Carbon in Down Woody Materials of Eastern U.S. Forests[1]

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Abstract

To better manage global carbon storage and other ecosystem processes, there is a need for accessible carbon data on components of down woody materials (DWM) in forests. We examined the feasibility of linking available data on DWM to the U.S. Department of Agriculture (USDA) Forest Inventory Analysis (FIA) database, which covers the nation's forest lands. We developed regression models to predict coarse woody material (CWM), fine woody material (FWM), litter, duff, and shrub/herb cover for extension to FIA's network of about 100,000 plots in the eastern U.S. Results showed (1) that on average, DWM constitutes about 25% of total aboveground forest carbon and (2) there are about 10,000 Tg (10^{12} gm) of aboveground carbon in eastern U.S. forests. Measurements of climate, mortality/harvest/disturbance, stand size/structure were the most promising predictors of down woody materials, but further study is needed to improve model precision. The 2,400 Tg of DWM in eastern U.S. forests is a significant consideration for managing the balance between sequestered and atmospheric carbon.

Introduction

In addition to carbon in living and dead standing trees, forests include considerable carbon in plant material lying on the forest floor, which is called down woody material (DWM) (Harmon and others 1986; Dodds and Smallidge 1999; Hagan and Grove 1999; McGee 2000). The components of down woody material vary in size, structure, and characteristics.

Coarse woody material (CWM) includes all dead and down pieces such as logs and fallen branches that are 76 mm diameter and larger (Figure 1). Sometimes CWM is also found in piles from logging or other disturbances, but these were omitted from this study.

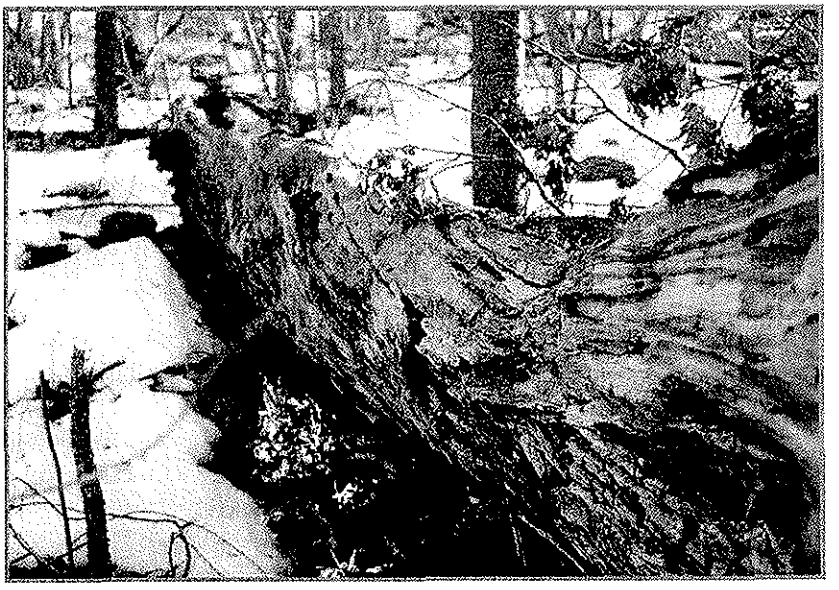

Figure 1—Coarse woody material is greater than 76 mm diameter at the small end, Shenandoah National Park, VA.

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Fine woody material (FWM) includes the smaller sized woody branch pieces (Figure 2). Everything else lying on the forest floor above the A1 mineral soil horizon is either litter (recognizable plant forms) or duff (original plant forms not recognizable). Litter, or the O_i organic soil horizon (Brady and Weil 2002), includes the dead detached plant material lying loosely on the forest floor that is 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 the partly decayed organic material between litter and the A1 soil horizon that bears little resemblance to original plant structures

Figure 2—Fine woody material is mostly fallen branches tallied in three diameter classes—< 6 mm, 6–25 mm, 25–76 mm. Litter includes leaves and all other recognizable plant parts, and duff is the black unrecognizable plant material below litter. (left: Scotts Run Nature Preserve, VA; right: Bent Creek Experimental Forest, NC).

