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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.

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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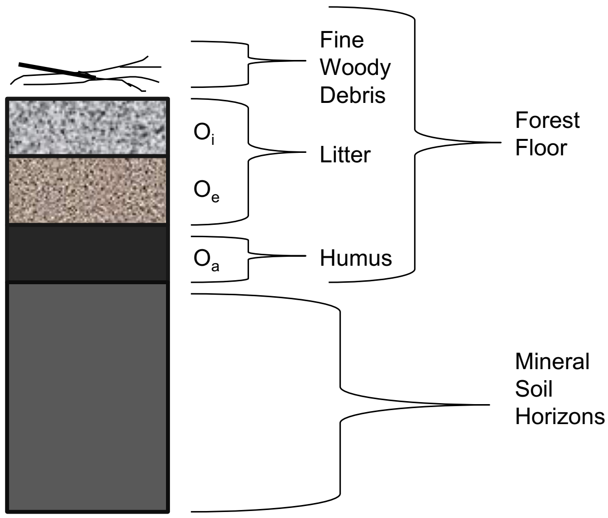

Fig. 1. Forest floor components defined by soil taxonomy notation and down woody material terminology.

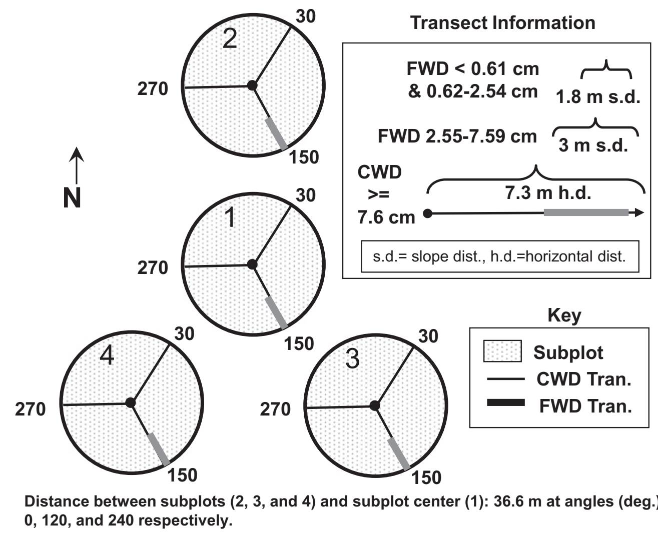

Fig. 2. US Department of Agriculture, Forest Service, Forest Inventory and Analysis program's down woody materials sample design, 2002–2008.

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 profile and using a ruler to measure depths to the nearest 0.25 cm. If a log or other large obstruction (e.g., boulder or slash pile) is present at the litter/humic sample location then no measurements are taken (for further sample protocol information see USDA Forest Service, 2007b; Woodall and Monleon, 2008; for QA information see Westfall and Woodall, 2007). In parallel to the DWM sample protocols, the soil indicator of the FIA program separates the FF into two components: litter and humus (i.e., duff) with definitions consistent with those reported above (USDA Forest Service, 2011b). The soil indicator measures the depth of the litter and humus at sampling points adjacent to subplots 2, 3, and 4 on the four cardinal points of a 30.5-cm diameter sampling frame. Following the depth measurements, field crews collect FF samples at the same three locations for subsequent lab analysis of bulk density, along with water, C, and N content (for further sample protocol information see USDA Forest Service, 2011b; for QA information see Hansen et al., 2009).

One is inclined to ponder: why are components of the FF separated into two distinct sampling efforts of the national FIA program? The FIA program separates numerous ecosystem attributes into distinct sampling efforts in order to effectively manage budgets, use sample protocols optimally suited to disparate ecosystem attributes (e.g., lichens versus dead wood), and adapt to national/regional stakeholder needs across time (Woodall et al., 2011). Unfortunately, the FF C stock is a continuum across soils and dead wood, thus it crosses the artificially delineated sampling efforts of FIA program. In this context, the strength of the DWM indicator lies in its measurement of downed dead wood and spatially repeated measurements of litter/humic layer depths; the strength of the soils indicator lies in lab analysis of soil properties conducted through destructive sampling (e.g., collection of soil cores) (Woodall et al., 2011). Although the FIA program measures aspects of FF C stocks in both the DWM and soil indicators, data from the DWM indicator was solely used in this study to isolate DWM measurements that could benefit FF C estimation. Once a refined understanding of FF C stock components in the DWM indicator is gained in this study, future alignment with soils indicator data can be more effectively facilitated (i.e., objective three of this study).

