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An empirical assessment of forest floor carbon stock components across the United States

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ABSTRACT

Despite its prevalent reporting in regional/national greenhouse gas inventories (NGHGI), forest floor (FF) carbon (C) stocks (including litter, humus, and fine woody debris [FWD]) have not been empirically measured using a consistent approach across forests of the US. The goal of this study was to use the first national field inventory of litter and humic layer depths, along with FWD volumes, to assess their basic attributes (e.g., depths/volumes) and refine NGHGI approaches to FF C stock monitoring. Results suggest that FF C stocks are present in nearly 99% of US forests with a median estimate of 25.6 Mg/ha, albeit with tremendous spatial variation in litter/humic depths and FWD volumes. Relative to aboveground live tree biomass C stocks, which typically range from 20 to 200 Mg/ha, nearly a quarter of US forests have minor FF C stocks (<14 Mg/ha), while approximately 10% of US forests may have substantial FF C stocks (>93 Mg/ha). Conditions conducive to large FF C stocks may be stochastic disturbance events that result in high volumes of FWD and/or climatic/physiographic conditions that slow decomposition (e.g., peatland ecosystems found in northern or coastal forest ecosystems). As soil and dead wood field inventories may only sample litter/humic depths and FWD counts by diameter class, C stock estimation procedures are heavily reliant on estimation constants (e.g., bulk/wood density). It was found that the variability in estimation constants may have a much stronger effect on resulting FF C stock estimates than the field measurements (e.g., litter layer depths) themselves. The monitoring of FF C stocks, along with the maintenance of site productivity and associated ecosystem services, would benefit from refined sample protocols in ecosystems with deep humic layers and coupling field data with lab analysis of bulk/wood density and C content from soil sampling programs.

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1. Introduction

Broad forest ecosystem components (e.g., aboveground live biomass) have been delineated to generalize carbon (C) stocks to meet international reporting agreements pursuant to refining understanding of global carbon cycling (e.g., United Nations Framework Convention on Climate Change) (Pan et al., 2011). One such forest C stock, the forest floor (FF), can be defined as including C from the litter and humic layers along with fine woody debris (FWD; pieces less than 7.5 cm in diameter) (IPCC, 1997; USEPA, 2011) (Fig. 1). In 2002, it was estimated that approximately 7% of forest ecosystem C (approximately 28 Pg C) could be found in the FF of the northern hemisphere (Goodale et al., 2002). In US forests, the FF stock has been estimated at approximately 4.9 Pg C, compared to 16.8 Pg C within the aboveground biomass stock (Heath et al., 2011). In 2008, it was estimated that FF annual carbon sequestration (i.e., net positive carbon stock change) was approximately 14% of annual sequestration of aboveground biomass in the US (Heath et al., 2011). Given the importance of FF C stocks within the global carbon cycle, accurately estimating their attributes and monitoring their status is critical.

The inventory and estimation of FF C stocks is often challenging due to inherent microsite variation in FF attributes within the soil profile as affected by variations in tree species compositions, micro-topography, and drainage (Smit, 1999; Ladegaard-Pedersen et al., 2005; Schulp et al., 2008). For many nations, the inventory of FF C stocks is often a Tier One approach using national defaults similar to what is done for soil organic carbon pools (Del Grosso et al., 2011). For nations that may have areal estimates of forest land use derived from remote sensing efforts, FF C stocks may be modeled as some proportion of standing live tree biomass and forest type/stand age. In the US, the C density of FF stocks is modeled based on field based measurements of forest inventory plot stand age and forest type within regions of the country (Smith and Heath, 2002; Chojnacky et al., 2006). Although adequate as an initial appraisal of FF C stocks across extensive land areas, the uncertainty associated with these estimates may exceed minor to moderate FF

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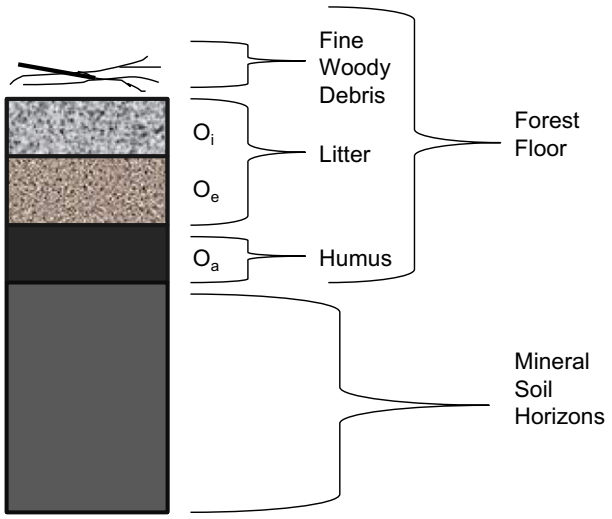

Fig. 1. Forest floor components defined by soil taxonomy notation and down woody material terminology.

