Linking Soils and Down Woody Material Inventories for Cohesive Assessments of Ecosystem Carbon Pools

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Abstract.—The Soils and Down Woody Materials (DWM) indicators collected by the Forest Inventory and Analysis program provide the only data available for nationally consistent monitoring of carbon storage in soils, the forest floor, and down woody debris. However, these indicators were developed and implemented separately, resulting in field methods and compilation procedures that overlap and are not entirely compatible. Here we outline an initial approach for combining carbon estimates from the soil and DWM indicators, highlight the potential limitations of this approach, and discuss future research or protocol changes that may improve regional C estimation.

Down woody materials (DWM), the forest floor, and the upper soil horizons have been identified as critical reservoirs for carbon over time scales ranging from decades to centuries. Sequestering carbon in these pools has been proposed as a way to offset CO_2 emissions from fossil fuels. As a result, monitoring changes in carbon storage is currently required by several national and international agreements including the Montreal Process Criteria and Indicators of Sustainable Forest Management. However, no data on carbon storage in DWM exist for many forests and current estimates of soil carbon storage are largely based on static soil maps that do not reflect changes resulting from differences in land-use or management practices. In addition, many soil maps are biased toward agricultural systems and may not fully account for carbon stored in the forest floor and upper mineral horizons. Measuring these carbon reservoirs and the rates at which carbon accumulates and decomposes is critical for constraining carbon budgets in forests.

Forest Inventory and Analysis (FIA) Detection Monitoring plots (Phase 3) are the only nationally consistent data available for monitoring changes in carbon storage in forest soils, the forest floor, and woody debris. However, the Soil and DWM indicators were developed and implemented separately without reference to one another, resulting in field methods and compilation procedures that overlap and, in some cases, are not compatible for carbon accounting. This paper presents an initial approach for integrating carbon storage estimates from soil and DWM inventories to provide a cohesive, dynamic assessment of forest floor and soil carbon pools. At this early stage of implementation, there were insufficient data to provide meaningful estimates of carbon storage at the regional level. Instead, the focus of this analysis is to identify the strengths and potential limitations of combining the carbon accounting approaches for these two indicators in order to streamline data collection and compilation and improve future carbon estimates.

Methods

Field Methods

Soil chemical and physical properties were assessed by collecting of soil samples, which were then analyzed at a regional laboratory. Soil samples were collected within the annular plot along soil sampling lines adjacent to subplots 2, 3, and 4 (fig. 1). During the first visit to a plot, soil samples were collected at the point denoted as Soil Visit #1. On subsequent visits to a plot, soil sampling sites visit #2 or larger will be sampled. The soil sampling sites were spaced at 10-ft intervals alternating on opposite sides of soil sampling site number 1.

Samples were collected from the forest floor (subplots 2, 3, and 4) and underlying mineral soil layers (subplot 2). Forest floors were sampled after measuring the thickness at the north, south, east, and west edges of a sampling frame of known area. Once the forest floor had been removed, mineral and organic

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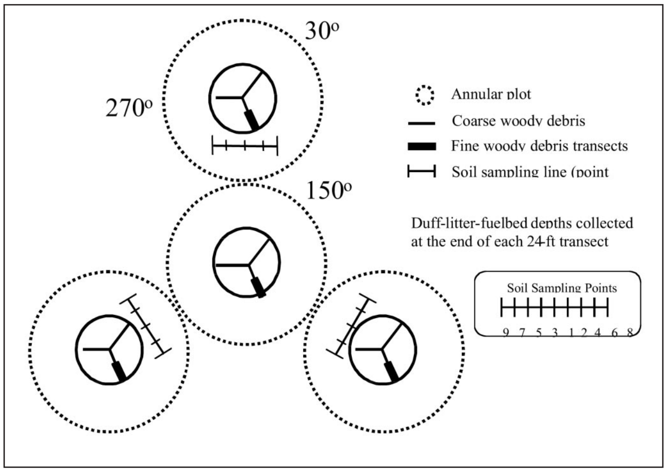
Figure 1.—*Diagram of the soil and DWM sampling design.*