The remaining DWM component—the understory (shrub/herb) cover—really isn't "lying down" or necessarily dead. It includes all understory shrubs and herbs of both live and dead plants that are still standing upright.

These definitions of DWM are from the U. S. Department of Agriculture (USDA) Forest Inventory and Analysis (FIA) program (FIA 2003a). DWM together with FIA's live and standing-dead tree inventory constitute measurement of total aboveground forest carbon.

The primary inventory database of U.S. forests is the Forest Service's national FIA program (FIA 2003b), which collects data from and continually monitors field plots across all land ownerships in the U.S. This inventory collects forest data in three phases. A remote-sensing phase (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 a third phase (P3) is used to collect more detailed forest health information. The P2 plots sample the nation's 302 million ha of forestland with about 1 plot per 2,500 ha, and the P3 plots subsample $1/16^{th}$ of the P2 plots.

In 2001, FIA collected data on DWM on a P3 subsample of plots in several states. We examined the feasibility of linking these subsampled data to the entire FIA database to produce reliable assessments of

carbon in DWM in eastern U.S. forests. Data on down woody materials were available from the FIA program for 778 plots measured in 27 eastern states in 2001. Our task was to use these data for constructing plot-level models to estimate DWM for all FIA plots. Details of this work are in Chojnacky and others [in press]. Given here are results of estimating carbon in (1) down woody materials compared to (2) carbon in standing trees for the eastern U.S.

Methods

Slightly different methodology was used to sample and compile the different components of down woody materials—CWM, FWM, litter, duff, and shrub/herb—into estimates of carbon for the 778 plots. These methods were developed for an inventory of fire fuels (Brown 1974) in the western U.S. In addition to the measurement data, the compilation of carbon required auxiliary information for density of materials and some other regression relationships. Because much of the auxiliary data was unavailable for eastern forests, we used data from western forests. Details are given in Chojnacky and others [in press].

Data were compiled into dry-weight mass measurements (Mg/ha) (commonly assumed to be 50% carbon for trees). To extend the DWM data to all plots in the FIA database, we modeled the DWM components either from variables in the FIA database or from variables that could easily be linked to FIA plots. Although we had 778 plots that included down woody materials, only 581 could be matched with appropriate FIA plot data for modeling at this time.

As a first approximation for modeling DWM, seven regression equations were developed for each

$$\mathrm{DWM}_C = \beta_0 + \beta_1 X_1 + \beta_1 X_1 + \ldots + \beta_{10} X_{10}$$

where

DWM_C = carbon of CWM, small FWM, medium FWM, large FWM, litter, duff, or shrub/herb (Mg/ha)

X_1 = proportion of dead trees (≥ 12.7 cm dbh) tallied on FIA plot

X_2 = total basal area of live trees (≥ 12.7 cm dbh) on FIA plot (m^2/ha)

X_3 = number of live trees (≥ 12.7 cm dbh) tallied on FIA plot (No./ha)

X_4 = quadratic mean diamter of live trees (≥ 12.7 cm dbh) tallied on FIA plot (cm) (1)

$$X_5 = \begin{cases} 1 \text{ if forest type is coniferous forest} \\ 0 \text{ otherwise} \end{cases}$$

X_6 = longitude of county center for all FIA plots in that county (decimal degrees)

X_7 = latitude of county center for all FIA plots in that county (decimal degrees)

X_8 = average precipitation of county center for all FIA plots in that county (mm/yr)

X_9 = average number of days rain or snow fell in county center for all FIA plots in that county (No./yr)

X_{10} = average relative humidity for county center for all FIA plots in that county (%)

The tree variables ($X_1 - X_5$) represented a simple description of live and dead forest structure that could be easily calculated from the FIA data. Variables $X_6 - X_{10}$ represented auxiliary climate variables, which were based on 30-year averages for 4-km grid cells (Climate Source 2001). The geographic coordinate variables (X_5, X_6) were included in place of temperature because of such high correlations with temperature (0.92 to 0.99). All auxiliary variables were county averages applied to all FIA plots within each county. A county scale was used because FIA no longer discloses geographic coordinates for each plot, which would be necessary for finer-scale merging to auxiliary data.

