/ha ≥70 cm dbh. Target levels for downed CWD volume would be less (perhaps 25% less) than the 139 m^3/ha reported here, considering the influence of beech bark disease on the stands we studied. These goals can be accomplished by increasing diameter limits in selection systems, by extending even-aged rotations beyond 100 yr, and implementing ''reserve shelterwood'' cuts that retain large trees in regenerated, even-aged stands. Retaining large trees will provide more future options to increase the proportion of large standing and downed CWD in managed stands.

Key words: coarse woody debris, biomass and decay distribution; even-aged rotation; forest management; habitat heterogeneity; management of structural complexity; reserve shelterwood; reserve trees; selection system, forest management; snags.

Introduction

Structural heterogeneity provided by standing and downed coarse woody debris (CWD) and old trees increases biological diversity in forest ecosystems (Hansen et al. 1991, Swanson and Franklin 1992, Franklin 1993, FEMAT 1993, Meadows 1994). Logs and standing dead trees (snags) provide habitat in several different forest types for numerous taxa including amphibians (Aubry et al. 1988, Gilbert and Alwine 1991*a*, Dupuis et al. 1995), mammals (Gilbert and Alwine 1991*b*, Carey and Johnson 1995), and arthropods (Warren and Key 1991, Chandler and Peck 1992). Amphibians and mammals also use decaying logs for nesting, denning, prey avoidance, travel, perching and foraging (Loeb 1996). In northern hardwood stand types in New England, approximately one-half to one-third of the indigenous amphibian and mammal species rely on logs for some aspect of their life histories (DeGraaf et al. 1992). Coarse woody debris also provides favorable germination and establishment sites of some vascular plants (Bratton 1976, Webb 1988, Harmon and Franklin 1989, McGee and Birmingham 1997) and substrate for bryophytes (Soderstrom 1988, Lesica et al. 1991, McGee 1998) and fungi (Amaranthus et al. 1994, Bader et al. 1995). Large, old trees provide specialized habitat for arthropods (Warren and Key 1991, Schowalter 1995), nesting, denning and foraging habitat for birds and mammals (Conner et al. 1975, Mannan et al. 1980, DeGraaf et al. 1992, Paragi et al. 1996), and persistent or unique substrate for epiphytic bryophytes and lichens (Lesica et al. 1991, Rose 1992, Selva 1994, Esseen et al. 1996, McGee 1998).

Available information suggests that structural attributes of old-growth stands are often limited in young, second-growth forests and some forests managed for commodity production (e.g., Gore and Patterson 1986,

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Spies et al. 1988). In efforts to maximize tree growth and yield, minimize disease and mortality, harvest merchantable timber, and regenerate forests effectively, some management strategies homogenize the forest floor and canopy structure (Hansen et al. 1991, Perry 1994). Yet, when cutting intensity is low, structural differences between managed and old-growth stands may be negligible (e.g., Hardt and Swank 1997).

Emerging philosophies of forest ecosystem management (FEM) stress the maintenance of biological diversity and ecological functions, putting a new emphasis on actively maintaining structural complexity within managed stands (Franklin 1989, Swanson and Franklin 1992). This may include retaining large, old (and oftentimes merchantable) trees and standing and downed CWD, and extending the lengths of even-aged rotations (e.g., in western conifer systems from 80 to >250 yr; FEMAT 1993).

The scientific basis for FEM principles were developed primarily in the western United States, and while the concepts are being applied across many forest types, managers working in eastern North America have few guidelines for enhancing structural complexity of forests. Because of regional differences in climate, disturbance regime, species composition, and annual growth rates, live tree diameter distributions, and amounts and sizes of CWD vary by forest type (Harmon et al. 1986). Therefore, developing ecologically meaningful guidelines requires knowing appropriate live tree diameter distributions and CWD accumulation patterns for different forest types.

Our knowledge is not yet adequate to determine how CWD accumulation in managed eastern forests compares to natural levels, let alone to know minimum threshold levels for sustaining various ecological functions. Some studies in eastern North America (Lang and Forman 1978, MacMillan 1981, MacMillan 1988, Muller and Liu 1991, Tyrrell and Crow 1994) assessed CWD volume/biomass in old-growth oak–hickory, mixed oak, beech–oak, and hardwood–hemlock stands without comparisons to managed or second-growth stands. Only two studies have considered the influence of partial cutting on CWD accumulation. Hardt and Swank (1997) evaluated selective harvests made prior to 1930 in two southern Appalachian hardwood stands. Gore and Patterson (1986) evaluated one northern hardwood stand where a selection cut was applied. Neither of these studies found substantial differences in volumes/biomass of downed CWD between old-growth and the cut stands, but differences existed in the size class distributions of CWD (Gore and Patterson 1986). Given the widespread application of uneven-aged management in several eastern hardwood forest types, assessing the influence of these management systems warrants more attention.

Our understanding of CWD accumulation during even-aged stand development is also incomplete for eastern deciduous forests. In particular, accumulation of CWD during the late stem-exclusion stage through the understory reinitiation stage (sensu Oliver and Larson 1996) is not documented for eastern forest types. Most data are from stands <90 yr old (Tritton 1980, McCarthy and Bailey 1994, Goebel and Hix 1996, Shifley et al. 1997). Only two studies included stands up to 110 yr old (Gore and Patterson 1986, Goebel and Hix 1996). It is important to understand CWD accumulation patterns over time frames relevant to even-aged rotations. For instance, even-aged sawtimber rotations of 100–120 yr are commonly recommended for northern hardwoods (Solomon and Leak 1986, Leak et al. 1987, Seymour 1995).

The size of CWD determines, in part, the functions that it provides. Therefore, developing meaningful FEM guidelines for deadwood requires considerations of CWD size class distributions. Large logs usually have more, and larger, cavities than small logs, thereby providing denning sites and shelter for a greater variety of animals (Harmon et al. 1986). Also, the use of logs by some small mammals has been correlated with log diameter (Hayes and Cross 1987). Furthermore, the greater variety of microsite conditions within large logs (averages and extremes of moisture and temperature) provide more heterogeneous habitat for insects (Hanula 1996) and fungi (Bader et al. 1995). Many studies that have compared CWD volume/biomass in stands of differing disturbance and management histories have not considered size class distributions (but see Gore and Patterson 1986, McCarthy and Bailey 1994).

The decay stage of CWD also influences the use and establishment of a variety of organisms. Several studies have demonstrated or suggested a succession of bryophytes (Andersson and Hytteborn 1991, McGee 1998), fungi (Bader et al. 1995) and invertebrates (Hanula 1996) during wood decay. Decay stage is an important characteristic in determining small-mammal usage of logs, with some preferring soft, decayed logs (Barnum et al. 1992). The influences of different even-aged rotations and uneven-aged entry cycles on CWD decay distributions is not well understood.

The objective of this research was to compare the structural characteristics (CWD volume, and size and decay distributions, and live-tree diameter distributions) among three stand types of differing disturbance and management histories. Specifically, we compared commercially managed, uneven-aged; maturing (90–100 yr old), unmanaged, even-aged; and old-growth northern hardwood stands.