A total of 10,350 unique conditions (e.g., forest type or stand age) were sampled on FIA plots across the US (sampled between 2002 and 2009) and were included in this study with no observations in the states of OK, HI, WY, MS, NM, LA, and interior AK due to on-going implementation of a national annual inventory (Fig. 3). As unique forest conditions are delineated within FIA inventory plots for which FF C stocks are modeled, these will be considered individual observations in this study. For example, if an FIA plot consisted of two subplots in an even-aged pine plantation and two subplots in an uneven-aged hardwood forest then this plot would be separated into two separate observations for this study. It should be noted that due to a special study, sample intensity was increased in TX which was subsequently accounted for in analytical procedures. For details regarding the public databases (USDA Forest Service, 2011a) containing this study's data please refer to Woodall et al. (2010) and Woudenberg et al. (2010).

2.2. Analysis

The frequency distribution of plot mean litter/humic depths and FWD volumes were examined across the US. As sample intensity varied from the national base (1 plot per 2428 ha) for a few states, the frequency distribution was weighted by each state's sample intensity. To explore the intra-plot variability of litter/humic depth measurements, coefficients of variation ($CV = \frac{\sigma}{\mu}100$) were determined for each plot (up to 12 depth measurements per fully forested plot) with mean CVs calculated by major forest type groups and nationally. Using major forest type groups aids with inferring regional trends and possible effects of species composition (e.g., hardwoods versus softwoods). For the purpose of this analysis, only fully forested plots were considered so that CVs would be based on the same number of depth measurements per plot.

The inter-plot variability of litter/humic depths and FWD volumes was assessed by determining the CV for plot mean litter/humic depths and FWD volumes by forest type groups and nationally

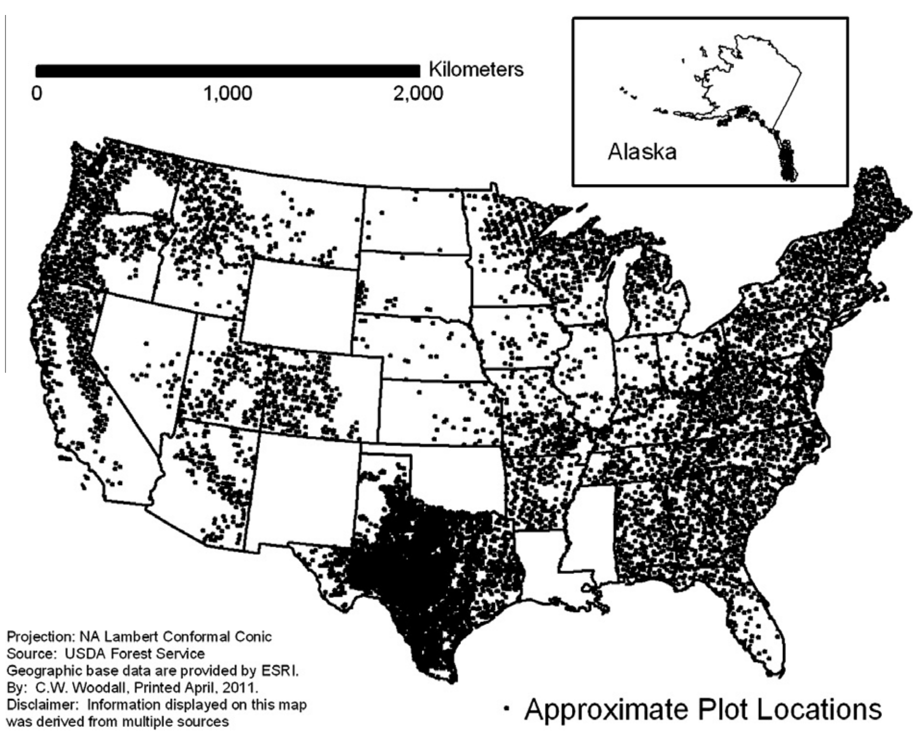

Fig. 3. Approximate location of study plots across US, 2002–2008.

using all study observations. Analogous to the intra-plot variability assessments, our use of major forest type groups will enable identification of regional trends and species composition effects. In order to avoid incorporation of measurement errors into study results, outliers were removed from this individual analysis using 10 times the interquartile range as a metric which resulted in the removal of less than 0.6% of observations. To visually assess the distribution of litter/humic depths and FWD volumes across forests of the Nation, an inverse-distance weighted map of plot-level mean litter/humic depths and FWD volumes was developed (Geostatistical Analyst; ESRI, 2011).