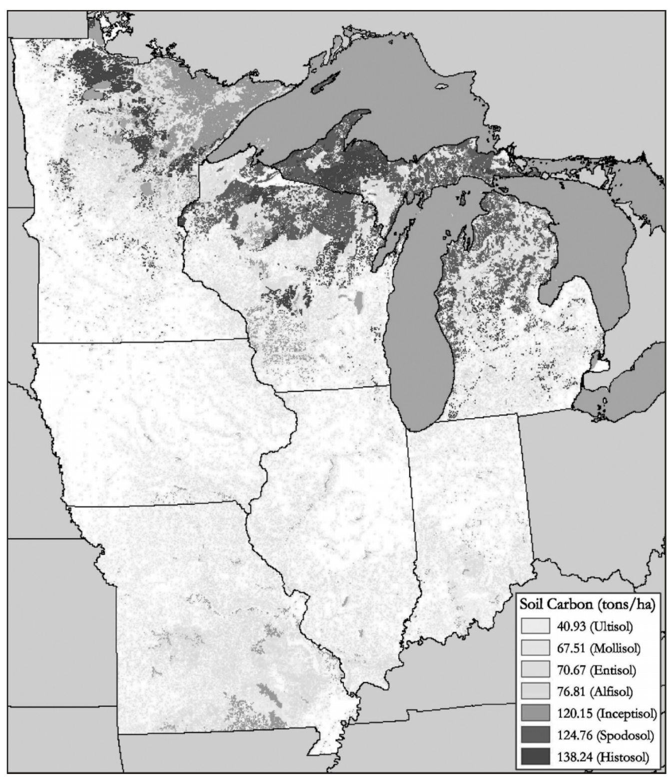
soils were sampled volumetrically by collecting bulk density cores from two depths: 0 to 10 cm and 10 to 20 cm. In organic soils, samples are collected from the litter layer and the 0 to 10 cm and 10 to 20 cm organic layers. If the soil could not be sampled at the designated sampling point due to trampling or an obstruction (e.g., boulder, tree, standing water), the sampling point was relocated to any location within a radius of 5 ft. A maximum of five samples (three forest floor and two mineral soil samples from a single core) were collected per plot. The samples were then sent to one of three regional laboratories where the carbon concentration (%) and bulk density (g cm^{-3}) were determined analytically (Palmer *et al.* 2001).

DWM were sampled using a planar-intersect method in which three 24-ft transect lines were established on each subplot (fig. 1). Coarse woody debris (larger than 3 inches in diameter) was sampled along the entire length of the transect. Crews recorded the length, diameter of the large and small ends, and the decay class of each CWD piece to allow for estimating volume. Down woody materials smaller than 3 inches in diameter, or fine woody debris (FWD), were divided into three size classes (0.0-0.25, 0.25 to 1.0, and 1.0 to 3.0 inches) and sampled along sub-sections of the transect lines. For FWD, only the number of pieces crossing the transect line was tallied. Duff, litter, and fuelbed depths were measured at a single point at the end of each transect line for a total of 12 measurements on each FIA plot.

Carbon Estimation Procedures

Carbon estimation for the soils indicator consisted of three parts (table 1). First, carbon concentration and bulk density data determined in the laboratory were combined to produce estimates of carbon storage within a single soil sample. The compilation differs slightly for mineral and forest floor samples due to the different number of samples collected for each soil layer. Next, data from each soil layer (forest floor, 0-10 cm, 10-20 cm) were aggregated within genetic soil mapping units using a digitized soil map. For this study, we used State soil survey data from the NRCS STATSGO (State Soil Geographic) database mapped according to soil order. Plot estimates of carbon storage for each layer were overlain onto a digital coverage of soil orders. The mean value of all plots that fell within a given soil order was then used to develop a spatial coverage of carbon storage within a given soil layer. Finally, the mean carbon storage estimates within each soil layer were summed to

Figure 2.—*Soil carbon storage in tons ha^{-1} (1999–2001 data). Areal carbon estimates for each soil layer were aggregated to the soil order taxonomic level using NRCS STATSGO data. The mean values for each soil order were then summed across all soil layers. Data were then masked using a forest/ nonforest map from Phase 1 of the FIA inventory. Map is not based on a full panel of data and carbon estimates are preliminary.*



provide a mean estimate of carbon storage in the upper 20 cm for a given map unit (fig. 2).