The regression equations for each component included only those variables that were statistically significant (Table 1). Although the R^2 goodness-of-fit statistics were low, ranging from 0.02 to 0.30, the models are unbiased for application within the range of the data for estimating regional statistics.

Table 1—Regression model for estimating carbon of down woody material components.

	Regression coefficients										
Material	β_0	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8	β_9	$\mathbf{R^2}$
CWM	-2.09	9.9536	0	0	0.0914	0	0	0	-0.0044	0.0876	0.19
FWM (25-76 mm)	3.36	3.2936	0	-0.0052	0	0	0.0202	0.0651	0	0	0.02
FWM (6-25 mm)	-0.58	0	0	0	0	0.2028	0	0.0255	0	0.0101	0.06
FWM (< 6 mm)	0.55	0	0	0.0013	0	0.209	0.0135	0.0189	0	0	0.13
Litter	14.28	0	0	0.0096	0	0	0	-0.1899	0.0021	-0.0406	0.3
Duff	30.48	0	0	0	0	3.0994	0.5126	0.5481	0	0	0.28
Shrub/ Herb	4.86	0	-0.0297	0	0	0.2924	0	0	0	-0.0202	0.16

$$\text{Material} = 0.5\left(\beta_0 + \beta_1 X_1 + \beta_1 X_1 + \ldots + \beta_9 X_9\right)$$

where

Material = carbon of down woody and understory components (Mg/ha)

X_1 = proportion of dead trees (≥ 5.0 dbh) tallied on FIA plot (value from 0 to 1)

X_2 = total basal area of live trees (≥ 5.0 dbh) on FIA plot (m^2/ha)

X_3 = number live trees (≥ 5.0 dbh) tallied on FIA plot (No./ha)

X_4 = quadratic mean diamter of live trees (≥ 5.0 dbh) tallied on FIA plot (cm)

$$X_5 = \begin{cases} 1 & \text{if forest type is coniferous forest} \\ 0 & \text{otherwise} \end{cases}$$

X_6 = longitude of county center for all FIA plots in that county (decimal degrees)

X_7 = latitude of county center for all FIA plots in that county (decimal degrees)

X_8 = average precipitation of county center for all FIA plots in that county (mm/yr)

X_9 = average number of days rain or snow fell in county center for all FIA plots in that county (No./yr)

The equations were then applied to 99,312 plots in the FIA database for estimating carbon in the eastern U.S. The FIA plot data were extracted in 2000 and included some states sampled more intensively than the usual 5-km grid; actual inventory dates ranged from 1983 to 1998, with most from mid 1990s. Carbon of living and dead standing trees was also estimated for these plots by using tree-level biomass equations (Jenkins and others 2003) and by assuming that biomass is 50% carbon. The ratios of carbon per ha for a particular state were averaged by state and multiplied by the state's forest area (Smith and others 2002, Table 1) to obtain total DWM carbon estimated for the eastern U.S.

Results and Discussion

For the 778 study plots, carbon among components of down woody material was generally less than 5 Mg/ha per component, totaling about 15 Mg/ha for all components (Figure 3). Amounts of duff, CWM, and FWM were greatest in the North and less in the South. This seems attributable to more favorable conditions for rapid decomposition in the warmer South. On the other hand, litter and shrub/herb carbon was greater in the South than in the North. There may be good reason for this opposite pattern but explanation is complicated by possible methodology inconsistencies. The litter data for the South were adjusted for some field discrepancies in measurements units, but our assumptions may not have fully corrected the problem. Also, shrub and herb estimates could have substantial extrapolation error because regression equations were for western species since eastern equations were unavailable. Since FIA inventories collect more data every year, these problems should be resolved as new data become available.