As bulk/wood density selection is a critical component of C estimation for FF components, ranges of bulk density for litter/humic layers and wood density for FWD were acquired from literature (humus/litter: Nichols and Boelter, 1984; Christensen et al., 1999; Kasischke et al., 2005; FWD: Harmon et al., 2008; Fasth et al., 2010) and used to estimate the median and 95th percentile of their associated C stocks (Mg/ha) by classes of bulk/wood density. For the purpose of this analysis the C content of detrital mass for each FF component was held constant at 50% to isolate effects of bulk/wood densities, although lab analysis of actual content should refine C stock assessments and is subsequently discussed.

Using approximate median bulk/wood density values from the literature (humus/litter: Nichols and Boelter, 1984; Christensen et al., 1999; Kasischke et al., 2005; FWD: Harmon et al., 2008; Fasth et al., 2010) (humic = 0.15 g/cm^3, litter = 0.08 g/cm^3, FWD = 0.50 g/cm^3), the frequency distribution of FF C stocks was estimated empirically using all study plots. As sampling intensity varied from the national base (1 plot per 2428 ha) for a few states, the frequency distribution was weighted by each state's sample intensity.

3. Results

Weighted frequency distributions (by state sample intensity) of litter/humic depths and FWD volumes across the US indicate that half of sampled forests have humic depths less than 1.1 cm (Table 1). The deepest humic horizons are located in southeastern coastal areas, New England, upper Lake States, and the Pacific Northwest (Fig. 4a). Half of US forests had litter depth less than or equal to 2.5 cm. The deepest litter depths were scattered across hardwood regions of the eastern US (Fig. 4b). The median value of observed FWD volumes was 8.9 m^3/ha with higher amounts in the northern Rocky Mountains, Pacific Northwest, and hardwood forests of the eastern US (Fig. 4c). Although median litter depths greatly exceed median humic depths, the range of humic depths greatly exceeds the range of litter depths (Table 1). The range of humic depth was 213.4 cm compared to 20.3 cm for litter. Although measurement units differed between FWD volume (m^3/ha) and litter/humic depths (cm), there was considerable range in FWD volume estimates from zero to a maximum of 1306 m^3/ha.

Table 1
Univariate distribution of plot level litter/humic depths and fine woody debris (FWD) volumes (m^3/ha) across the US weighted by state-level plot sample intensity.

Percentile	Humic depth (cm)	Litter depth (cm)	FWD (m^3/ha)
Max	213.4	20.3	1306.1
99th	24.3	10.8	71.3
95th	14.7	6.8	36.9
90th	10.1	5.4	28.4
75th	4.0	3.9	16.5
Mean	3.7	2.9	13.4
Median	1.1	2.5	8.9
25th	0.2	1.4	3.7
10th	0.0	0.5	0.8
5th	0.0	0.3	0.1
1st	0.0	0.0	0.0
Min	0.0	0.0	0.0

An assessment of litter and humus intraplot depth measurements suggested tremendous variation. On average, litter and humic depths had intraplot CVs exceeding 100% (Table 2). The western pines/pinyon/juniper forest type group (besides the non-stocked classification) had the highest mean litter depth CV (122.9%) and mean humic depth CV (182.5%). In contrast, the eastern spruce/fir forest type group had the lowest mean humic depth CV (59.1%), while the northeastern pines forest type group had the lowest mean litter depth CV (57.1%). The national average CV for litter and humic layers were 86.7% and 114.7%, respectively.