In this approach, bulk density is necessary for converting percent C concentration data to an aerial (tons ha^{-1}) basis. However, volumetric sampling for bulk density was not added to the soils protocol until 2000. In addition, not all samples collected since 2000 have a bulk density value due to the difficulty of using the impact driven corer in certain soil types. In order to use laboratory data from these plots, we applied a bulk density value estimated from STATSGO. This was done by calculating a depth- and spatially weighted average bulk density for

Figure 3.—*Carbon storage in DWM in tons ha^{-1} (2001) data. Plot level estimates of C storage were interpolated using ordinary kriging with an exponential model. Data were then masked using a forest/nonforest map from Phase 1 of the FIA inventory. Map is based on a single year of data and carbon estimates are preliminary.*

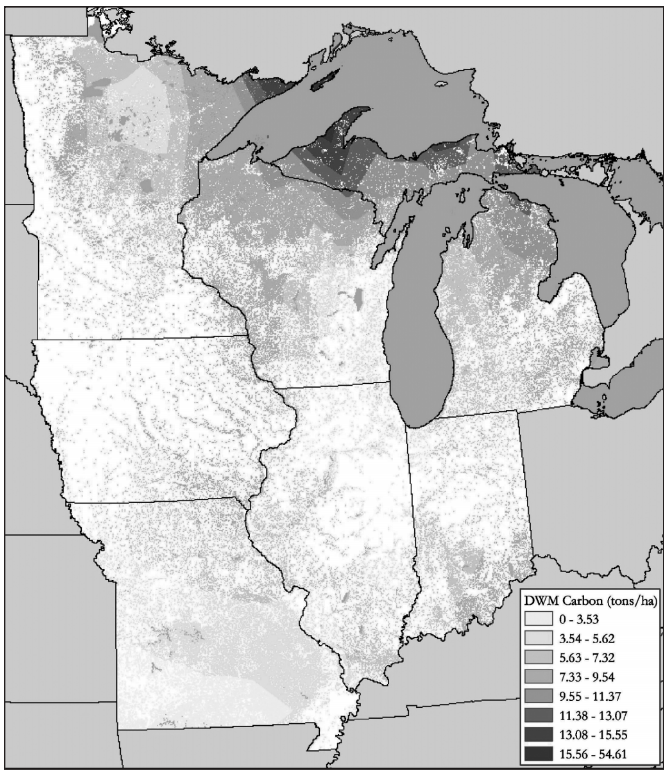


Figure 4.—*Carbon estimates in DWM, the forest floor, and the upper 20 cm of the mineral/organic soil. Data layers from figures 1 and 2 were converted to a raster image and then combined by summing across 250-m cells. Map is not based on a full panel of data and carbon estimates are preliminary.*

