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Estimates of Down Woody Materials in Eastern US Forests

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ABSTRACT / Down woody materials (DWMs) are an important part of forest ecosystems for wildlife habitat, carbon storage, structural diversity, wildfire hazard, and other large-scale ecosystem processes. To better manage forests for DWMs, available and easily accessible data on DWM components are needed. We examined data on DWMs, collected in 2001 by the US Department of Agriculture (USDA) Forest Inventory and Analysis (FIA) program on some plots in several states. We compiled DWM data from 778 plots to compute biomass for the following components: coarse woody material, fine woody material (three size classes), litter, duff, and shrub/herb cover. We developed regression equations to predict DWM components for extension to FIA's more intensive plot network. Seven regression equations were applied to the FIA data to create maps of DWM biomass. As a first attempt to summarize FIA DWM measurements and extend them to plots without these data, our model produces reasonable results except possibly for duff and litter.

Down woody materials (DWMs), also known as down woody debris, are vital to the function and structure of a healthy forest ecosystem. They are important for carbon sequestration, nutrient cycling, soil stability, wildlife habitat, and many other purposes (Harmon and others 1986; Dodds and Smallidge 1999; Hagan and Grove 1999; Robertson and Bowser 1999; McGee 2000; Karjalainen and Kuuluvainen 2002).

The components of DWMs vary in size, structure, and characteristics. Coarse woody material (CWM) includes all down and dead pieces 76 mm in diameter and larger (Figure 1). Fine woody material (FWM) includes the smaller-sized woody branch pieces. Everything else lying on the forest floor above the A1 mineral soil horizon is either litter (original *recognizable* plant forms) or duff (original plant forms *not recognizable*). Litter, or the O_i organic soil horizon (Brady and Weil 2002), includes all other dead detached plant material lying loosely on the forest floor, distinguishable as needles, leaves, cones, bark, rotted wood chunks, or other plant parts. Duff, or the O_e and O_a organic soil horizons, includes all of the partly decayed organic material between litter and the A1 soil horizon that bears little resemblance to original plant structures. The remaining DWM component—the shrub/herb cover—really is not "lying down" and is not necessarily dead, but Forest Inventory and Analysis (FIA) includes it in this category for convenience. Included are all understory shrubs and herbs of both live and dead plants that are still standing upright (down material is included in litter or duff). All of these definitions of DWMs are from the US Department of Agriculture (USDA) Forest Inventory Analysis program (FIA 2003a). The DWMs together with FIA's live and standing-dead tree inventory and soil inventory constitute measurement of total forest carbon.

Of the DWM components, CWMs have been most widely studied, but there have also been several recent investigations on FWMs, litter, and duff (Lee and others 1997; Wei and others 1997; Vande Walle and others 2001; Hely and others 2000; Klopatek 2002; Waddell 2002). Although much of the initial work was limited to DWMs in old-growth forests, a few recent studies focus on DWMs in managed forests (Guby and Dobbertin 1996; DuVall and Grigal 1999; Hale and others 1999; Fridman and Walheim 2000). Studies such as these cover detailed aspects of how DWMs interact with specific environments in Asia, North and South America, and Europe. However, none of these studies offer land managers much help for managing DWMs for their

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Figure 1. Coarse woody material and leaf litter in Rock Creek Park, Washington, DC.

particular situations. Furthermore, these studies really are not amenable to a meta-analysis or other analyses that might generalize specific studies into widely applicable results. Therefore, it would be helpful to have DWM data in widely available and easily accessible forest inventory databases, which would at least offer managers the opportunity to use DWM data along with conventional data on forest conditions. Data on the various components of DWM would contribute important details to management of global carbon storage, fire hazards, wildlife habitat, and other large-scale ecosystem processes.

One widely available inventory database is produced by the USDA Forest Service's national FIA program (FIA 2003b), which collects data from and continually monitors field plots across all land ownerships in the United States. This inventory collects forest data in three phases. A remote sensing phase 1 (P1) is used to determine forest area; a grid of 120,000 field plots at 5-km intervals is used to measure trees in phase 2 (P2); and a subsample of these plots in phase 3 (P3) is used to collect more detailed forest health information. The P2 plots sample the nation's 302 million hectares of forestland with about 1 plot per 2500 ha, and the P3 plots subsample 1/16 of the P2 plots.

In 2001, FIA collected data on DWMs on some P3 plots in several states. We wanted to connect these data to the entire eastern FIA database to produce reliable and timely information that could be used to assess fire-fuels conditions. Our objectives were to (1) compile down woody materials data available from P3 plots, (2) merge this DWM information with all P2 plots in the FIA database for the eastern United States to construct models, and (3) apply the resulting regression models to the FIA database to produce maps of DWM biomass.

Methods

Data on down woody materials were available from the FIA program for 778 plots measured in 2001. However, it was quite complicated to compile the data [in SAS (2003)] and to estimate biomass for each DWM component. Even though the DWM inventory was based on measurements needed for available transect sampling formulas, the FIA methods were adapted to fit within their plot sampling scheme, which can include "variable subplot sizes" when a plot samples an interface of two or more forest conditions. Therefore, the FIA plot sampling design had to be considered in order to determine the exact number and length of each transect for each subplot condition. In this section, we outline the DWM sampling design, discuss DWM biomass compilation formulas, mention other FIA data needed, and provide an overview of modeling methods.