Inter-plot CVs were often larger than associated intra-plot CVs (Table 3). Mean between plot litter depth CVs ranged from 52.8% (northeastern pines) to 188.5% (non-stocked) with a national average of 94.1%. Humic depth had considerably higher CVs, ranging from 113.8% (northeastern pines) to 397.4% (other western hardwoods) with a national average of 223.3%. By contrast, plot-level estimates of FWD volume had a moderate range in CV, from 81.5% (aspen/birch) to 188.0% (other western hardwoods) with a national average of 127.2%.

In order to estimate the C stocks of various FF components, either the bulk/wood density needs to be empirically derived for said components or general density assumptions adopted. Ranges of bulk/wood densities from the literature were used to test the effect of bulk/wood density assumptions on resulting FF component C stocks with an assumption of a constant 50% C content. For all FF components, increases in bulk/wood density had a tremendous effect on resulting C stock estimates with a tendency for extreme C estimates if the highest bulk/wood density was assumed for C estimation (Fig. 5a and b). In particular, when the upper range of bulk density for the humic layer (0.45 g/cm^3) was used for C estimation the 95th percentile of C stock estimates was in excess of 325 Mg/ha (Fig. 5b). Given the relative mass distribution of the three components of the FF pool, the effect of bulk/wood density assumptions on total FF stock decreases sequentially from humic, to litter, and finally to FWD.

The national median values (Mg/ha) of FF C stock components across the US were 7.9, 10.2, 2.5, and 25.6 for humic, litter, FWD, and total stocks, respectively (Table 4). The humic component of FF C stocks appeared to heavily influence the largest FF C stocks. At the 95th percentile, FF C total stocks were approximately 132 Mg/ha, while humic components were approximately 109 Mg/ha.

4. Discussion

The results of this study indicate that most forests have relatively minor FF C stocks (<25 Mg/ha), when compared to aboveground live tree stocks (>100 Mg/ha; Heath et al., 2011). Despite this result, the presence of FF C stock components is pervasive across US forests. For forests in coastal areas or higher latitudes/elevations, the contributions of humic layers to the FF C stock can be tremendous (>100 Mg/ha). In mature hardwood regions of the eastern US, contributions of litter layers to FF C stocks may exceed 25 Mg/ha. In areas where recent stochastic disturbances have occurred (e.g., wind storms), the FWD contribution may only exceed 10 Mg/ha, which stands in contrast to substantial contributions of litter and humic layers to FF C stocks. Overall, given that the FF C pool broadly encompasses a diversity of forest ecosystem attributes (e.g., detritus and soil components) it is not surprising that almost every forest has some component of the FF C pool. For some forests, recent disturbances may be the primary determinant of FF C stocks. For other forests, slow decomposition and attributes of climax forest successional states may be a primary determinant.