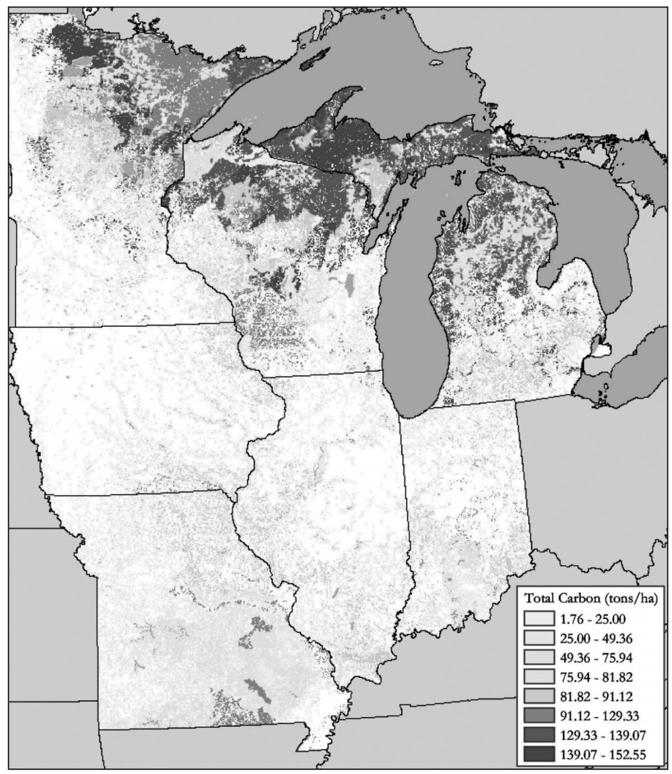


Table 1.—*Compilation and estimation procedures for the soil indicator*

	Estimate level	Units	Equation
Plot (1 sample)	Mineral Soil (0–10 cm; 10–20 cm)	g C cm^{-2}	Bulk density (g cm^{-3}) x thickness (cm) x %C
Plot (3 samples)	Mean forest floor	g C cm^{-2}	[Oven dry weight (g)/Area(cm^{-2}) x %C] / # of samples
Map Unit	Layer (forest floor, 0–10 cm, 10–20 cm)	tons C ha^{-1}	Mean of plot level estimates within a soil taxonomic unit
Map Unit	Total (forest floor –20 cm)	tons C ha^{-1}	Summation of layer C across all soil layers

each map, overlaying the FIA plots, and extracting the mean bulk density value at those locations. Carbon estimates were limited to forest soils by using a forest/non-forest map based on the Phase-1 National Land Cover Database (NLCD) imagery (Vogelmann *et al.* 2001) (fig. 2). Regional carbon estimates were based on 1,198 soil samples from 467 plots collected from 1999 to 2001.

Carbon estimates for DWM were determined at the plot level. Transect data for each size class were combined through a series of algorithms and models into plot level of estimates of volume per acre. The algorithms used for these calculations are provided in Woodall and Lutes (2005). Carbon contents were then determined by multiplying biomass estimates by a conversion factor (Birdsey *et al.* 1992, Waddell 2002). Birdsey *et al.* (1992) provide conversion factors for both softwood (0.521) and hardwood species (0.491). However, since species data were not collected on the smaller DWM size classes, we applied the mean value of these two conversion factors (0.506). Carbon storage for < 0.25 inch size class was subtracted from plot totals because this pool is also measured as part of the forest floor sample in the soils indicator. Regional estimates of DWM carbon were interpolated from plot estimates using ordinary kriging with an exponential model (fig. 3). Carbon estimates for soils and DWM were then combined by converting the spatial data layers for these indicators into a raster format and then summing across 250-m cells. The legend intervals were rescaled and then the final product was masked using a forest/nonforest map from Phase 1 of the FIA inventory (fig. 4).

Results and Discussion

Comparison of Field Methods

The key differences between the two indicators in terms of sampling design were: (1) the samples were collected on different portions of the plot; (2) the methods were designed for aggregation at different levels; (3) for the soil indicator, both the number of samples and the method used to collect these samples can vary from plot to plot; and, (4) the smallest size class of DWM (<0.25 in diameter) was also sampled as part of the forest floor sample in the soil indicator and must be subtracted from the DWM estimate to avoid double counting.

Comparison of Estimation Procedures

Carbon estimation procedures for soils and DWM differ in a number of key areas that limit both the precision and the spatial scale of combined estimates (table 2). First, both carbon concentration and bulk density were determined analytically for each soil sample in a laboratory. In contrast, the carbon content of individual pieces of DWM were either modeled (CWD) or estimated (FWD) and carbon concentrations were not empirically derived, but based on published conversion factors. Second, the DWM protocol was designed to provide a plot-level estimate of variance, with three transect lines sampled on each of the four subplots. In contrast, soil estimates were based on a single set of samples per plot (forest floor, 0-10 cm, and 10-20 cm); on some plots, the difficulty of sampling prevented collecting even a single set of measurements. This requires that C estimation for soils must be aggregated at a level above the plot scale, such as the soil order. Finally, the scaling approaches for expanding data beyond the grid framework differed, with soils data aggregated using digital soil mapping data and DWM scaled to the regional level using either ecological provinces or interpolation.