This research focuses on northern hardwood stand types, which form a substantial component of North America's eastern deciduous forest. Northern hardwoods occur in the US from New England to the northern Lake States, and in adjacent provinces of Canada, with outlying associations occurring southward through the Appalachian Mountains (Braun 1950, Smith 1995). Northern hardwoods comprise 43 and 21% of the forest cover in the northeastern and Lakes

TABLE 1. Physiographic characteristics of northern hardwood study sites in Adirondack Park, New York, USA. Two 0.1-ha permanent plots were established at each site.

Study sites	Coordinates	Elevation (m)	Slope (°)	Slope position	Aspect (°)
Maturing					
Hennessy Mt.	44°18′ N, 74°02′ W	550–570	5°–20°	mid-lower	210°–300°
Mt. Van Hoevenberg	44°13′ N, 73°56′ W	730–770	5°–25°	mid-upper	60°–120°
Gooseberry Mt.	44°04′ N, 74°15′ W	570–630	5°–20°	mid-upper	140°–180°
Bigsby Pond	43°51′ N, 73°54′ W	490–510	0°–10°	mid-lower	180°–200°
Partially cut					
Tupper Lake	44°06′ N, 74°31′ W	570–580	0°–20°	mid-upper	30°–70°
Fishing Brook	43°58′ N, 74°20′ W	560–580	10°–20°	mid-lower	40°–50°
Goodnow Flow	43°56′ N, 74°12′ W	590–610	5°–20°	mid-lower	280°–0°
Brady Flow	43°33′ N, 74°19′ W	550–560	0°–5°	mid-lower	200°–340°
Oak Mt.	43°32′ N, 74°21′ W	590–610	10°–20°	mid-upper	40°–80 °
Pine Mt.	43°31′ N, 74°18′ W	510–520	0°–15°	mid-upper	110°–120°
Old growth					
Ampersand Mt.	44°15′ N, 74°14′ W	470–480	0°–10°	lower	10°–50°
Whaletail Mt.	44°10′ N, 73°57′ W	700–720	10°–25°	mid-lower	10°–30°
Adirondack Mt. Reserve	44°07′ N, 73°49′ W	680–690	5°–10°	mid-lower	300°–0°
Catlin Lake	44°01′ N, 74°17′ W	540–560	15°–20°	mid-upper	30°–80°
Sucker Brook	43°39′ N, 74°26′ W	620–680	0°–10°	mid-upper	120°–180°
Mason Lake	43°36′ N, 74°25′ W	570–590	5°–10°	mid-lower	80°–90°

states region of the United States, respectively (Johnson 1995, Seymour 1995). This study was conducted in the Adirondack Mountains of New York, USA, a region described by Braun (1950) as the Adirondack Section of the hemlock–white pine–northern hardwoods region. Here, northern hardwoods are dominated by *Acer saccharum, Fagus grandifolia,* and *Betula alleghaniensis,* with an important conifer component composed of *Picea rubens* and *Tsuga canadensis.* Additional species include *Fraxinus americana, Prunus serotina, Acer rubrum,* and *Tilia americana* (nomenclature follows Gleason and Cronquist 1991). Within the Adirondack region, northern hardwoods occur at elevations below 980 m (Heimburger 1934). The climate of the Adirondack region is continental. Average January and June temperatures from 1941 to 1979 were −9°C and 16°C, respectively, in the central Adirondacks (SUNY-CESF Huntington Wildlife Forest Weather Station, Newcomb, New York, elevation 490 m, *unpublished data*). Annual precipitation during the same period averaged 102 cm, including 308 cm of snowfall. Soils of the region are complex, but northern hardwood types typically occur on loamy glacial till soils overlaying a variety of bedrock, but primarily granitic gneiss (Heimburger 1934). Disturbance regimes in the eastern region of the northern hardwoods are dominated by single-, or multiple-tree, gap formation. These frequent, small-scale disturbances annually affect ~1% of the forest canopy area (Runkle 1982), and are caused primarily from high winds accompanying thunderstorms. Less frequent catastrophic disturbances result from other forms of frontal (e.g., downbursts and tornadoes) storms (Jenkins 1995) or cyclonic (hurricanes) wind storms (Bormann and Likens 1979), and glaze ice storms (Seischab et al. 1993). Small, lightning-ignited fires often occur, but fire is not an important natural form of disturbance in the eastern region of the northern hardwoods (Bormann and Likens 1979, Seymour 1995).

METHODS

Study site descriptions

Sixteen study sites were established in three northern hardwood stand types (Table 1). Some aspects of four of the six old-growth sites were previously described (Leopold et al. 1988, Woods and Cogbill 1994). We defined old-growth stands as those containing canopy dominant trees of ages at least one-half the maximum life expectancy for respective species. Confirmation of tree ages was complicated by heart rot in many of the old trees. To estimate ages of these trees, the average increments from outer, sound, core sections were applied to inner, decayed sections (McGee 1998). This method yields a conservative estimate of tree age for shade-tolerant species such as *A. saccharum, P. rubens,* and *T. canadensis,* since saplings often grow slowly during canopy suppression. This method indicated that average ages of canopy-dominant stems at the six old-growth sites ranged from 149 to 259 yr. Selective logging of conifers, but primarily large red spruce, was widespread in the Adirondacks during the mid-1800s. These cutting activities may have likely occurred on four of the old-growth sites prior to their incorporation into the Adirondack Park between 1892 and 1899 (McMartin 1994; B. McMartin, *personal communication*). Records for two of the sites indicate no past cutting (Glennon 1994, McMartin 1994). Old-growth remnants in eastern North America often occur on poor and unproductive sites, thereby calling their representativeness into question. However, the State of New York acquired much land in the Adirondack Park prior to excessive human encroachment and exploitation. Therefore, old-growth forests exist there over a range of site conditions, and are not merely on overlooked or unproductive sites (McMartin 1994). Because of the mix of private and public lands within Adirondack Park, managed and natural stands occur there in close proximity.

The six commercially owned, uneven-aged sites (referred to hereafter as ''partially cut'') have received a variety of undefined partial cuttings for at least the past 100 years. Stand-level records do not exist for these sites, but each probably received at least one selective cutting of large red spruce prior to ∼1890, followed by removal of smaller spruce (>12 cm diameter at breast height (dbh)) after 1890. Selective harvests of large-diameter hardwoods began in the early 1900's. By the 1960's local paper mills began using hardwoods for pulp, reducing the merchantable size of hardwoods (McMartin 1994; J. Hanley, International Paper Corporation; D. Osterberg, Finch and Pruyn, Incorporated, *personal communication*). Several of the sites received beech salvages beginning in the 1960s, and all have been commercially cut at least once since 1980. Four of the sites are managed primarily for sawtimber production, under 15–20 yr cutting cycles, with maximum diameters of 45–60 cm dbh, depending on species, and residual basal areas of approximately 16 m^2/ha (J. Hanley, *personal communication*). Two of the sites have been managed primarily for pulp production, with more frequent entries, and lower diameter limits and residual basal areas (D. Osterberg, *personal communication*). Preliminary comparisons reveal that the four sawtimber stands tend to contain greater basal areas (mean ± 1 SD; 19.0 ± 1.8 m^3/ha vs. 16.8 ± 0.5 m^3/ha) and larger residual diameter limits (53 ± 1 cm dbh vs. 44 ± 4 cm dbh, present diameters) than the two pulpwood stands. However, for the purpose of this study these stands were combined into one partially cut stand type.