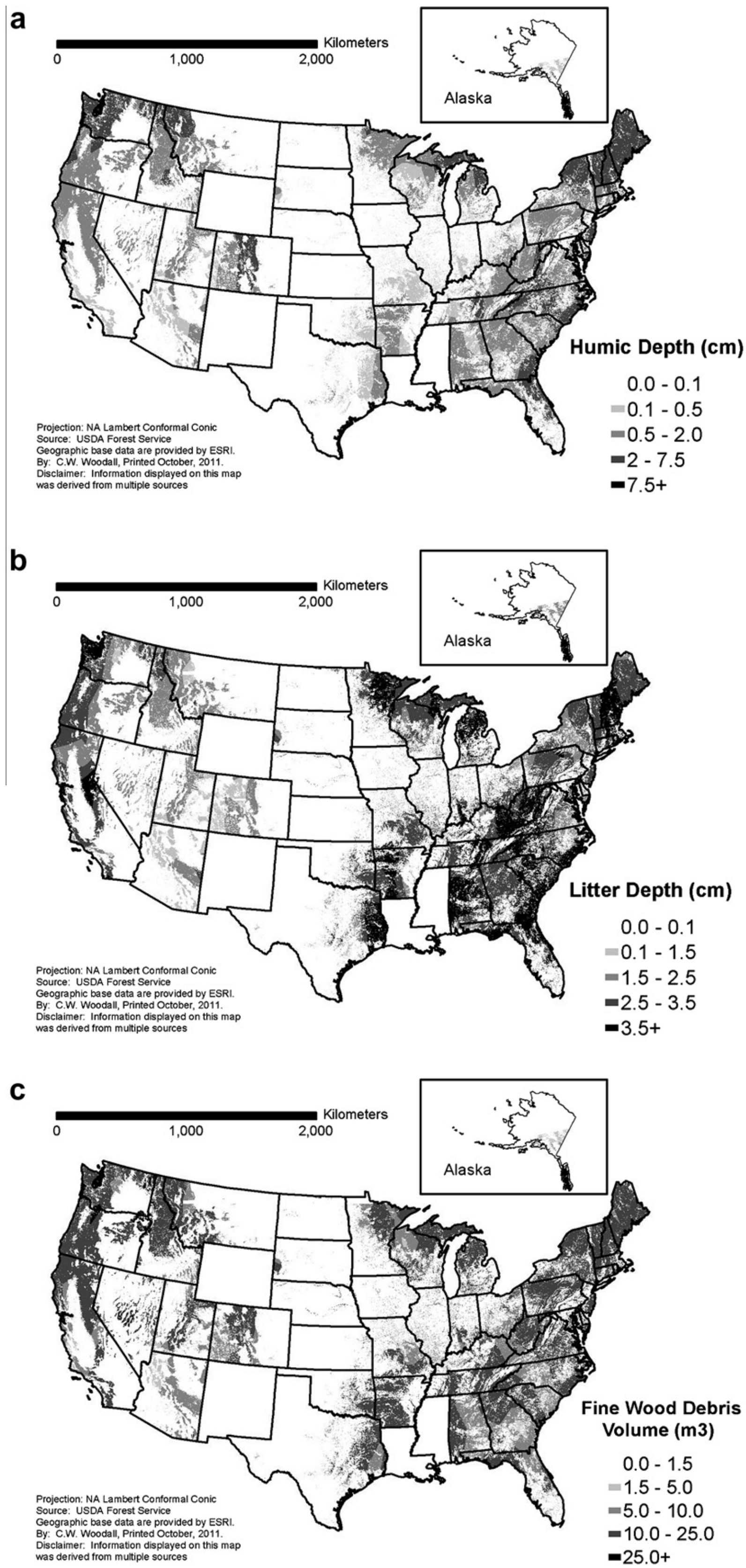

Fig. 4. Interpolated map of (a) humic depths, (b) litter depths, and (c) fine woody debris volumes, US, 2002–2009.

As evidenced by the range and variability of litter/humic depths and FWD volumes, the field sampling of FF C stock components is challenged by field/technical issues. There can be numerous obstacles to measurement such as logs, rocks, and seasonal inundation.

Table 2
Mean intraplot coefficient of variation among humic and litter depths by forest type group and nationally (*Note:* number of observations (*n*) varies between humic and litter depth measurements due to measurement obstructions in some ecosystems; only fully forested plots included).

Forest type group	Humic layer CV (%)			Litter layer CV (%)		
	Mean	*n*	Std. dev.	Mean	*n*	Std. dev.
Northeastern pines	83.7	47	44.7	57.1	47	31.6
Eastern spruce/fir	59.1	98	31.5	89.7	100	44.5
Southern/tropical pines	151.9	267	100.6	80.9	350	59.9
Western pines/pinyon/juniper	182.5	529	92.5	122.9	856	83.1
Western spruce/firs	91.3	431	56.1	85.3	438	35.3
Other western conifers	153.1	63	87.1	75.9	65	32.8
Oak/pine	117.7	121	84.7	72.6	152	47.4
Oak/hickory	113.7	914	104.7	72.9	1272	71.7
Oak/gum/cypress	157.0	64	119.4	90.9	100	61.4
Elm/ash/cottonwood	118.8	81	118.0	74.4	164	72.5
Maple/beech/birch	85.3	352	64.8	57.9	364	29.3
Aspen/birch	73.3	147	63.2	59.6	148	28.6
Other western hardwoods	156.5	197	94.2	108.5	786	106.8
Other/non-stocked	185.0	52	103.9	119.0	128	104.7
National	114.7	3363	96.6	86.7	4970	85.6

Table 3
Coefficient of variation (i.e., interplot) for plot-level mean humic/litter depths and FWD volume by forest type group and nationally (*Note:* number of observations (*n*) varies between humic/litter depth measurements and FWD transects due to measurement obstructions in some ecosystems, outliers removed 10 × interquartile range).