DWM Sampling Design

In 2001, FIA collected DWM data by overlaying transect procedures on its P3 plot design, which includes four circular 0.017-ha subplots in a cluster where three subplots surround a central subplot at 120° angles at 37-m distances (FIA 2003b, see Field Guide methods under links to FIA program information). The four-subplot design can be subdivided in any possible fashion to match actual vegetation conditions on the ground. For example, forest and nonforest proportions are mapped out when a plot straddles an agriculture field and forest edge.

Forest Inventory and Analysis used slightly different methods to sample each of the five DWM variables (coarse wood, fine wood, duff, litter, and shrub/herb cover). The CWM and FWM variables were sampled along transects using "line-intersect sampling," where pieces of material were measured if crossed by the transect. This is a probability proportional-to-size (PPS) method that has been used in forestry for about 40 years (Brown 1974). It is based on a famous 1700s mathematical problem "on the probability of a random scatter of needles intersecting a line under some assumptions" (de Vries 1986). An elegant feature of the method is that log volume can be calculated from log diameter measured where the transect crosses; log length and end diameters are not needed because these algebraically cancel out if the log is assumed a cylinder. Although it is more appealing to think of logs as cones (with varying diameters) rather than cylinders (with uniform diameter), it is more time-consuming and it can be difficult to measure end diameters on partially rotten material that is often splintered at the ends. Therefore, one "randomly selected" intersect di-

Table 1. Classification of the stage of decay for down woody materials

Decay class[a]	Structural integrity	Wood texture	Wood color	Presence of invading roots	Condition of branches and twigs
1	Sound	Intact, no rot; conks on stem absent	Original color	Absent	If branches present, fine twigs still attached with tight bark
2	Heartwood sound; sapwood somewhat decayed	Mostly intact; sapwood partly soft and starting to decay; wood cannot be pulled apart by hand	Original color	Absent	If branches present, many fine twigs gone; fine twigs still present have peeling bark
3	Heartwood sound; log supports its weight	Large, hard pieces; sapwood can be pulled apart by hand	Red-brown or original color	Present in sapwood only	Large branch stubs will not pull out
4	Heartwood rotten; log does not support its weight, but shape is maintained	Soft, small blocky pieces; metal pin can push apart heartwood	Red-brown or light brown	Present throughout log	Large branch stubs pull out easily
5	No structural integrity; no longer maintains shape	Soft, powdery when dry	Red-brown to dark brown	Present throughout log	Branch stubs and pitch pockets have rotted away

[a]The decay class recorded for a log is the stage of decay that predominates along the length of the log.
Source: Waddell (2002).

ameter (with log cylinder assumption) might prove best from an overall sampling perspective, given practical measurement limitations. Although log length and end diameters can be used in a slightly more complicated line-intersect estimator, for this study the single-diameter method was used for simplicity.

The CWM (> 76 mm diameter) was sampled on two 18-m transects for each FIA subplot, which meant a total transect length of 144 m for each plot. Pieces were classified into five decay classes (Table 1). FWM was sampled in three diameter classes (0–6 mm, 6–25 mm, and 25–76 mm), in shorter transects than for CWMs and from only one transect per subplot. Total transect length per plot of the largest FWM class was 24 m; the smaller classes totaled 12 m. Duff and litter depths were sampled at two points on each CWM transect. Shrub/herb cover and height were sampled on a 0.00135-ha microplot within each subplot. These definitions of variables were from FIA's *Phase 3 Field Guide on Down Woody Debris and Fuels*, March 28, 2001 version (FIA, personal comunication).

Biomass Compilation

Before data could be compiled, an exact length of some transects had to be calculated to be consistent with FIA protocol, which subdivides plots that straddle different or nonforest conditions. This amounted to about 4% of the total number of transects (which affected 22% of the plots) that were truncated or subdivided to stay within FIA-defined forest conditions.

We computed the biomass of CWMs using a simple linear equation where only log diameter (at transect intersection), transect length, and transect slope were measured variables:

$$\mathrm{CWM} = \sum_{i=1}^{n} \frac{f\,\mathrm{dia}_i^2\,\rho\,d\,c}{L}, \tag{1}$$

where CWM is the coarse woody material > 76 cm diameter (Mg/ha); n is the total pieces of wood sampled on transect; f is the units conversion factor (11.64) (2000)/[(2.2046) (0.0404686) (1000) = 26.09366], dia is the log diameter (to nearest inch) at transect intersection of logs > 76 mm (small end) for decay classes 1 to 4 and logs > 127 mm (small end) for decay class 5 (see Table 1 for decay classes definitions); ρ is the specific gravity of wood species, from Forest Service, Forest Products Laboratory; d is the decay class deduction (for conifer: class 1 = 1.0, class 2 = 0.84, class 3 = 0.71, class 4 = 0.45, class 5 = 0.35; for hardwood: class 1 = 1.0, class 2 = 0.78, class 3 = 0.45, class 4 = 0.42, class 5 = 0.35) (Waddell, personal communication, 2000), $c = \sqrt{1 + (\text{slope percent}/100)^2}$ [from Brown (1974)]; and L = transect length (ft).

Plot-level estimates were calculated by treating all transects within a plot as one "single" transect, which avoided effects of shortened transects on plot averages.