Three of the 90–100-yr-old, even-aged stands (referred to hereafter as ''maturing'') initiated following the widespread Adirondack fires between 1903 and 1908 (B. Barnard, New York Department of Environmental Conservation, *personal communication*). The fourth stand regenerated after a fire in the mid-1890s (*personal communication* with local landowners). The stand-initiating fires of that time occurred during a period of drought, were ignited primarily by human activities, and were fueled by extensive logging slash that remained following selective harvesting practices of the time (McMartin 1994). Maximum diameters of the postfire regeneration ranged from 40 to 50 cm dbh, and maximum ages of cored trees were 89, 90, 93, and 103 yr in the four stands. Scattered, larger (50–80 cm dbh) individuals that survived the fires were present in these stands. Ages of these residual trees ranged from 107 to 203 yr (McGee 1998). None of the maturing stands have been logged since establishment. Since logging slash and preharvest deadwood at other northern hardwood sites have completely decayed within 20–50 yr after clearcutting (Bormann and Likens 1979, Tritton 1980, Arthur et al.1993), most likely any CWD present in our study stands was produced during development of the present stands. These maturing, 90–100 yr old, fire-initiated stands are used here to study structural characteristics in even-aged stands in the late stem-exclusion stage of development (sensu Oliver and Larson 1996). Clearcuts and shelterwood cuts were not technically feasible in the Adirondacks until after the 1940s (B. Barnard, New York Department of Environmental Conservation, *personal communication*). Therefore, opportunities are limited for studying silviculturally regenerated, even-aged stands in late stem-exclusion developmental stages.

Field sampling

Two 0.1-ha (50 × 20 m) permanent plots were randomly established at each site. Six of the eight plots in four old-growth sites were randomly established by Woods and Cogbill (1994) during an earlier study. We measured dbh of all trees ≥10.0 cm dbh on each 0.1-ha plot, as well as standing and downed CWD of various sizes. Snags were defined as vertical deadwood >1 m tall, and included stems with and without branches. Downed CWD included short stumps (≤1 m tall) and logs (horizontal or leaning deadwood). Short stumps included cut stumps, and naturally decayed and collapsed stems. Predominant decay stages (modified from Fogel et al. 1972) were determined for each piece of CWD based upon the presence of branches, and hardness/texture of wood. The length and end diameters of log sections within the plot boundaries were measured. The top (if below 1.4 m) or breast height diameters and heights of stumps, and breast height diameters of snags were measured. Large CWD (≥25.0 cm dia.) was sampled on the entire 0.1-ha plot. Medium CWD (10.0–24.9 cm diameter) was sampled on three 0.01-ha subplots, and small CWD (1.0–9.9 cm diameter) was sampled on 10 0.0004-ha subplots that were systematically nested within the main plots.

Random subsamples of CWD, stratified by size (≤10 cm, 11–24 cm, ≥25 cm diameter), decay stage, and species, were taken (as available) from each 0.1-ha plot for bulk density determinations. These were dried in a forced-air oven at 65°C for 1 wk, and then weighed. Subsample volumes were found either by measuring lengths and diameters, or by water displacement for samples of irregular shape. We found that two laboratory technicians could coordinate the submersion of wood with immediate readings of volume before noticeable amounts of water were absorbed. If this method introduced any bias, it would result in low volume measurements, thereby inflating bulk density estimates.

Data analysis and experimental design

Volumes were calculated for logs and short stumps, and basal areas for snags. Log and stump volumes were

TABLE 2. Basal area and density of live tree (≥10 cm dbh) species in northern hardwood forests of Adirondack Park, New York.

Species	Basal area (m²/ha)		Density (no./ha)	
	Mean ± 1 SD	Range	Mean ± 1 SD	Range
Maturing (n = 4)				
Acer saccharum	16.5 ± 4.2	11.2–20.1	245 ± 72	150–305
Fagus grandifolia	4.2 ± 1.8	2.3–5.9	136 ± 92	30–255
Betula alleghaniensis	3.5 ± 1.9	2.0–6.2	76 ± 53	40–155
Acer rubrum	2.1 ± 1.8	0.0–3.7	29 ± 25	0–50
Fraxinus americana	1.1 ± 1.0	0.0–2.5	8 ± 9	0–20
Prunus serotina	0.9 ± 1.9	0.0–3.8	9 ± 18	0–35
Tsuga canadensis	0.5 ± 1.0	0.0–2.0	3 ± 5	0–10
Populus grandidentata	0.2 ± 0.3	0.0–0.6	1 ± 3	0–5
Ostrya virginiana	0.1 ± 0.1	0.0–0.1	1 ± 3	0–5
Total	29.1 ± 4.0	24.6–34.1	508 ± 107	390–650
Partially cut (n = 6)				
Acer saccharum	10.1 ± 4.8	4.7–16.4	181 ± 99	55–320
Fagus grandifolia	5.5 ± 4.0	0.5–10.4	193 ± 112	35–300
Fraxinus americana	1.0 ± 0.8	0.0–2.2	13 ± 9	0–25
Betula alleghaniensis	0.8 ± 1.1	0.0–2.7	16 ± 21	0–50
Acer pensylvanicum	0.2 ± 0.2	0.0–0.6	12 ± 13	0–35
Ostrya virginiana	0.1 ± 0.1	0.0–0.2	2 ± 3	0–5
Picea rubens	0.2 ± 0.5	0.0–1.2	3 ± 8	0–20
Tilia americana	0.2 ± 0.4	0.0–1.1	1 ± 2	0–5
Acer rubrum	0.1 ± 0.1	0.0–0.1	1 ± 2	0–5
Total	18.2 ± 1.7	16.5–20.4	422 ± 74	330–530
Old growth (n = 6)				
Acer saccharum	20.5 ± 8.8	11.8–31.7	132 ± 57	65–210
Fagus grandifolia	6.2 ± 3.5	1.6–11.4	169 ± 91	80–310
Betula alleghaniensis	3.5 ± 2.4	0.8–6.8	14 ± 7	5–20
Tsuga canadensis	1.6 ± 2.4	0.0–5.1	21 ± 38	0–95
Acer pensylvanicum	0.3 ± 0.4	0.0–1.0	23 ± 33	0–70
Picea rubens	0.7 ± 0.6	0.0–1.4	14 ± 13	0–35
Ostrya virginana	0.2 ± 0.4	0.0–0.9	11 ± 27	0–65
Tilia americana	0.5 ± 0.8	0.0–1.8	3 ± 6	0–15
Fraxinus americana	0.1 ± 0.1	0.0–0.3	4 ± 6	0–15
Abies balsamea	0.1 ± 0.1	0.0–0.1	1 ± 2	0–5
Total	33.7 ± 4.3	28.3–39.6	392 ± 46	345–470

calculated using the equation for a frustum of a cone:

$$\text{Volume} = \frac{1}{3}\pi l(r^2 + R^2 + rR)$$

where r = small radius (m), R = large radius (m), l = length (m). In the case of stumps, where only top diameter was measured (r), it was assumed that $R = r$. Also, height is substituted for length.