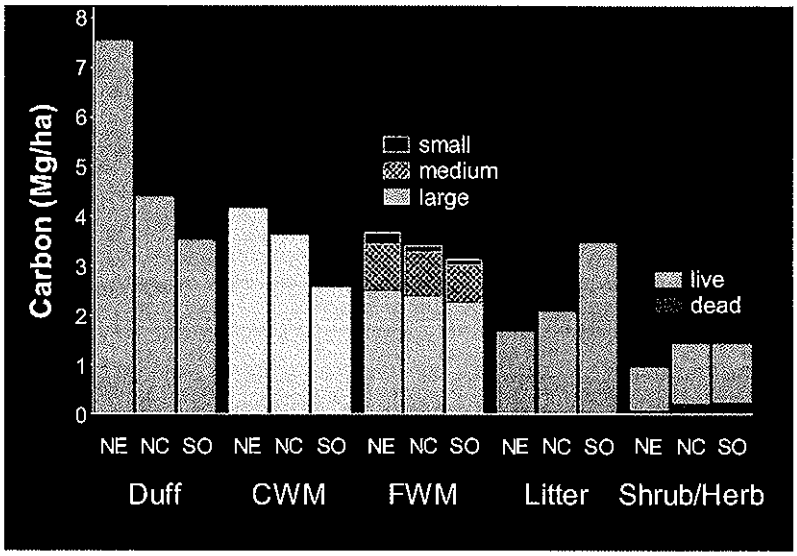

Figure 3—Duff includes the most carbon among down woody material components for 778 plots measured in 27 eastern states in 2001. Amounts of duff, CWM, and FWM are greater in Northeast (NE) and North Central (NC) states than in the South (SO). This pattern is reversed for litter and shrub/herb components, which show greater amounts in the South than in the North.

Application of DWM equations (Equation 1) to the 99,312 plots in the eastern portion of the FIA database indicated that carbon in DWM was about one-fourth of that in standing trees (Figure 4). The estimate of total DWM carbon shows a total of about 2,400 Tg (10^{12} gm) of DWM in the 33 eastern U.S. states (Figure 5). Combining this with standing trees, eastern U.S. forests include about 10,000 Tg of aboveground carbon.

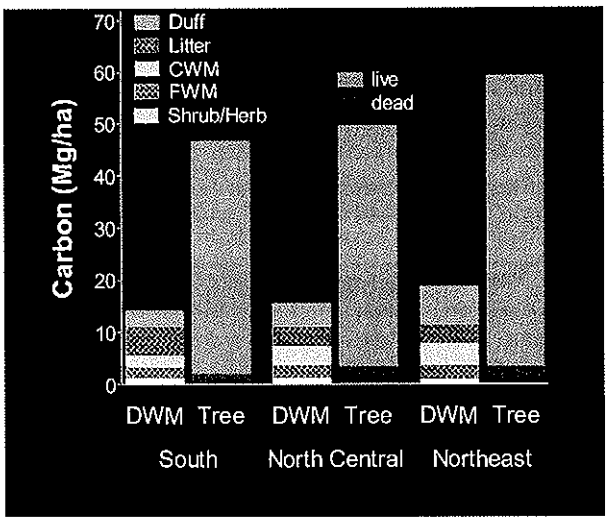

Figure 4—On average, the estimated carbon in down woody materials (DWM) is about one-fourth of that in standing trees (Tree) for 99,312 plots in the FIA database, 2000.