The biomass for FWM was calculated in a similar fashion except that the diameter was an auxiliary variable because the number of pieces (T) were tallied in classes. What to use for diameter class in the formula was a problem because the class midpoint was not necessarily appropriate for tree branch material. Given that trees repeatedly branch from single large to multiple smaller-sized material, there will generally be more smaller-diameter branches than larger branches in any given sample. Consequently, an exponential or inverse J is a more appropriate distribution for describing branch diameters sampled within a class, which means that the actual diameter class mean will always be less than the class midpoint; however, the amount of difference is likely to depend on class size and species. We used composite diameter class means [see dclas in Equation (1)] for western conifers based on empirical work because nothing else was available (Brown 1974). We did look at modeling tree-branch distributions (Chojnacky and Born 1992), but species-specific parameters would still be needed. The new variable a in the FWM equation—not used in the CWM formula—is a theoretical orientation constant needed to adjust the probability of selection because not all small branches lie flat on the ground. We used 1.13, a western conifer number (Brown 1974). The rest of the variables—f, ρ, d, c, and L—are similar to those defined for CWMs:

$$\text{FWM} = \sum_{i=1}^{3} \frac{f\, T_i\, \text{dclas}_i^2\, \rho\, d\, c\, a}{L_i}, \qquad (2)$$

where FWM is the fine woody material < 76 cm diameter (Mg/ha, i is the three diameter classes of FWM (0–6 mm, 6–25 mm, 25–76 mm); T_i is the tally of the number of pieces in each diameter class; dclas_1^2 = 0.0151 [diameter (in.) squared for 0–6-mm material]; dclas_2^2 = 0.2890 [diameter (in.) squared for 6–25-mm material]; dclas_3^2 = 2.7600 [diameter (in.) squared for 25–76-mm material]; ρ = 0.46, which is median specific gravity of all US tree species; d = 0.9, which assumes some decay because FWM changes to litter or duff as decay increases, and a = 1.13, which assumes an average correction factor for all material not lying flat on ground.

Litter and duff biomass were calculated by assuming that the depth measurement represents a "uniform cylinder of constant specific gravity":

$$\text{Litter or duff} = f\, D\, \rho, \qquad (3)$$

where Litter is the recognizable plant material on the forest floor (Mg/ha); Duff is the unrecognizable plant material below litter and above mineral soil (Mg/ha); f = units conversion factor 43560/[(2.2046) (0.404686) (1000)] = 48.82473D is the material depth (ft); ρ is the material density (lbs/ft^3) [for litter = 0.9, for duff = 2.0 (source: minimum values from western US forest data, Woodall (2002), and personal communication)].

Our material density values came from data compiled by the USDA, Forest Service Fire Sciences Lab, Missoula, Montana. Plot-level estimates were calculated from an average of all points sampled within a plot.

To compute shrub and herb biomass, we applied regression equations developed in the western United States (Mitchell and others 1987; Brown and Marsden 1976), using the same equations for both live and dead cover:

$$\text{Shrub} = \frac{109.0 - (2.161 C_s) + (0.1078 C_s^2)}{100}, \qquad (4)$$

where Shrub is the live or dead biomass (Mg/ha) and C_s is the horizontal projection of live or dead shrub cover above plot surface (%).

$$\text{Herb} = \frac{13.66 C_H}{1000}, \qquad (5)$$

where Herb is the live or dead biomass (Mg/ha) and C_H is the horizontal projection of live or dead herb cover above plot surface (%).

Plot-level estimates for shrubs and herbs were calculated from an average of all microplots sampled within a plot. Because we used equations developed for western species, our results are obviously rough; however, they should at least be useful for judging order of magnitude and should motivate new research on similar equations (compatible with FIA data) for eastern species.

FIA P2 Data Needed

In addition to computations for DWM (from FIA P3 data), FIA P2 data for tree measurements were also needed for the 778 plots. However, we could match P2 data to only 581 of the 778 plots for limited variables at this time because the FIA's P3 database is under construction.

We also needed a compilation of all FIA plots for the eastern United States, which was supplied by the Forest Service, Southern Global Change Program. These data were used for applying final DWM model results to 99,312 plots for all forested counties in the eastern United States. For comparison to DWM, total above ground and belowground biomass for the FIA data was also estimated from live and dead trees using Jenkins

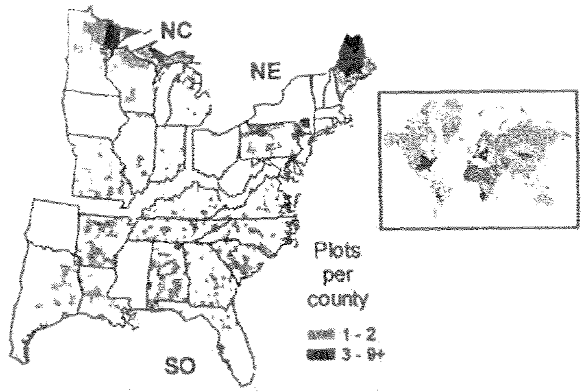

Figure 2. County-scale distribution of 581 plots having both DWMs and FIA P2 data available for the eastern United States. The North Central (NC) FIA region includes 115 plots, the Northeast (NE) includes 180 plots, and the South (SO) includes 286 plots. Counties within the Allegheny National Forest in northwest Pennsylvania and the upper Delaware River Basin in southeast New York include 19–23 plots because these were sampled more intensively for other studies.

and others' (2003) equations (which separate all US species among 10 dbh-based equations).