Bulk density averages for each decay class were used to convert volume to dry mass biomass using the following equation:

$$\text{CWD mass per plot} = \sum_{i=1}^{6} v_i d_i$$

where v_i = volume of the ith decay stage per plot, d_i = bulk density of ith decay stage, and where average (±1 SD) bulk densities were $d_1 = 0.58 \pm 0.19$ g/cm³, $d_2 = 0.45 \pm 0.17$ g/cm³, $d_3 = 0.32 \pm 0.12$ g/cm³, $d_4 = 0.24 \pm 0.11$ g/cm³, $d_5 = 0.19 \pm 0.08$ g/cm³, and $d_6 = 0.14 \pm 0.05$ g/cm³.

The experimental design incorporates three stand types (old-growth; partially cut; maturing) replicated six, six (four sawtimber and two pulpwood), and four times, respectively. Mean estimates of CWD volumes, mass and basal areas were determined for each study site based upon measurements taken from the 0.1-, 0.01-, and 0.0004-ha sampling units.

Analysis of variance and Tukey's hsd tests (Littell et al. 1991) were used to analyze differences in downed CWD volume, and standing CWD density and basal area. All data were square-root transformed to homogenize variances. The analyses had two treatment degrees of freedom and 13 error degrees of freedom. Coarse woody debris decay distributions, and live tree diameter distributions were analyzed using the Kolmogorov-Smirnov test for goodness-of-fit (Sokal and Rohlf 1981).

RESULTS

Canopy composition and structure

The basal area of live trees ≥10 cm dbh averaged (mean ± 1 SD) 29.1 ± 4.0 m²/ha in the maturing, even-aged stands (Table 2). Average stand diameters of trees in the postfire regeneration cohorts ranged from 23 ± 10 to 25 ± 10 cm dbh (average quadratic stand diameter, QSD, was 27 cm dbh). The largest stems of

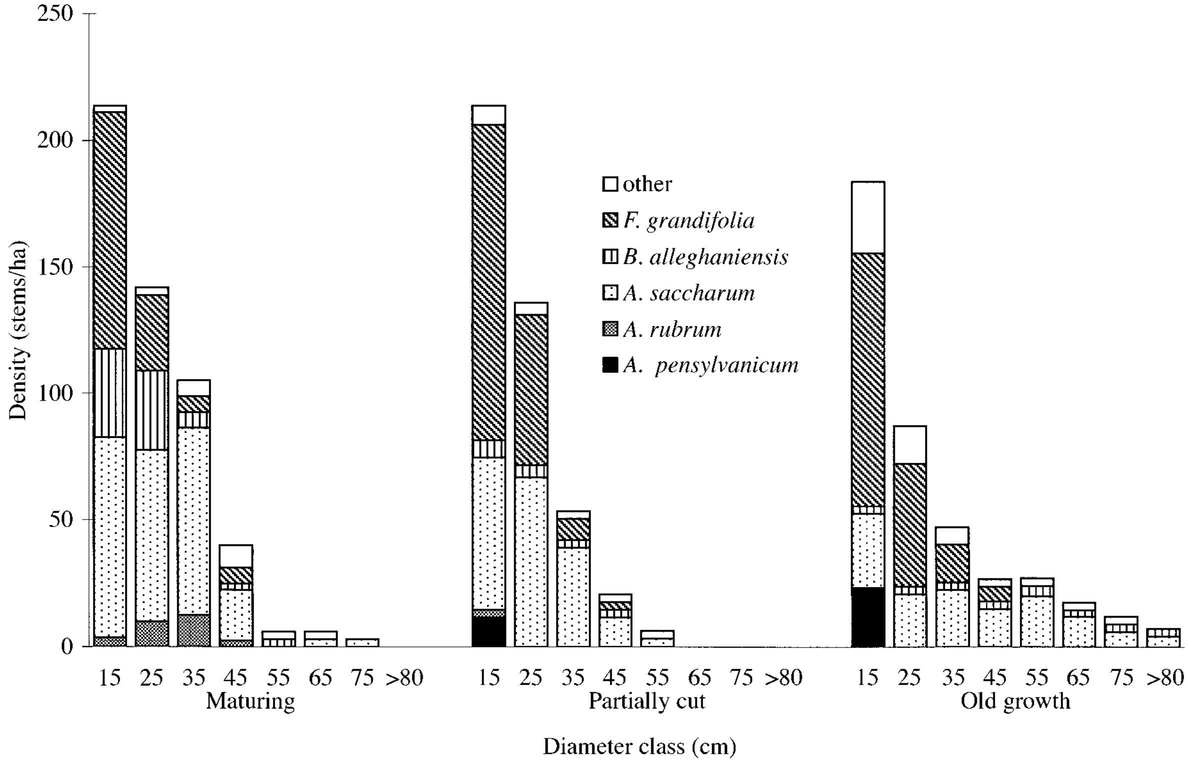

FIG. 1. Tree diameter distributions in maturing, managed, and old-growth northern hardwood stands of Adirondack Park, New York, USA. See Table 2 for species included in ''other'' category for the respective stand types. Abscissa values are diameter class (cm dbh) midpoints.

the postfire cohorts ranged from 48 to 53 cm dbh, with 1.3 stems/ha ≥50 cm dbh. Approximately 8 stems/ha, all ≥50 cm dbh, were determined by increment coring to be postfire residuals. A Kolmogorov-Smirnov test for goodness-of-fit indicated the diameter distributions of the maturing stands differed from the other two stand types ($P \leq 0.01$). The partially cut stands tended to have greater densities in smaller diameter classes than the maturing stands, and the old-growth stands had lower densities in the mid-diameter classes (30–50 cm dbh) but higher densities in the large diameter classes than the maturing stands (Fig. 1). The postfire cohorts were dominated by *A. saccharum*, with lesser amounts of *F. grandifolia, A. rubrum, F. americana, P. serotina,* and *P. grandidentata.* As a group, species of low to moderate shade tolerance (*B. alleghaniensis*, *F. americana*, *A. rubrum*, *P. serotina*, and *P. grandidentata*) accounted for 27% of the live basal area. *Betula alleghaniensis* was common in these stands, but not among the larger size classes of the postfire cohort. *Fagus grandifolia* and *A. saccharum* were common in the understory of these stands (Fig. 1).

Live basal areas of the partially cut, uneven-aged and old-growth stands averaged 18.2 ± 1.7 and 33.7 ± 4.3 m^2/ha, respectively (Table 2). Mean stand diameters ranged from 19 ± 10 to 24 ± 10 cm dbh, and 24 ± 16 to 32 ± 11 cm dbh, respectively. A Kolmogorov-Smirnov test for goodness-of-fit indicated significant differences ($P < 0.01$) between the diameter distributions of the two stand types. The partially cut stands had greater densities in the 10–40 cm dbh classes, and the old growth greater densities of trees ≥50 cm dbh. The partially cut stands averaged 5 trees ≥50 cm dbh/ha, with no stems ≥55 cm dbh, while the old-growth stands averaged 55 stems ≥50 cm dbh/ha, including 14 stems ≥ 70 cm dbh/ha. In both stand types *A. saccharum* and *F. grandifolia* dominated the canopies and subcanopies, and *A. pensylvanicum* was an important component of the subcanopies (Table 2; Fig. 1). Species of low to moderate shade tolerance accounted for 10% and 11%, respectively, of the basal area in the partially cut and old-growth stands. Beech bark disease (caused by *Nectria* spp.) was apparent in all stand types, but especially in the partially cut and old-growth stands. The partially cut stands had no beech greater than 40 cm dbh, due to past salvage cuts. The old growth had no living beech >60 cm dbh and few >50 cm dbh.