Forest type group	Coefficient of variation (%)								
	Humic depths	*n*	Std. dev.	Litter depths	*n*	Std. dev.	FWD volumes	*n*	Std. dev.
Northeastern pines	113.8	114	2.2	52.8	114	1.7	114.5	114	15.6
Eastern spruce/fir	119.6	173	6.6	94.2	173	2.7	84.3	173	12.3
Southern/Tropical pines	181.5	792	2.3	65.4	792	2.5	123.2	792	11.2
Western pines/pinyon/juniper	201.9	1395	1.0	109.9	1400	1.3	149.3	1400	10.0
Western spruce/firs	122.3	697	3.9	67.4	699	1.7	92.7	699	17.1
Other western conifers	121.8	105	1.5	57.2	106	2.1	84.5	106	16.4
Oak/pine	140.7	335	1.9	64.1	335	2.2	104.4	335	12.3
Oak/hickory	170.8	2633	1.3	70.2	2633	2.0	112.4	2633	12.5
Oak/gum/cypress	213.0	260	4.0	85.0	260	2.3	102.4	260	11.3
Maple/beech/birch	137.6	576	3.0	55.0	576	1.8	88.3	575	13.5
Aspen/birch	161.3	277	3.4	60.9	277	1.9	81.5	277	11.2
Other western hardwoods	397.5	2039	0.8	168.9	2043	1.6	188.0	2043	9.9
Other/non-stocked	319.9	376	0.9	188.5	378	2.1	181.2	378	11.6
National	223.3	10,267	2.3	94.1	10,281	2.1	127.2	10,280	12.9

The delineation between the mineral, humic, and litter layer depths is a subjective assessment of qualitative features (e.g., fibrous content of organic soil layers). Field personnel that conduct FF measurements are often foresters with minimal advanced training in soil sciences. Westfall and Woodall (2007) found that FIA field crews were able to repeat (within 1.3 cm of first measurement) measurements of litter and humic layers 69.8% and 75.0% of the time, respectively. Fine woody debris measurement can be impacted by massive disturbance events where hundreds of FWD pieces may cross a sampling transect necessitating field crew visual estimation of FWD piece counts. As hundreds of field variables must be measured by FIA field crews simultaneously on plots within a limited time span, accuracy of FWD counts may be reduced in locations with recent disturbances (e.g., windthrows) (Woodall and Nagel, 2007; Westfall and Woodall, 2007). While environmental conditions with large FF C stocks may be prone to measurement error, the field measurements themselves may serve as an indicator of locations where more intensive sampling or refined field protocols may be needed (e.g., avalanche probe sampling or ground penetrating radar, see Sucre et al., 2011). Given that humic layers had the greatest range in depths and associated C stocks, regions of the US with the deepest humic depth (coastal plains of mid-Atlantic and southeast, New England, upper lake states, and Pacific Northwest) should be considered for refined FF sampling. Just as the DWM indicator has exceptions to standard field protocols in blowdown situations where field crews may need to visually estimate FWD counts into the hundreds (Woodall and Monleon, 2008), perhaps alternate field protocols should be employed in situations of very deep litter/humic layers to increase measurement accuracy.

Field-based monitoring of FF C stock components requires not only measurements of the dimensional attributes of said components (e.g., litter depths), but also valid C stock estimation procedures. Carbon stock estimators for litter/humus and FWD components require assumptions about bulk density and C content. As demonstrated in the results of this study, arbitrary selection of a relatively high bulk density value for the calculation of litter/humic C stocks can turn a relatively minor forest ecosystem C stock into the largest stock (>300 Mg/ha). Although not directly examined in this study, the same might be said for the selection of C content used in C stock calculation. As FIA's DWM field inventory was the basis for this study, the use of litter/humic bulk density and C content lab analysis from FIA's soils indicator (O'Neill et al. 2006; Perry et al., 2009) may be used in future efforts to more accurately monitor FF C stocks. As the lab analysis from the soils indicator uses site specific samples of the FF, estimation constants from these efforts should be considered superior to general values pulled from literature when estimating FF C stocks. Future efforts to seamlessly link soils lab analysis data with extensive litter/humic depths from the DWM indicator may benefit the estimation of FF C stocks. As FWD can sometimes account for a majority of FF C stocks (Chojnacky et al., 2006) (particularly in disturbed areas), refining constants needed for estimating FWD C attributes