We could have used more information on dead trees than what is included in the FIA database. The FIA generally includes a tally of dead trees for each P2 plot, but further calculations with these data (for basal area, trees per hectare, and other variables for all dead trees) rely on mortality sampling, which is based on the difference between two inventories and has been recently affected by changes in field procedures. Because FIA data include calculated plot-level expansion factors instead of actual dimensions of sample plots, it is difficult to reconstruct sampled-based statistics beyond what is included in the FIA data. Therefore, a tally of dead trees expressed as a proportion of live tally was the only dead-tree statistic used for this study.

DWM Modeling

To test the extension of the DWM data to all plots in the eastern FIA database, we modeled the DWM variables from the FIA P2 measurements that were available for the 2001 plots or from other data that could be linked to FIA plots. As previously mentioned, we could match P2 data to only 581 of the 778 DWM plots at this time.

The 581 plots sampled for DWM were fairly well distributed—with one or two plots per county—throughout most states included in the 2001 survey (Figure 2). Not all states are included yet in FIA's P3 sampling, and some counties were sampled more extensively than others. For example, sampling was greatly intensified in Pennsylvania's Allegheny National Forest and in the upper reaches of the Delaware River Basin.

As a first approximation for modeling DWM, seven regression equations were developed for the following components: CWMs; small, medium, and large FWMs; litter; duff; and shrub/herb cover. In a previous study on CWMs in Maine forests (Heath and Chojnacky 2001; Chojnacky and Heath 2002), we found CWM mass most related to dead standing trees and cut tree stumps. That work suggested considering 10 variables for the regression model:

$$\text{DWM component} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_{10} X_{10}, \quad (6)$$

where X_1 is the proportion of dead trees ($\geq$ 12.7 cm dbh) tallied on the FIA plot; X_2 is the total basal area of live trees ($\geq$ 12.7 cm dbh) on that FIA plot (m^2 /ha); X_3 is the number live trees ($\geq$ 12.7 cm dbh) tallied on the FIA plot (No./ha); X_4 is the quadratic mean diameter of live trees ($\geq$ 12.7 cm dbh) tallied on the FIA plot (cm); X_5 (1 if forest type is coniferous forest, 0 otherwise); X_6 is the longitude of the county center assigned to all FIA plots in that county (decimal degrees); X_7 is the latitude of the county center assigned to all FIA plots in that county (decimal degrees); X_8 is the average precipitation of the county center assigned to all FIA plots in that county (mm/year); X_9 is the average number of days that rain or snow fell (wet days) in the county center assigned to all FIA plots in that county (No./year); and X_{10} is the average relative humidity of the county center assigned to all FIA plots in that county (%).

The tree variables (X_1 to X_5) were from previously compiled plot-level data (raw tree-level data were unavailable at this time). These variables represented a simple description of live and dead forest structure that could be easily calculated from the FIA data. The dead tree variable (X_1) was the best overall statistic on dead trees that could be calculated at this time, because, as mentioned earlier, FIA's dead tree emphasis is on estimating mortality rate and salvable dead wood, which leaves gaps in a comprehensive standing-dead tree inventory.

The other variables (X_6 to X_{10}) are auxiliary climate variables, which were based on 30-year averages for 4-km grid cells (Climate Source 2001). These were county averages applied to all FIA plots within each county. A county scale was used because geographic coordinates were unavailable for each plot, which would be necessary for finer-scale merging to auxiliary data.

Because the climate variables were already modeled, they were examined for cross-correlations with each other and with geographic coordinates, which seemed the primary predictor of temperature variables. All temperature variables were eliminated because of 0.92–0.99 correlations (Pearson correlation coefficient) with each other or with geographic coordinates. Except for the 0.75 correlation between longitude and wet days (X_6 and X_9), correlations among selected variables ranged from 0.08 to 0.56.

Dummy variables (allowing separate regression intercept) for the Northeast, North Central, and South regions were initially considered and found highly significant in some cases, but these were dropped from consideration because they produced illogical model results with abrupt changes at boundaries between FIA administrative regions. We suspected the dummy variables might be modeling slight differences in application of measurement procedures among regions; although each FIA region used the same field guide, there were probably differences in interpretation, training, and quality control because of decentralized management within each region. Nonetheless, it seemed best not to consider more flexible modeling of regional differences (to avoid the abrupt changes inherent with dummy variable methods) until more experience can be gained from 2002 data and beyond.

Results

There were three distinct results from the analysis: (1) down woody materials were compiled from 778 FIA plots sampled in 2001; (2) 581 of these plots were merged with FIA P2 data to construct models; and (3) resulting models were applied to the FIA database to produce maps of DWM biomass.

DWM Compilation

The biomass for the different DWM components (CWM, FWM, litter, duff, shrubs/herbs)—separated into Northeast, North Central, and South FIA regions—were found to be generally less than 10 Mg/ha (Figure 3). However, FWM, duff, and litter biomass could be much different depending on what values are used for auxiliary variables in the above compilation. Because many of the auxiliary variables were taken from western forests, these results should be viewed with some caution. On the other hand, the equations are simple enough that users could devise ratios for a range of auxiliary parameters in order to bound estimates by high and low ranges. For example, if material