Standing coarse woody debris

Standing deadwood (≥10 cm diameter and >1 m tall) densities averaged 96 ± 48, 43 ± 25, and 60 ± 22 stems/ha, respectively, in the maturing, partially cut, and old-growth stands (Table 3). These values were not significantly different. Dead stems ≥50 cm dbh accounted for 31% of total standing CWD density in the

TABLE 3. Means and ranges of standing (>1 m tall) coarse woody debris (CWD) densities (no./ha) and basal areas (m²/ha) in northern hardwood stands of Adirondack Park, New York.

Standing CWD	Diameter (cm)	Maturing (n = 4) Mean ± 1 SD	Maturing Range	Partially cut (n = 6) Mean ± 1 SD	Partially cut Range	Old growth (n = 6) Mean ± 1 SD	Old growth Range
Density (no./ha)	≥50	1.3 ± 2.5[b]	0.0–5.0	0.0 ± 0.0[b]	0.0–0.0	18.3 ± 6.8[a]	10.0–25.0
	25–49	32.5 ± 11.9[a]	20.0–45.0	6.7 ± 5.2[b]	0.0–15.0	19.2 ± 12.0[a]	10.0–40.0
	10–24	62.5 ± 55.1	0.0–133.3	36.1 ± 22.2	16.7–66.7	22.2 ± 22.8	0.0–50.0
	Total	96.3 ± 48.0	40.0–153.3	42.8 ± 25.3	16.7–71.7	59.7 ± 21.7	35.0–80.0
Basal area (m²/ha)	≥50	0.2 ± 0.5[b]	0.0–1.0	0.0 ± 0.0[b]	0.0–0.0	6.0 ± 2.9[a]	2.6–9.4
	25–49	2.6 ± 1.2[a]	1.5–4.1	0.5 ± 0.4[b]	0.0–1.1	2.0 ± 1.3[a]	0.9–4.2
	10–24	1.3 ± 1.3	0.0–3.1	0.7 ± 0.4	0.3–1.4	0.6 ± 0.6	0.0–1.6
	Total	4.1 ± 1.1[b]	3.1–5.5	1.2 ± 0.7[c]	0.6–2.5	8.6 ± 3.2[a]	4.4–12.5

Notes: Statistically significant differences ($P \leq 0.05$; Tukey's hsd) in densities between stand types for each size class category are denoted with different superscript letters. Data were square-root transformed to homogenize variances.

old-growth, 1% in the maturing, and 0% in the partially cut stands. Standing CWD <25 cm diameter was 84% of the total standing CWD density in the partially cut, 65% in the maturing, and 37% in the old-growth stands (Table 3). The high proportion of large dead stems in the old growth resulted in greater standing dead basal areas in these stands (8.6 ± 3.2 m²/ha) compared to the maturing (4.1 ± 1.1 m²/ha) and partially cut (1.2 ± 0.7 m²/ha) stands (Table 3). These values equal 26, 14, and 7% of the live basal areas for the respective stand types.

Downed CWD

The old-growth stands had approximately twice the volume of downed CWD (139 ± 22 m³/ha) as the maturing (61 ± 16 m³/ha) and partially cut (69 ± 17 m³/ha) stands (Table 4). The volume of downed CWD <25 cm diameter was similar among the stand types. Logs ≥50 cm diameter were uncommon in the maturing and partially cut stands, where they contributed 4% and 8%, respectively, of the total log volume. Logs ≥50 cm diameter accounted for 17% of the total log volume in the old-growth stands. The contribution of low stumps to total downed CWD volume was greatest in the partially cut stands (9.2 ± 4.2 m³/ha; 13% of the total downed CWD volume), reflecting the presence of cut stumps (Table 4). Total downed CWD biomass was 44.7 ± 5.9 Mg/ha in the old-growth, 20.3 ± 4.5 Mg/ha in the maturing, and 22.2 ± 5.1 Mg/ha in the partially cut stands.

CWD decay distributions

Downed CWD was distributed in equal proportions among decay stages in all stand types (Fig. 2; all pairwise Kolmogorov-Smirnov test P values >0.40). In all cases there was a depression at decay class 4 (soft throughout). The standing CWD decay distributions were consistently skewed toward less decayed classes with modes at decay class 2 (stumps with hard wood and branches off). No standing dead stems had decayed beyond class 3 in the partially cut stands; however, pairwise Kolmogorov-Smirnov tests for goodness-of-fit found no significant differences in decay distributions among the stand types ($P_{\text{partial vs. old}} = 0.33$; $P_{\text{partial vs. maturing}} = 0.08$; $P_{\text{maturing vs. old}} = 0.82$).

DISCUSSION

Canopy structure

The uneven-aged, partially cut stands in this study represent two management objectives: sawtimber production (four stands) and pulpwood production (two stands). Collectively, they had an average of 5 trees ≥

TABLE 4. Means and ranges for downed coarse woody debris (CWD) volume (m³/ha) in northern hardwood forests of Adirondack Park, New York.

Downed CWD	Diameter (cm)	Maturing (n = 4) Mean ± 1 SD	Maturing Range	Partially cut (n = 6) Mean ± 1 SD	Partially cut Range	Old growth (n = 6) Mean ± 1 SD	Old growth Range
Low stumps	≥50	0.2 ± 0.3[b]	0.0–0.5	4.5 ± 3.0[a]	2.1–8.8	0.8 ± 1.0[b]	0.0–2.3
	25–49	0.8 ± 0.5[b]	0.3–1.5	4.5 ± 1.5[a]	2.7–6.3	0.6 ± 0.4[b]	0.2–1.2
	10–24	0.5 ± 0.3	0.2–0.9	0.2 ± 0.2	0.0–0.4	0.4 ± 0.5	0.0–1.3
	Total low stumps	1.5 ± 1.0[b]	0.4–2.7	9.2 ± 4.2[a]	4.8–15.5	1.8 ± 1.1[b]	0.5–3.4
Logs	≥50	2.1 ± 3.2[b]	0.0–6.8	4.7 ± 6.9[b]	0.0–17.2	23.2 ± 11.1[a]	4.5–34.2
	25–49	10.8 ± 11.9[b]	4.3–28.6	15.8 ± 8.4[b]	8.3–31.6	69.8 ± 17.6[a]	47.7–95.8
	10–24	27.9 ± 8.6	17.8–37.3	20.2 ± 8.3	11.4–30.9	29.6 ± 7.2	22.8–38.5
	1–9	18.2 ± 5.7	13.1–26.3	19.2 ± 5.9	14.0–27.6	14.1 ± 4.2	9.7–21.7
	Total logs	59.0 ± 15.9[b]	44.5–80.6	59.9 ± 16.6[b]	46.7–90.0	136.7 ± 22.0[a]	119.9–179.3
Total downed		60.5 ± 16.4[b]	45.5–82.4	69.1 ± 16.7[b]	55.3–100.9	138.5 ± 22.0[a]	120.6–180.9

Notes: Statistically significant differences ($P \leq 0.05$; Tukey's hsd) in volumes between stand types for each size class category are denoted with different letters. Data were square-root transformed to homogenize variances.