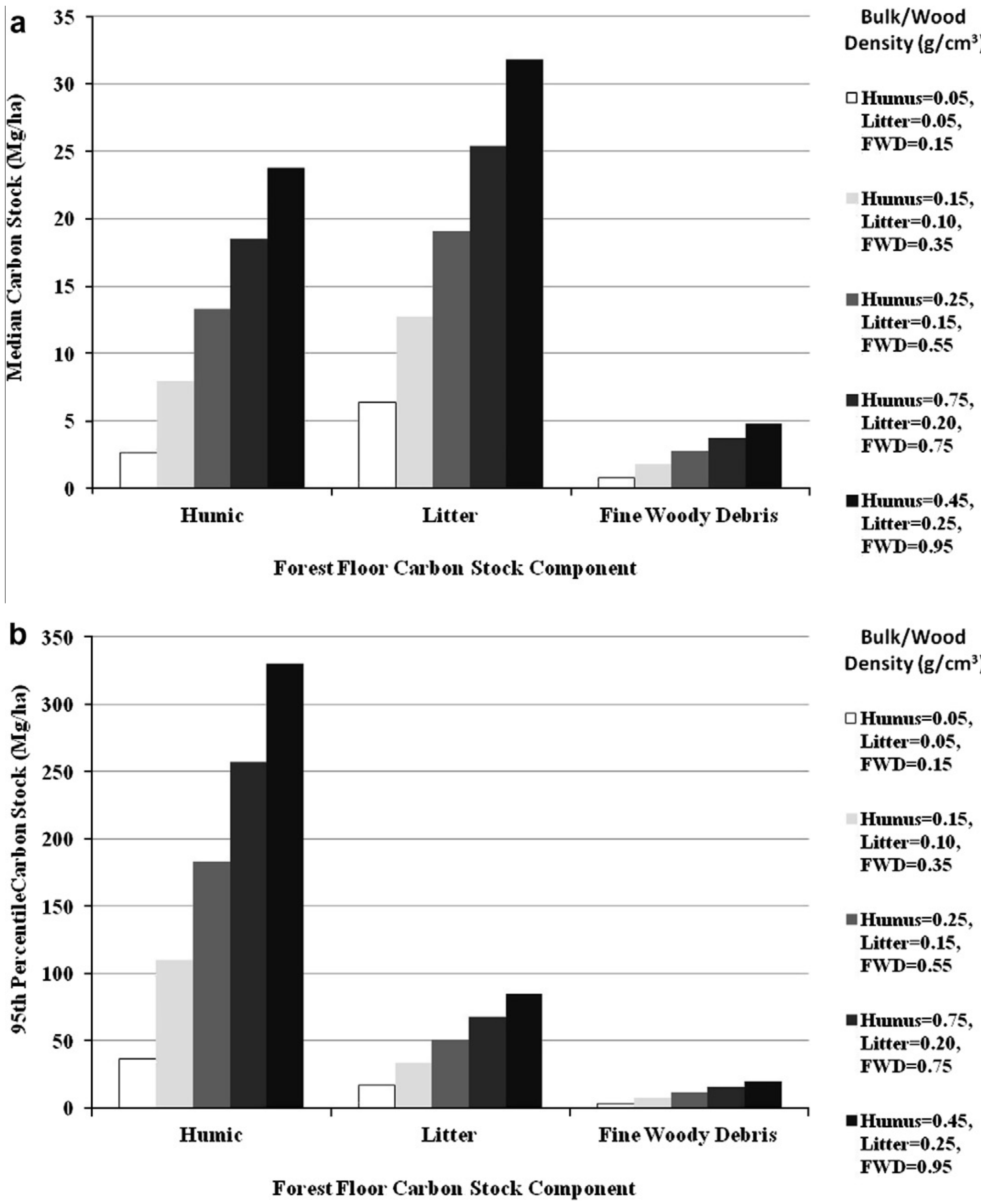

Fig. 5. Estimates of (a) median and (b) 95th percentile carbon stocks by forest floor pool component (humus, litter, and fine woody debris [FWD]) and associated bulk/wood density constant (g/cm^3) used in stock estimation.