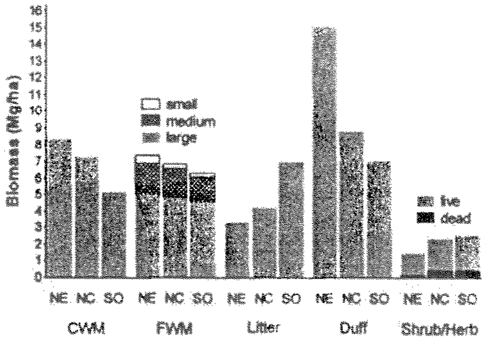

Figure 3. Biomass of down woody materials (including shrub and herb) for 778 plots in Northeast (NE), North Central (NC), South (SO) FIA regions (2001 inventory). Coarse woody material (CWM) is > 76 mm in diameter; fine woody material (FWM) includes large (25–76 mm in diameter), medium (6–25 mm in diameter), and small (< 6 mm in diameter) sizes; litter is recognizable plant material; and duff is nonrecognizable plant material above mineral soil.

density of duff or litter were thought to be half of what we used, our results could simply be divided by 2.

The means of the biomass components are from highly variable data with a few large extreme values (Table 2). Medians of all components were always less than means (e.g., the median CWMs in the South was less than one-third of the mean), indicating the effects of the large extremes. Coefficients of variation were generally over 100%.

Model Construction

Each component model included three or four variables (Table 3), selected by using stepwise regression (based on maximum R^2 for variable selection) and other graphical examinations. Generally, variables included in the regression models were significant at the 0.05 probability level, but final variable selection was also influenced by model extrapolation, biological interpretation of variables, and examination of regression residual graphs. Obviously, much more rigor could have been incorporated into modeling, but our initial data sample of only 581 plots did not warrant such effort. When more DWM data become available, more modeling rigor can then be applied.

Nine different variables were selected among models, but these were essentially functions of either climate or live/dead forest structure. The climate variables (which included latitude and longitude) were useful because they seemed correlated with decomposition rate, which is affected by temperature and moisture. Latitude and longitude (geographic coordinates) were included as "climate" variables because the cli-

Table 2. Biomass statistics of down woody material components from 778 FIA plots in the eastern United States (2001 inventory)

		Biomass (Mg/ha)								
			FWM (diameter in mm)					Shrub and herb		
FIA region	Statistic	CWM	25–76	6–25	< 6	Litter	Duff	Live	Dead	Plots
Northeast	Mean	8.3	5.0	1.9	0.4	3.3	15.1	1.3	0.1	229
	Median	6.5	3.6	1.6	0.3	2.9	11.6	1.1	0.0	
	95th Percentile	23	12	4	1	7	40	3.6	0.8	
	Maximum	46	101	11	7	13	166	6.2	1.1	
	CV[a] (%)	91	159	69	183	62	104	84	189	
North Central	Mean	7.3	4.8	1.8	0.3	4.2	8.8	1.9	0.5	249
	Median	4.1	3.4	1.3	0.2	4.0	5.4	1.6	0.4	
	95th Percentile	25	14	5	1	9	24	4.5	1.1	
	Maximum	70	32	10	4	25	145	7.1	1.4	
	CV (%)	129	106	99	135	67	150	67	87	
South	Mean	5.2	4.5	1.6	0.2	7.0	7.0	2.1	0.5	300
	Median	1.7	3.1	1.1	0.1	6.9	4.9	1.6	0.3	
	95th Percentile	15	12	4	1	13	21	5.3	1.1	
	Maximum	230	47	28	4	22	41	9.5	4.3	
	CV (%)	356	127	140	137	51	99	78	107	
Total	Mean	6.8	4.7	1.7	0.3	5.0	9.9	1.8	0.4	778
	Median	3.8	3.4	1.3	0.2	4.5	7.0	1.4	0.3	
	95th Percentile	23	13	4	1	11	27	4.7	1.1	
	Maximum	230	101	28	7	25	166	9.5	4.3	
	CV (%)	196	133	106	177	67	126	79	118	

[a]Coefficient of variation (CV) is standard deviation divided by mean and multiplied by 100.

Table 3. Preliminary regression model for estimating down woody materials for the eastern United States

	Regression coefficients										
Material[a]	β_0	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8	β_9	R^2
CWM	−2.0875	9.9536	0	0	0.0914	0	0	0	−0.0044	0.0876	0.19
FWM											
25–76 mm	3.3599	3.2936	0	−0.0009	0	0	0.0202	0.0651	0	0	0.02
6–25 mm	−0.5813	0	0	0	0	0.2028	0	0.0255	0	0.0101	0.06
< 6 mm	0.5458	0	0	0.0002	0	0.2090	0.0135	0.0189	0	0	0.13
Litter	14.2787	0	0	0.0016	0	0	0	−0.1899	0.0021	−0.0406	0.30
Duff	30.4797	0	0	0	0	3.0994	0.5126	0.5481	0	0	0.28
Shrub/herb	4.8554	0	−0.0297	0	0	0.2924	0	0	0	−0.0202	0.16

[a]Material = $\beta_0 + \beta_1X_1 + \beta_1X_1 + \beta_9X_9$.
See text for explanation of variables.

mate variables themselves were previously modeled and most were strongly correlated with geographic coordinates. Therefore, the climate/geographic variables were useful in modeling increasing or decreasing trends in DWM across the eastern United States.

The forest structure variables generally seemed related to the source of a particular down woody component. For example, standing dead trees were important for predicting CWMs and large FWMs because dead trees are primary source of these materials. Trees per hectare were important for litter and FWMs because live trees annually add to these materials. Tree basal area was inversely related to predicting shrub and herb biomass because trees and understory are in direct competition for growing space.