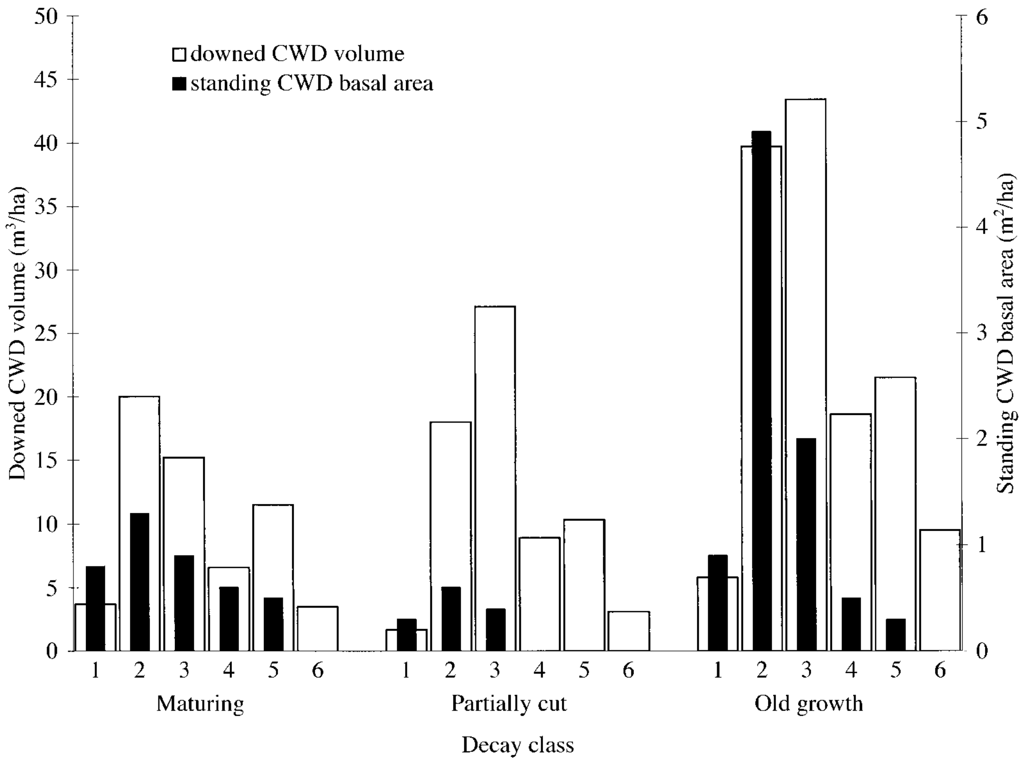

FIG. 2. Decay class distributions of standing coarse woody debris (CWD; snags and stumps >1 m tall) basal areas, and downed coarse woody debris (logs and stumps ≤1 m tall) volumes in maturing, managed, and old-growth northern hardwood stands of Adirondack Park, New York. Decay definitions are modified from Fogel et al. (1972) and are, briefly: (1) wood hard, branches and twigs present; (2) wood hard, branches absent; (3) wood soft outside; (4) wood soft throughout; (5) collapsed or collapsible under slight pressure of foot; (6) low, collapsed stump, or collapsed log with oval cross-section, no structural integrity, crumbly or fibrous texture.

50 cm dbh/ha with none greater than 55 cm dbh. The maximum diameter limits in the sawtimber stands (53 ± 1 cm dbh) and pulpwood stands (44 ± 4 cm dbh) are consistent with several cutting guides for uneven-aged, northern hardwoods. These guidelines recommend maximum, residual diameter limits of 45–60 cm dbh for sawtimber production (Arbogast 1957, Gilbert and Jensen 1958, Leak et al. 1969, Hansen and Nyland 1986, Reed and Mroz 1997), and 40–45 cm dbh for fiber production (Gilbert and Jensen 1958, Hansen and Nyland 1986). Tree diameter (≥10 cm dbh) in maturing, even-aged, 90–100 yr old stands averaged 24.0 cm dbh (27.0 cm dbh QSD) among the postfire regeneration, with 1.3 stems/ha ≥50 cm dbh. This is similar to other studies that have also reported average tree size (QSD) for unmanaged, even-aged northern hardwoods at 95–120 yr to be 25–35 cm dbh, depending on site conditions (Leak et al. 1969, Solomon and Leak 1986, Seymour 1995). The old-growth stands in this study averaged 55 trees ≥50 cm dbh/ha, including 14 trees/ha ≥70 cm dbh. Tree sizes reported for other old-growth northern hardwoods range from 16 to 73 stems ≥50 cm dbh/ha, including 5–20 stems ≥70 cm dbh/ha. The majority of studies report an average of ~50 stems ≥50 cm dbh/ha, including 9 stems ≥70 cm dbh/ha (Table 5; see also Tyrrell et al. 1998).

Where forest management objectives include providing habitat for a broad range of cavity-nesting birds and mammals, or substrate for dispersal-limited organisms, landowners should consider the option of retaining some old trees. Based upon this and other studies (Table 5), maintaining diameter distributions with 16 stems ≥50 cm dbh/ha, including 5 stems ≥70 cm dbh/ha, would approximate minimum levels observed in northern hardwood old growth. Such diameter limits may be an appropriate starting point in attempts to balance commodity production with old-growth characteristics. Where landowners seek to restore old-growth conditions to northern hardwoods using silvicultural techniques, distributions of 50 stems ≥50 cm dbh/ha, including 9 stems ≥70 cm dbh/ha would reflect typical reported values (Table 5).

Data gathered in this study show that developing even-aged stands containing residuals from the former rotation have special structural attributes, compared to stands having only a single age class. Enhancement of structural diversity in developing even-aged stands can be accomplished with a reserve shelterwood system

TABLE 5. Density (no./ha) of live trees ≥50 cm dbh in old growth, northern hardwood stands of eastern North America.

Diameter				
≥50 cm dbh	≥70 cm dbh	Location	No. sites/plots	Reference
73	···	Michigan	2	Mroz et al. (1985)†
61	15	Michigan	1	Tubbs (1977)†
55	14	New York	6	This study
54	8	Michigan	1	Eyre and Zillgitt (1953)†
50	6	Michigan	several/unspecified	Eyre and Zillgitt (1953)†
52	6	New York	30	Roman (1980)
48	7	New Hampshire	2	Leak (1973)
31	9	New Hampshire	3	Leak (1987)†
16	5	Nova Scotia	3	Greenidge (1987)†

† Some tabular and graphed diameter distributions had diameter classes that did not coincide with the present 50 and 70 cm dbh cutoffs. In these cases, values reported here were estimates based upon interpolations of broad diameter classes or extrapolation of adjacent diameter classes.