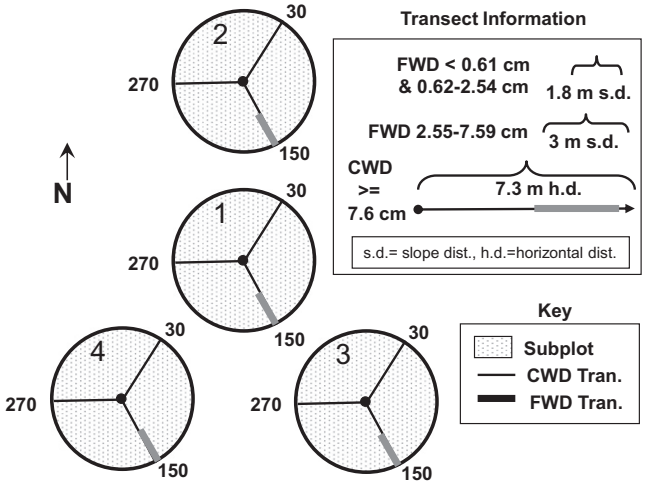

Fig. 2. US Department of Agriculture, Forest Service, Forest Inventory and Analysis program's down woody materials sample design, 2002–2008.

C stock changes due to global climate change effects (Yanai et al., 2003). Across all US forests, the components of the FF C stock have only recently been measured in a systematic manner (O'Neill et al., 2006; Woodall et al., 2008; Perry et al., 2009). The Forest Inventory and Analysis (FIA) program of the US Department of Agriculture Forest Service began measurement of FF C stock components in 2001 with two sets of field protocols that may contribute towards FF C assessment (Woodall et al., 2011). First, the down woody materials (DWM) indicator of the FIA program measures FWD and depths of litter/humic layers (Woodall et al., 2008). Second, the soils indicator of the FIA program collects three samples of the FF at each inventory plot for lab analysis of physical/chemical attributes (e.g., C content) (O'Neill et al., 2006; Perry et al., 2009). Due to their relatively recent implementation, these field-based measurements of FF C stock components have not replaced the purely simulated FF stocks currently reported in NGHGIs nor have both indicators been joined in comprehensive FF C stock assessments. As it has been demonstrated that national FF C models may not reflect regional FF C stocks (Schulp et al., 2008), an initial evaluation of FF components systematically measured across forests of the US by the FIA program (humus, litter, and FWD) should enable future efforts to refine estimation/modeling of FF C stocks.

The goal of this study was to assess attributes of components of FF C stocks (as defined by the US's NGHGI; FWD, litter [O_i, O_e, soil horizons], and humus [O_a soil horizon]) across US forests using FIA's DWM inventory with specific objectives being: (1) assess inter- and intra-plot variability and frequency distribution of litter/humic layer depths and FWD volumes across US, (2) evaluate the effect of bulk/wood density selection on resulting FF component C stock estimates, and (3) suggest refinements and knowledge gaps in estimating FF C stocks for the purpose of NGHGIs.

2. Methods

2.1. Data

The FIA program conducts a 3-phase inventory of forest attributes of the US (Bechtold and Patterson, 2005). The FIA sampling design is based on a tessellation of the US into hexagons approximately 2428 ha in size with at least one permanent plot (0.07 ha) established in each hexagon. In phase 1, the population of interest is stratified and plots are assigned to strata, such as forest, nonforest, and edge, to increase the precision of population estimates (e.g., total forest biomass in one state). In phase 2, tree and site attributes are measured for plots established in the 2428-ha hexagons. Phase 2 plots consist of four 7.32-m fixed-radius subplots (0.017 ha) on which standing trees are inventoried with measurement of numerous individual tree variables such as species, diameter, and total height (for more information, see USDA Forest Service, 2007a; Bechtold and Patterson, 2005) (Fig. 2).

In phase 3, a 1/16 subset of phase 2 plots is measured for forest health indicators such as down woody materials (DWM) and soils (Woodall et al., 2011). Down woody material attributes are measured within the fixed-radius subplots used for measuring standing tree attributes (i.e., phase two plots) (Fig. 2). Within each subplot, three 7.32-m sample transects are established from each subplot center radiating outward at angles of 30°, 150°, and 280° for the purpose of sampling coarse woody debris (CWD). Coarse woody debris data will not be used in this study as it is part of the dead wood carbon pools as defined by the US's NGHGI. The sampling of FF components occurs at various locations along the CWD sampling transects. Fine woody debris is sampled on the 150° transect according to size classes often used in line-intersect sampling that correspond to three time-lag fuel classes (Deeming et al., 1977): small FWD, 0.00–0.62 cm diameter; medium FWD, 0.63–2.54 cm; large FWD, 2.55–7.60 cm. Small and medium FWD are sampled on a 1.83-m slope distance portion of the established sampling transect (4.27–6.09 m on the 150° transect). Large FWD are sampled on a 3.05-m slope-distance portion (4.27–7.32 m from subplot center) of the 150° transect. For the purposes of this study, the FF soil horizon containing decomposing litter material (soil horizons O_i and O_e) will be referred to as the "litter" layer (although FIA uses "duff" terminology in field guides). Litter is defined by as FIA as a FF layer of freshly fallen leaves, needles, twigs, cones, bark chunks, dead moss, dead lichens, dead herbaceous stems, and flower parts in various stages of decay but still recognizable as individual plant parts (i.e., visible fibrous materials). The organic soil horizon containing highly decomposed (i.e., unrecognizable) plants parts (soil horizon O_a) will be referred to as the "humic" layer. This terminology aligns with FIA's definition of FF components which is the primary data source in this study (Woodall and Monleon, 2008). The depth of litter and humic layers are measured at 12 locations (7.32 m slope-distance on each CWD sampling transect) by simply exposing a small (width typically less than 2 cm) portion of the soil