Model Application: Mapping Results

The eventual objective of the study was to estimate DWM for all forest lands in the eastern United States. This was done by applying the seven regression equations (Table 3) to the entire FIA database for the eastern United States for regional summary.

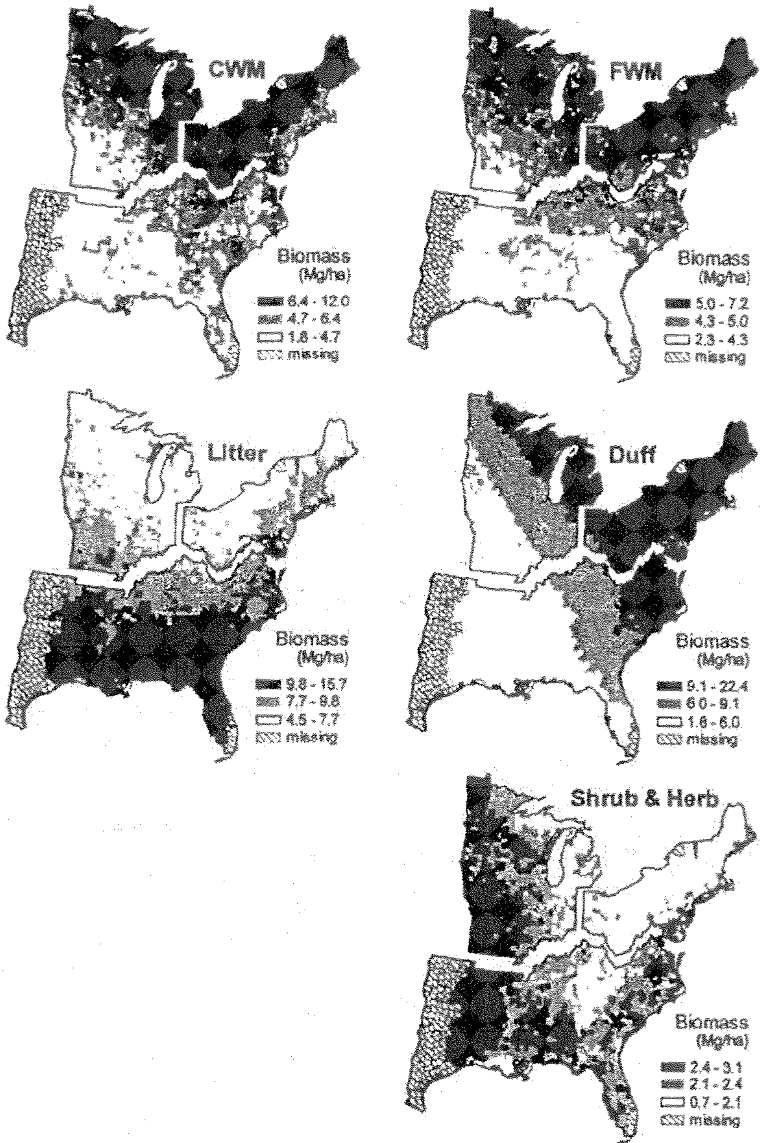

Figure 4. Average county-scale estimates of DWMs calculated from regression models in this study and the FIA database.

Although the plot-level estimation of DWM was not an end-product objective, these data were examined for negative predictions, which were possible because equations were not constrained against negative estimation. Only duff and small FWM estimates had many negative predictions, which included 1379 negative estimations for duff (1% of 99,312 FIA plots) and 5153 negatives (5%) for small FWMs. However, most of these were less than −1.0 Mg/ha for duff and less than −0.1 Mg/ha for FWMs. In addition, 98% of the negative estimates were restricted to Texas, Louisiana, Mississippi, Arkansas, Oklahoma, Florida, and Alabama. The negative plot-level values were left in for county-level summary, but there were too few to produce negative estimates at the county scale for any component.

Maps illustrate preliminary trends in these results in relation to forest structure and climate patterns (Figure 4). The legends on all the maps represent the distribution for mean county biomass (Mg/ha) divided into thirds (0 to 33rd, 33rd to 66th, 66th to 100th percentiles).

The greatest amount of CWMs was seen in the north, decreasing when moving southward, apparently because of increasing decomposition rates. FWMs and duff also decreased from north to south. Litter and shrub/herb cover, on the other hand, increased from north to south.

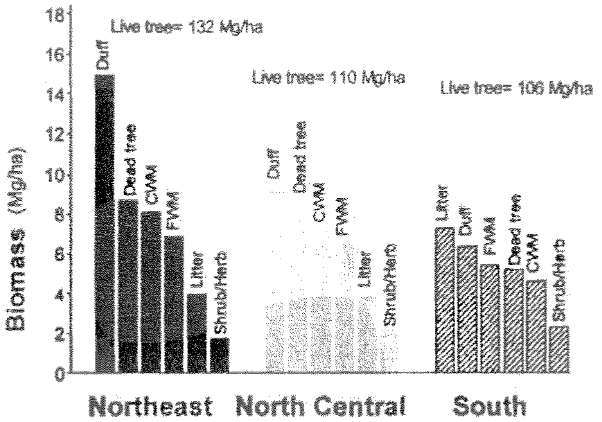

Figure 5. Average biomass of live and dead trees (above and below ground) compared to components of DWMs estimated from this study's equations applied to the FIA database.