(Nyland 1996) that retains some large, old trees within the younger, even-aged cohort. With traditional shelterwood systems, residual trees are selected from the best phenotypes available, and uniformly spaced to serve as seed sources for the new cohort and to ameliorate environmental conditions for regeneration. Once the new cohort is established, the older trees are removed, leaving a single-cohort stand. In reserve shelterwood systems, trees are retained for an extended period into the new rotation. These reserve trees can be selected for multiple functions. Those of good form and vigor will provide future, high-value wood products. Even if portions of these stems are defective, logs of higher quality may be harvested with decayed or unmerchantable portions left to provide the ecological benefits of large CWD. Other trees with broken tops or evidence of cavities could be reserved for wildlife habitat. Culls and other trees in advanced stages of decline can be retained and/or girdled to provide standing and downed CWD. Some reserve trees could be uniformly spaced to provide shelter for regeneration, with others aggregated to provide refugia for dispersal-limited organisms.

Standing coarse woody debris

Densities of standing CWD were 60–120% higher in the maturing stands than the other two stand types, although these differences were not significant (Table 3). The lack of statistical significance is probably due to the small sample sizes employed in this study, resulting in standard deviations approaching 50% of the estimated means for standing CWD. Shifley and Schlesinger (1994) determined that 32–100 0.1-ha plots are necessary in old-growth stands to estimate snag densities with standard deviations equaling 25% of the mean. High densities of dead trees, especially among smaller size classes, characterize even-aged stands in the stem exclusion phase of development (Table 6). Standing dead basal areas were greatest in old growth due to the greater density of large stems. For instance, stems ≥50 cm diameter accounted for 32% of the standing dead density in old growth, compared to 1% and 0% in maturing and partially cut stands, respectively. The large standing dead material in the maturing stands were decayed stumps of old, prefire trees that had died since stand initiation. The lack of large, standing CWD in the maturing stands suggests a potential ecological benefit of reserve shelterwood systems. After 40–50 yr of even-aged northern hardwood stand development, all residual snags will likely have collapsed and decayed (Bormann and Likens 1979). Therefore, although snags are produced during the first 100 yr of stand development, they will tend to be small, suppressed stems. Large snags will not develop until the onset of the understory reinitiation phase (∼170 yr in northern hardwoods; Bormann and Likens 1979) when causes of mortality shift from competitive suppression to senescence of old trees. Retaining large trees in reserve shelterwood systems will provide a source of future large snags in the developing stand. The partially cut stands contained the lowest densities and basal areas of standing CWD largely because past cutting removed trees of large sizes potentially subject to mortality and reduced intertree competition among the residual growing stock. This is consistent with the few studies that have compared these features in eastern forests (Table 6).

The decay distributions for standing CWD were negatively skewed, with modes at decay stage 2–3 in all stand types (Fig. 2). This pattern is likely an artifact of our CWD definitions, reflecting the deterioration of standing dead trees into logs and low stumps following snapping and collapse. The partially cut stands had no standing dead material beyond decay class 3, likely due to management objectives of maintaining vigorous, healthy growing stock and/or reducing safety hazards by felling snags (J. Hanley, International Paper Corporation, *personal communication*).

Downed coarse woody debris

The downed CWD loads in the old-growth stands (45 ± 6 Mg/ha, 139 ± 22 m^3/ha) are similar to those reported from other studies of northern hardwood old growth (Table 7). Studies reporting CWD biomass

TABLE 6. Mean (± 1 SD) densities and basal areas of standing dead trees in various hardwood stand types of the eastern United States.

Study	State	Forest type	Number of sites	Minimum diameter (cm)/ height (m)	Density (no./ha)	Basal area (m^2/ha)
Old growth						
This study	NY	northern hardwoods	6	10/1.0	61 ± 21	8.2 ± 3.6
Carbonneau (1986)	NH	northern hardwoods	5	10	47 ± 12	3.9 ± 1.0
Roman (1980)	NY	northern hardwoods	30	10	36 ± 22	4.5 ± 3.9
Dunwiddie (1993)	MA	northern hardwoods	7	10	26 ± 22	3.2 ± 3.7
Goodburn and Lorimer (1998)	WI/MI	northern hardwoods	6	10/1.5	39	6.0
Tyrrell and Crow (1994)	WI/MI	hemlock–northern hardwoods	25	10/1.0	79 ± 36	5.6 ± 2.6
Dunwiddie (1993)	MA	hemlock–northern hardwoods	12	10	45 ± 22	4.5 ± 3.8
McComb and Noble (1980)	CT	hemlock–northern hardwoods	1	10/1.8	39	···
Goodburn and Lorimer (1998)	WI/MI	hemlock–northern hardwoods	4	10/1.5	73	10.9
Forrester (1998)	OH	sugar maple–beech	1	10/1.0	28	3.9
Hardt and Swank (1997)	NC	sugar maple	1	20	17	···
McComb and Muller (1983)	KY	mixed mesophytic	1	10/1.3	43	···
Onega and Eichmeier (1991)	TN	mixed mesophytic	1	10	17	···
Muller and Liu (1991)	KY	mixed mesophytic	1	20	12	···
Goebel and Hix (1996)	OH	mixed oak	4	10/1.4	40 ± 8	2.0 ± 1.4
Roovers and Shifley (1997)	IL	oak–hickory	1	10	39	2.4
Shifley et al. (1997)	MO	oak–hickory/mesic oak	5	10	35 ± 3	1.9 ± 0.2
Rosenberg et al. (1988)	VA	oak–hickory/chestnut oak	15	10/1.0	64	···
Maturing						
This study	NY	northern hardwoods (89–103 yr)	4	10/1.0	96 ± 48	4.1 ± 1.1
Kruse and Porter (1994)	NY	northern hardwoods (80 yr)	2	10/2.0	80	···
Goodburn and Lorimer (1998)	WI/MI	northern hardwoods (65–75 yr)	6	10/1.5	90	2.8
McCarthy and Bailey (1994)	MD	mixed mesophytic (65–89 yr)	3	2.5	384 ± 51	6.8 ± 0.9
Goebel and Hix (1996)	OH	mixed oak (70–89 yr)	6	10/1.4	53 ± 40	2.3 ± 2.8
Goebel and Hix (1996)	OH	mixed oak (90–109 yr)	5	10/1.4	20 ± 25	0.8 ± 1.2
Rosenberg et al. (1988)	VA	oak–hickory (80–90 yr)	15	10/1.0	69	···
Shifley et al. (1997)	MO	oak–hickory/mesic oak (70+ yr)	6	10	31 ± 5	1.3 ± 0.2
Uneven-aged managed						
This study	NY	northern hardwoods	6	10/1.0	43 ± 17	1.2 ± 0.7
Kenefic (1995)	NY	northern hardwoods	1	10/1.8	11	···
Goodburn and Lorimer (1998)	WI/MI	northern hardwoods	10	10/1.5	38	2.8
Goodburn and Lorimer (1998)	WI/MI	hemlock–northern hardwoods	5	10/1.5	26	2.0
McComb and Noble (1980)	CT	hemlock–northern hardwoods	1	10/1.8	15	···
Hardt and Swank (1997)	NC	mixed oak	2	25	16	···
Stribling et al. (1990)	PA	oak–hardwood (TSI)	2	10/1.8	2	···
Stribling et al. (1990)	PA	oak–hardwood (TSI w/snag retention)	2	10/1.8	13	···