Limitations and Directions for Future Research

For the soil indicator, several limitations need to be kept in mind when estimating carbon storage. Soils are sampled destructively, which means that remeasurements will reflect a component of spatial variability in addition to change over time. Destructive sampling also has important implications for quality assurance since it is difficult for field crews to assess measurement error in bulk density. Compiling soil data is complicated by the fact that plot conditions such as difficulty in accessing soil sampling points (e.g., obstructions, water on plot), the presence of nonforested conditions, or the absence of a forest floor at the sampling point, may prevent collecting all five samples on the plot and preclude estimating C storage at the plot level. In addition, not all soils can be sampled using the bulk density corer, so crews may need to use an alternate method, such as excavation, to collect a sample for chemical analysis. Samples collected using an excavation method are not volumetric and require the use of ancillary data or interpolation

Table 2.—*Comparison of field methods and estimation procedures for the soils and DWM indicators*

	Soil	DWM
Carbon concentration	Weight %C is directly determined for sample by lab analysis (Dry combustion method).	Predicted using set conversion factors from the literature. In this study, assumed to be 0.506 for all DWM pieces.
Density	Determined directly from field samples. Oven dry weight of soil sample (g) is divided by the volume that the sample was collected from (cm^3) to provide bulk density ($g\ cm^{-3}$). In cases where sample was not collected volumetrically, determined from spatially weighted mean values from digital soil survey data (STATSGO).	For CWD (> 3.0 in diameter), estimated from the length, diameter, and decay class estimate recorded in the field. For FWD, density is determined from models.
Estimation level	Methods designed for a single estimate (without variance) at the plot level. Population estimate must be determined by averaging data within a larger unit such as soil order.	Multiple measurements collected per plot. Methods designed for determining plot level mean values.
Expansion/interpolation	Scaling to the regional level requires use of ancillary data set such as ecoregion section or soil taxonomic unit (e.g., soil orders)	Scaling done by interpolation (e.g., kriging) of plot level mean values. Plot level means can also be aggregrated using ancillary data such as ecoregion section.

based on existing data in order to scale carbon concentrations to a weight per unit area basis.

Another critical issue related to sample collection is that only one mineral core was collected per plot. This prevents assessing within-plot spatial variability and may limit our ability to detect change in carbon storage over time. Collecting additional mineral cores on subplots 3 and 4 would provide an estimate of within-plot variability that would improve carbon accounting. Although additional samples would increase the cost of laboratory analysis, modifying the field collection strategy by either lengthening the sampling cycle and reducing the number of plots sampled per year or collecting additional samples only on a subset of plots may offset these costs. Alternate sampling techniques such as composite sampling, in which multiple samples are collected in the field and then combined into a single sample for laboratory analysis, may also improve estimates in a cost-effective manner and should be investigated.

For DWM, carbon accounting limitations involve post-field sampling data processing and scaling. The DWM indicator does not directly sample carbon concentrations, but rather predicts carbon content based on the inventory of down woody components. Currently, a single conversion factor is used to predict %C. This methodology needs to be refined to better incorporate the species, decay, and inherent differences among individual DWM components. Another concern is that the DWM sample methods and data compilation routines obfuscate determination of variance estimates for different DWM components within any given sample plot. For example, different transect lengths were used to sample fine and coarse woody debris, resulting in different, but unquantified, levels of confidence in estimates. Finally, to create regional maps of DWM carbon concentrations, peer-reviewed scaling techniques need to be developed. Currently, only two methods have been proposed: ancillary data layers (e.g., ecological provinces or forest types) or data interpolation (e.g., kriging or nearest neighbor).

Summary

Although the current protocols for the soil and DWM indicators were designed and implemented separately, these data are the only source of information for monitoring changes in carbon storage in woody materials and forest soils for reporting under the Montreal Process Criteria and Indicators. For this reason, it is critical that FIA take the lead in developing statistically valid methods of carbon accounting that combine data from these two indicators. This study presented an initial approach for combining carbon estimates from the soil and DWM indicators into a regional estimate of carbon storage. As additional data become available, it will become possible to compare C estimates from this approach with values reported in the literature. Meanwhile, results from this study can be used as a basis for streamlining the field and compilation procedures for these two indicators in order to facilitate better and more efficient carbon accounting in the future. Additional research is needed to integrate these estimates with carbon models developed for other phases of the FIA program.

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