Comparison of DWM to aboveground and belowground biomass of live and dead trees showed dead trees as comparable to DWMs, but live trees were more than 10 times larger than all other components (Figure 5). In Table 4, estimated tree and DWM biomass are presented by state.

Discussion

The compilation of DWMs and application of these results (through regression equations) to FIA data in the eastern United States is a first attempt to do this at such a large scale. The regression equations (Table 3) were designed to predict DWM components for FIA's intensive network of P2 plots. Although these preliminary models had low R^2 statistics, their use with the eastern FIA data should give reasonable state or regional estimates of DWM components. This is because the estimation process is somewhat comparable to a classical stratified-sampling design for ratio or regression estimators (Lohr 1999, p. 59). Our regression model functions roughly as an "auxiliary variable" that adjusts each FIA plot for the amount of DWMs within several climate and stand structure strata. Furthermore, the low R^2 statistics are less of a concern in a sampling context because this simply means that the "auxiliary adjustment" tends to default to the mean of the DWM distribution (or is a ratio instead of regression estimator). For example, maximum CWMs can range from 46 to 230 Mg/ha in our data (Table 2), but our low-R^2 model predicts CWMs from 1.8 to 12 Mg/ha (Figure 4), which is comparable to the means and medians of our regional CWM data (Table 2). On the other hand, a greater concern is that our relatively small subsample (581 auxiliary plots of DWM data from 99,312 FIA plots) could be misrepresenting state and regional means for DWMs. In the future, when FIA fully implements P3 sampling, there will be about 6200 plots of DWMs per 100,000 FIA plots—over 10 times the sampling intensity as our current study. Therefore, until our work can be updated when more data become available, we advise caution when using our results.

We also advise great caution when using our methodology for local-scale projects. Because our regression equations can easily be applied to estimate DWMs for any subset of FIA plots, users may wish to assess biomass or carbon of DWMs for small projects from a few or representative FIA plots. For these situations, we suggest bounding all estimates for uncertainty by using the coefficients of variation (CV in Table 2) for a rough 67% confidence interval (CI) or twice the CV for a rough 95% CI. For example, CWM estimates for northeastern states would be viewed as between ± 91% for 67% CI or ± 182% for 95% CI. Such practice of multiplying DWM estimates by factors of 2, 4, or more is probably more conservative than necessary; however, it should illustrate that our methodology is useful for estimating order of magnitude (tens or hundreds) but little else at a local scale.

In addition to providing rough methodology for estimating DWMs, we also gained some experience for guiding future work. We find the model variables for climate and forest structure variables most promising for future study. For example, all categories of DWM were related to climate, which is logical when considering that moisture and temperature determine the rate of decomposition: the faster the rate, the less material on the ground, and vice versa. Also, the largest size material was correlated with amount of standing-dead trees, which is the preceding state of large DWMs.

Of all the down woody components, CWM is the most studied. The sampling and compilation are well supported by other studies (Wei and others 1997; Sturtevant and others 1997; Hely and others 2000; Tinker and Knight 2001). Although our values for CWM (Table 4) are generally lower than what is published for eastern forests, they appear reasonable considering that the FIA plots cover all forest conditions, including many plots of managed forest with little or no CWMs. The spatial map for CWMs looks reasonable and the model variables make some sense. Specific gravity or density of material in various decay classes is the only parameter in the model that was not well documented for eastern forests, which we suggest as a priority for future work.

Although data on FWMs have been reported (Lee and others 1997; Rice and others 1997; Harmon and

Table 4. Average biomass estimates for live and dead trees (above and below ground) and DWMs materials for eastern US states