ranged from 26 to 43 Mg/ha (Roskoski 1977, Tritton 1980, Gore and Patterson 1986), while another study reported volumes of 166 ± 42 m^3/ha (Carbonneau 1986). Collectively, available data suggest that northern hardwoods have greater amounts of downed CWD than other eastern, deciduous North American forest types (Table 7). The variability among forest types probably reflects differences in input and decay rates (Harmon et al. 1986), with northern hardwoods having higher input rates due to the frequency of damaging wind, snow, and ice. Also, decay rates are probably lower in the northern hardwoods than other eastern hardwood types due to cooler climate. Finally, disease plays an important role in CWD loading. In New England and New York, death of trees due to beech bark disease has added unnaturally high amounts of CWD to many stands. McGee (1998) estimated that downed CWD volumes might be 25% lower than reported here in the absence of beech bark disease. Others (Tritton 1980, Gore and Patterson 1986) working in northern hardwood stands have commented that beech bark disease influenced their CWD estimates. Similarly, the standing CWD densities and basal areas in northern hardwood stands free of beech bark disease could be at least 30% and 20% lower, respectively, than reported in this study (McGee 1998).

Some studies have suggested that CWD decay distributions may be incomplete, or show unnatural pulsing in managed forests (Soderstrom 1988, Andersson and Hytteborn 1991). This was not the case in the partially cut stands we sampled. Within the downed CWD component, all decay classes were present in equal proportions among the stand types (Fig. 3). In uneven-aged managed stands, pulsing of CWD loads would be expected to occur if logging entries are made on cycles equal or greater than the time required for slash to decompose (20–50 yr). With reentry periods of 15–20 yr, as used in the sample stands, portions of the CWD

TABLE 7. Mean (± 1 SD) volume and biomass of downed CWD in various hardwood stand types of eastern United States.

Study	State	Forest type	Number of sites	Minimum diameter (cm)	Volume (m^3/ha)	Biomass (Mg/ha)
Old growth						
Carbonneau (1986)	NH	northern hardwoods	5	10	166 ± 42	···
This study	NY	northern hardwoods	6	1	139 ± 22	45 ± 6
Gore and Patterson (1986)	NH	northern hardwoods	1	···	···	42
Tritton (1980)	NH	northern hardwoods	1	0.2	···	43
Roskoski (1977)	NH	northern hardwoods	2	1	···	26 ± 12
Goodburn and Lorimer (1998)	WI/MI	northern hardwoods	6	10	102 ± 6	29
Goodburn and Lorimer (1998)	WI/MI	hemlock–northern hardwoods	4	10	94 ± 11	20
Hardt and Swank (1997)	NC	sugar maple	1	20	86	···
Harmon et al. (1986)	TN	beech–birch	1	7.5	82	29
Forrester (1998)	OH	sugar maple–beech	1	10	80	22
Tyrrell and Crow (1994)	WI, MI	hemlock–northern hardwoods	25	20	55 ± 5	···
Onega and Eichmeier (1991)	TN	mixed mesophytic	<1	···	···	17
Muller and Liu (1991)	KY	mixed mesophytic	1	20	48	15
MacMillan (1988)	IN	mixed mesophytic	1	···	···	18
Lang and Forman (1978)	NJ	oak	1	10	47	21
Goebel and Hix (1996)	OH	mixed oak	4	10	30 ± 31	···
Harmon et al. (1986)	TN	mixed oak	1	7.5	94	24
Harmon et al. (1986)	TN	chestnut oak	1	7.5	132	21
Roovers and Shifley (1997)	IL	oak–hickory	1	10	81	···
Shifley et al. (1997)	MO	oak–hickory/mesic oak	5	10	36 ± 4	···
Maturing						
This study	NY	northern hardwoods (89–103 yr)	4	1	61 ± 16	20 ± 5
Gore and Patterson (1986)	NH	northern hardwood (100 yr)	1	···	···	54
Tritton (1980)	NH	northern hardwood (83 yr)	1	0.2	···	20
Goodburn and Lorimer (1998)	WI/MI	northern hardwoods (65–75 yr)	6	10	25 ± 4	6
McCarthy and Bailey (1994)	MD	mixed mesophytic (65–89 yr)	3	2.5	42	18
Goebel and Hix (1996)	OH	mixed oak (70–89 yr)	4	10	17 ± 20	···
Goebel and Hix (1996)	OH	mixed oak (90–109 yr)	4	10	22 ± 20	···
Shifley et al. (1997)	MO	oak-hickory/mesic oak (70–90 yr)	6	10	18 ± 2	···
Uneven-aged managed						
This study	NY	northern hardwoods	6	1	69 ± 17	22 ± 5
Gore and Patterson (1986)	NH	northern hardwoods	1	···	···	35
Goodburn and Lorimer (1998)	WI/MI	northern hardwoods	10	10	61 ± 6	15
Goodburn and Lorimer (1998)	WI/MI	hemlock–northern hardwoods	5	10	56 ± 7	14
Hardt and Swank (1997)	NC	southern Appalachian hardwood	2	20	63 ± 27	···

load from previous entries remain at the time of the next cutting, thereby maintaining downed material in various stages of decay. The bimodal decay distribution of the downed CWD (Fig. 2) probably reflects our narrow definition of decay class 4 (soft throughout, but not yet collapsible).

The sizes of downed CWD differed among the stand types. We detected no differences in the smallest size class (1–9 cm diameter) of dead material, suggesting an equal input of twig litter, small trees, and limbs across the stand types. Tritton (1980) reported similar findings in northern hardwood stands from 40 yr old to old-aged. However, the old-growth stands contained four to seven times more downed CWD ≥25 cm diameter than the other stand types. Our data suggest that 100 yr of unmanaged, even-aged stand development is not sufficient to produce substantial loads of large dead material (Table 4). The CWD ≥50 cm that was present in the maturing stands was apparently from postfire residuals that died during development of the new stands. Gore and Patterson (1986) also found greater proportions of large CWD (>38 cm diameter) in old vs. young stands, and determined that residual trees were important sources of large logs in developing stands. In our study, large logs in the partially cut stands were portions of cull trees that had been felled and left. It was apparent within the partially cut stands we studied that uneven-aged management can supply at least a few large logs on a continuing basis.

Data from this study suggest approximately 110 m^3/ha of downed CWD as an average natural level in old-growth, northern hardwood stands free of extensive mortality by beech bark disease. Measures such as felling and leaving poor quality trees, or girdling the same, could yield additional downed CWD in selection stands. To best emulate old-growth conditions, ~50% of the volume should be from stems ≥25 cm diameter, and 10% from stems ≥50 cm diameter. Girdling, or mindfully retaining some culls in reserve shelterwood stands, will provide continued large CWD production through even-aged rotations. Also, foresters should feel comfortable leaving residue from even-aged thinning operations to add to the CWD load.

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