Table 4
Univariate distribution of empirical estimates of forest floor carbon stocks across the US weighted by state-level plot sample intensity (*Note:* outliers removed, 10 × IQR).

Percentile	Humus carbon stock (Mg/ha)	Litter carbon stock (Mg/ha)	Fine wood debris carbon stock (Mg/ha)	Forest floor carbon stock (Mg/ha)
Max	267.9	81.3	35.9	307.1
99th	179.9	43.2	18.3	198.4
95th	109.1	26.9	10.3	132.1
90th	73.5	21.5	7.9	93.9
75th	29.4	15.7	4.6	49.2
Mean	24.7	11.6	3.5	39.8
Median	7.9	10.2	2.5	25.6
25th	1.6	5.5	1.0	13.7
10th	0.0	2.2	0.2	5.8
5th	0.0	1.0	0.0	2.9
1st	0.0	0.0	0.0	0.3
Min	0.0	0.0	0.0	0.0

is paramount. The FWD C stock estimator requires quadratic mean diameter, wood density, decay reduction, and lean angle correction constants (Woodall and Monleon, 2008). Other studies have pursued refinement of some of these constants (for example see Woodall and Monleon, 2010), while this study only examined wood density. The national mean intra- and inter-plot variability of humic depth, litter depth, and FWD volumes ranged from 85 to 223 (coefficient of variation; percent). In contrast, median estimates of these FF components changed by up to 1000% (humic C stocks) when a range of bulk density was used in stock calculations. Although, field measurement protocols should be refined in regions of the US with large stocks (e.g., coastal areas), the variability in bulk/wood density may have an inordinate effect on resulting FF C stock estimates compared to field measurement variability. Given the results of this study, future efforts to reduce the uncertainty associated with FF C stock estimator components (e.g., bulk/wood density) could in turn substantially reduce the uncertainty of FF C stock estimates.

Soils may be one of the least understood components of terrestrial ecosystems (Harrison et al., 2011). Although components of FF C stocks have been measured by both the DWM and soils indicators of the FIA program, they have yet to be joined in a cohesive effort to produce empirical estimates of FF C stocks in the US. The results of this study suggest future directions for refined FF C stock monitoring, especially given its potential sensitivity to climate events and management (Gorham, 1991; Jauhiainen et al., 2005; Nave et al., 2010). First, the appraisal of FF C stocks may benefit from the delineation of forest ecosystems with inherently large FF C stocks (e.g., peatland areas with the potential for extremely deep organic soils that may be mistaken for humic layers). In this study, roughly 3% of humic depth measurements were equal or greater than 20 cm. If field crews encounter deep organic layers when sampling for litter/humic layer depths, perhaps an alternate sampling methodology should be employed. Second, as estimation constants can considerably influence FF C stock estimates, efforts should be undertaken to better link litter/humic bulk density and C content estimates from FIA's soils indicator lab data with litter/humic depth measurements (from the DWM indicator). Third, as FWD attributes can contribute considerably to FF C stocks, both refining their appraisal in disturbance events and reducing the uncertainty with their associated estimation constants (e.g., wood density or decay reduction) would benefit FF C stock estimation. As the US's NGHGI currently employs a model (Smith and Heath, 2002) to estimate FF C stocks, with only a moderate amount of additional effort (e.g., linking databases and refining estimation constants) an empirically-based approach to estimating these C stocks could be realized.

5. Conclusions

An empirical assessment of FF C stock components across most forests of the US indicates a substantial store of C, but with considerable variability at both small- (e.g., within an inventory plot) and large-scales (e.g., across regional forest types). The largest FF C stocks may be found in forest ecosystems with deep humic soil horizons (e.g., peatlands) and/or areas experiencing stochastic disturbance events with concomitant increases in FWD volumes (e.g., blowdown events). In order to increase the sensitivity of FF C stock monitoring to possible climate change events, it is suggested that the national field inventory of FF components be adopted in the US's NGHGI with continued refinement of field protocols and estimation procedures. Furthermore, a robust monitoring system of FF C components should use site or forest type specific C content and bulk/wood density constants coupled with consistent national field protocols and timely remeasurement. Beyond C accounting, because the FF is a determinant of forest health and site quality, the monitoring of this forest attribute is paramount to maintenance of ecosystem services into the future.

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