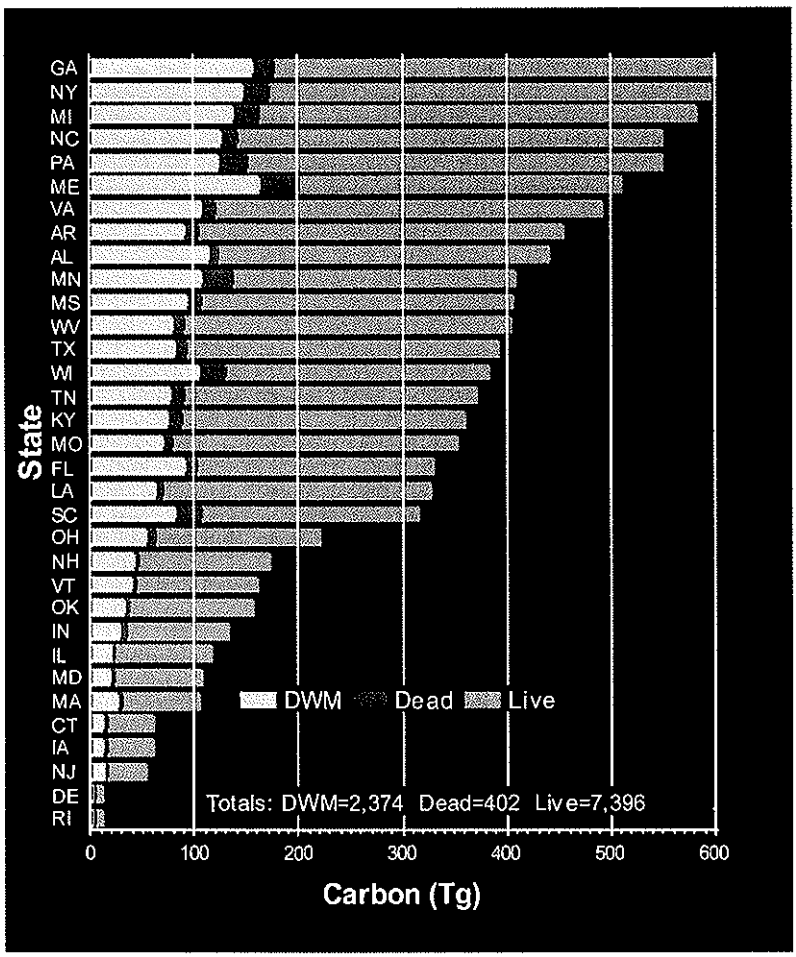

Figure 5—Carbon in forests of eastern U.S. states varies from 10 to 600 Tg (10^{12} gm). Estimates are from 99,312 plots in the FIA database, 2000.

Our findings compare favorably to the 15,000 Tg of aboveground-plus-root carbon estimated by Kimble and others (2003), which is the only other known estimate of carbon at a comparable scale.

Although roots were not included in our estimate, carbon of coarse roots is about 25% of tree carbon (Jenkins and others 2003). Adding estimated root carbon to our results would bring our estimate up to 12,000 Tg, which is within 20% of Kimble's figure. Kimble and others also include data for western states and soil carbon (about 50% of total) to arrive at 52,000 Tg total carbon in U.S. forests.

To put the forest carbon estimates in perspective of the greenhouse gas issue, the annual U.S. carbon emissions from anthropogenic sources is about 1,600 Tg carbon per year (EIA 2002). Kimble and others estimate that U.S. forests add carbon at a net rate (flux) of about 200 Tg per year. Therefore, the 2,400 Tg of carbon in DWM for eastern U.S. forests is a significant consideration for managing the balance between sequestered and atmospheric carbon.

Conclusions

Our equations and regression models offer a feasible way to estimate DWM from the FIA database for the eastern U.S. Furthermore, it would be easy to extend our methodology to western forests (when data become available) because much of the technique was developed for western forests.

Although detailed error assessment was beyond the scope of this study, our results were within 20% of similar calculations in the literature. Improvements in our methodology could be made by developing calculation parameters for eastern forest types, particularly for duff, litter, and FWM—in that order of priority. Our prediction equations might also be refined. We found measurements of climate, mortality/harvest/disturbance, stand size/structure as most promising predictor variables. However, a search for better predictor variables would be worthwhile because our regression models had low R^2 (goodness-of-fit) statistics ranging from 0.02 to 0.30.

Linkages established through this study between the FIA database and climate change research will be beneficial for understanding global warming, measuring carbon credits, assessing wildlife habitat, and other forest health issues related to dead wood.

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