State	No. of FIA plots	Total live tree (Mg/ha)	Total dead tree (Mg/ha)	Down Woody Materials: CWM (Mg/ha)	FWM (Mg/ha)	Litter (Mg/ha)	Duff (Mg/ha)	Shrub/herb (Mg/ha)	Total (Mg/ha)
Alabama	3,889	85.8	2.3	3.6	5.3	7.7	4.9	2.5	112.0
Florida	5,063	83.1	4.1	4.2	5.1	8.1	5.5	2.4	112.5
Oklahoma	908	90.7	2.7	3.0	4.9	7.3	1.5	2.8	112.8
Texas	2,067	96.5	4.0	4.1	4.9	7.9	0.3	2.7	120.4
Mississippi	3,097	95.4	4.1	4.0	5.3	7.9	3.3	2.5	122.5
Wisconsin	5,973	93.5	10.0	8.0	6.8	3.6	9.5	2.3	133.7
Louisiana	2,401	111.2	2.9	3.7	5.0	8.0	1.5	2.5	134.7
Minnesota	11,896	95.1	11.0	7.3	6.7	3.4	9.3	2.4	135.2
Arkansas	3,262	110.2	4.3	3.9	5.2	7.4	2.8	2.6	136.3
Georgia	8,361	103.0	5.7	5.1	5.5	8.0	7.0	2.2	136.5
South Carolina	4,143	98.3	11.8	5.4	5.8	7.1	8.9	2.4	139.8
Missouri	4,838	114.2	4.7	4.0	5.3	6.3	4.1	2.6	141.2
New Jersey	253	104.5	5.7	4.9	6.4	5.4	15.2	2.4	144.5
Illinois	1,123	126.7	1.8	4.7	5.5	5.5	6.2	2.4	152.8
Rhode Island	113	111.0	6.2	5.6	6.8	4.9	16.7	2.1	153.3
Tennessee	2,317	121.3	6.4	5.2	5.7	6.3	6.4	2.1	153.4
Ohio	1,726	118.2	8.3	8.0	6.4	4.4	10.3	1.9	157.5
Kentucky	1,978	126.3	6.6	5.9	5.9	5.7	7.7	2.1	160.2
North Carolina	5,481	125.3	5.1	4.9	5.8	6.4	10.4	2.2	160.3
Maine	2,767	104.6	12.4	9.0	8.0	3.3	21.3	1.9	160.4
Delaware	76	123.9	5.1	5.9	6.5	5.8	13.9	2.3	163.4
Indiana	2,093	129.6	9.0	6.8	6.1	5.1	7.9	2.1	166.6
Iowa	698	129.1	12.7	6.2	6.0	4.9	5.9	2.5	167.4
Michigan	10,017	128.4	7.9	8.9	6.8	2.9	12.0	1.7	168.8
Virginia	4,137	136.9	5.0	5.3	5.9	5.9	11.4	2.2	172.7
Massachusetts	380	136.6	6.1	6.2	6.9	4.7	17.2	2.0	179.6
New York	2,768	134.7	8.9	8.9	7.1	3.4	15.8	1.5	180.3
Maryland	515	144.7	5.1	6.4	6.2	5.2	12.8	2.1	182.6
Pennsylvania	2,905	138.8	10.0	8.4	6.7	4.0	13.2	1.7	182.9
Connecticut	292	140.6	7.1	5.5	6.7	5.0	16.3	2.1	183.3
West Virginia	2,569	152.2	5.5	8.0	6.2	4.4	10.4	1.5	188.1
New Hampshire	586	146.5	6.9	6.9	7.0	4.1	18.9	1.8	192.1
Vermont	620	147.3	8.6	8.0	7.2	3.4	18.2	1.6	194.3
Eastern U.S.	99,312	111.7	7.1	6.2	6.1	5.5	8.8	2.2	147.5

others 1995, Hely and others 2000, Vande Walle and others 2001), it is difficult to make comparisons to this study because of definition and methodology differences, but, generally, FWM has been reported as being much less than CWMs. Interestingly, our results show FWMs about the same magnitude as CWMs (Figures 3 and 4), which raises concern about possible technique problems. The field sampling and compilation of FWMs follow documented procedures (Brown 1974), but lack of study on auxiliary values in Equation (2) for eastern forests was a concern. For instance, the choice of mean diameter for the three size classes could vary considerably among species. Had diameter class midpoints (0.25, 0.75, 2.0, for small, medium, large classes, respectively) been used in Equation (2), for example, values for the variable $dclas_i^2$ (0.0625, 0.5625, 4.0) would have been over 120%, 60%, and 35% larger for small, medium, and large FWM classes, respectively, which would have linearly increased FWM by those percentages. Because most of the FWM biomass is in the largest class (Table 2), it might be more reasonable to measure diameters of the 25–76-mm size class to the nearest 1 or 2 cm than to develop mean class diameters for all eastern species. Also, field weighing of subsamples of all three FWM classes to refine density and decay deductions might be worthwhile. There is much opportunity for refining FWM estimation, but this study provides a valuable start.

Duff, litter, and shrub/herb biomass estimates for the eastern United States should be viewed at this time as a first approximation for comparisons with future work. The reason the duff map (Figure 4) looks so smooth is because the model is completely driven by climate variables. Also, there might be some duff measurement errors that still need editing (exhaustive evaluation of regional FIA quality control procedures were beyond the scope of this study). As noted earlier, the litter patterns are not easily explained; the high values in the South could be due to field crew measurement problems that could not be overruled at this time. From this analysis, it seems that auxiliary field sampling and laboratory analysis ought to be incorporated into the field procedures for duff and litter. These components seem too important for the current procedure of depth measurement only for an assumed cylinder of uniform density for all forest conditions. Perhaps estimation of duff and litter could be greatly improved by a double-sampling method where some weighing of material is combined with depth measurements. Likewise, double sampling could probably improve shrub/herb biomass estimates. Of all the components, the compilation procedure for shrubs and herbs is probably the most questionable because it relies completely on information from several isolated studies for western species. Weighing some shrub/herb material on a few plots would improve the use of any auxiliary equations.

Conclusion

We provide a compilation of FIA's 2001 DWM data and methodology to extend it to nearly 100,000 plots in the eastern United States where DWM data are not yet available. This first attempt to summarize FIA data on DWMs and extend the data to all plots seems reasonable except possibly for duff and litter. CWM in particular seems adequately measured by FIA procedures and it is the most promising for extension to FIA's P2 plots with a model that uses standing-dead trees and climate for predictor variables. Model improvements could probably be made with more auxiliary information on stand history and previous disturbance. Questions remain about compiling data on FWM. For example, what to use for diameter class means, specific gravity, and decay deduction need more study. Duff, litter, and shrub/herb compilation is also a work in progress that needs much more study. One possibility for improvement in FWM, duff, litter, and shrub/herb biomass is some actual field weighing in a double-sample design, where accurate weights could be used to adjust the crude field measurements.

Our goal in this study was to compile 2001 DWM data and extend to the entire FIA database for the eastern United States to produce information in the form of DWM biomass maps that could be used to assess regional fire-fuels conditions. This study indicates the feasibility of our approach; however, specific details need more work before using this information in earnest.

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