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National inventories of down and dead woody material forest carbon stocks in the United States: Challenges and opportunities

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ABSTRACT

Concerns over the effect of greenhouse gases and consequent international agreements and regional/national programs have spurred the need for comprehensive assessments of forest ecosystem carbon stocks. Down and dead woody (DDW) materials are a substantial component of forest carbon stocks; however, few surveys of DDW carbon stocks have been conducted at national-scales around the world. This study uses the DDW survey of the United States as a case study to examine the challenges of inventorying DDW at a national scale, reviews how dead wood carbon pools are currently estimated in the National Greenhouse Gas Inventory (NGHGI), and suggests opportunities for improving such inventories. The US currently estimates national DDW carbon stocks using models with standing live tree attributes as predictor variables, calibrated using preliminary DDW field estimates. In recent years, implementation of a national DDW inventory has resulted in inventory-based DDW estimates. National field-based DDW estimates follow the national patterns of DDW carbon dispersion seen in earlier model-based estimates. Although the current DDW inventory provides fairly repeatable measurements within a statistically defensible national sample design for producing national estimates of DDW carbon stocks, improving numerous aspects of the DDW survey would may improve the accuracy and precision of C estimates reported in the NGHGI.

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1. Introduction

Carbon (C) sequestration is becoming an increasingly important estimate from large-scale forest inventories because of the link between possible climate change and the accumulation of greenhouse gases in the atmosphere (Smith et al., 2004a). In 1992, 150 countries including the US signed the United Nations Framework Convention on Climate Change that resulted in the development of annual reports of greenhouse gas inventories including C in forests. In 2006, it was estimated that approximately 11% of all greenhouse gas emissions in the United States was sequestered annually in forests and forest products (Smith et al., 2004b; US EPA, 2006). Therefore, accurately estimating baseline forest C stocks and monitoring stock changes over time is essential.

The Intergovernmental Panel on Climate Change defines five broad pools for forest ecosystem C: aboveground biomass, belowground biomass, dead wood, litter (often called forest floor in the US because litter is commonly defined as only the top layer of the forest floor), and soil organic matter (Penman et al., 2003). Dead wood includes all nonliving biomass not included in the litter, including standing dead trees, dead trees lying on the ground, dead roots, and stumps larger than or equal to 10 cm in diameter or any diameter specified by a country. Additional categories used in the US are standing live trees, standing dead trees, understory vegetation, down and dead woody (DDW) materials, forest floor (litter), understory, and soils (Heath et al., 2003; Heath and Smith, 2004; Smith et al., 2006). The DDW pool essentially consists of down coarse woody debris (CWD), fine woody debris (FWD), and tree stumps. In the US, it has been estimated that 35% of the total forest C pool is in live vegetation, 52% in the soil, and 14% in dead organic material (excluding FWD) (Heath et al., 2003). There has been no long-term, comprehensive monitoring data available for C in forest floor and DDW. Additionally, the national annualized DDW inventory in the US has not been remeasured to allow for change detection (Birdsey, 2004). As recently as 2004, national estimates of DDW C were modeled based on other inventoried forest carbon pools (e.g., standing live tree mortality) rather than a field-based inventory (Smith et al., 2004b).

Only a small number of nations (European Union members, Russia, Canada, the United States, New Zealand, and Australia) are developing or currently conducting systematic field-based surveys

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of their forests. Unfortunately, of those few nations, even fewer conduct field-based inventories of DDW. The intensive forest management and utilization in the nations of the European Union limits the accumulation of down woody material in their forests (Kirby et al., 1998; Fridman and Walheim, 2000; Patenaude et al., 2003; Dudley et al., 2004). The Canadian inventory is still developing national protocols for sampling DDW (Graham, personal communication, 2005, senior economist, Canadian Forest Service, Natural Resources Canada, Vancouver, BC). To date, only a few nations (e.g., Russia, Australia, and Sweden) besides the United States have developed and initiated national surveys of DDW (Kukuev et al., 1997; Fridman and Walheim, 2000; Woldendorp et al., 2002; Woodall et al., in press). Estimates of DDW have been omitted from some large-scale C assessments (Goodale et al., 2002) because of the lack of sufficient inventory data.

In 2001, the Forest Inventory and Analysis (FIA) program of the USDA Forest Service began a national field survey of DDW components such as FWD and CWD (Woodall and Williams, 2005; Woodall and Monleon, 2008). Before this, most DDW data had been collected for localized studies focused on wildlife (Maser et al., 1979; Harmon et al., 1986; Bull et al., 1997), fuels (Rollins et al., 2004), or C (Heath and Chojnacky, 2001; Chojnacky and Heath, 2002). Although most DDW studies were not C focused, dead wood measurements that can be used to produce volume or biomass estimates may also be converted to estimates of dead wood C. This approach is used with the FIA survey.

The goal of this study was to use the US DDW inventory as a case study to examine the challenges and opportunities in conducting a national DDW inventory for estimating of DDW C pools in National Greenhouse Gas Inventories (NGHGI). Specific objectives were (1) to describe methods and basic results of the current US DDW inventory, (2) to describe how dead wood stocks are currently estimated in the US NGHGI, (3) to compare field-based DDW C estimates with simulated DDW C estimates currently used in the US NGHGI, (4) to identify limitations and challenges of the current US DDW inventory, and (5) to suggest opportunities for improving national inventories of DDW C stocks.

2. Methods

2.1. DDW C inventory field methods in the US

The FIA program conducts a 3-phase inventory of forest attributes of the United States (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 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 estimates. 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 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, 2003; Bechtold and Patterson, 2005).

In phase 3, a 1/16 subset of phase 2 plots (although if sufficient funding is available, the phase 3 sample intensity may be increased) is measured for forest health indicators such as DDW (Fig. 1). DDW is surveyed in two categories differentiated by size for more efficient sampling: CWD and FWD. CWD is defined by FIA as down logs and pieces with transect diameter ≥7.62 cm and length ≥0.91 m. Although CWD is often defined to include standing dead trees, FIA defines CWD as only dead and down wood, which includes dead trees held up by their roots leaning at an angle of 45° or less from the ground. FWD is defined as woody pieces and tree boles with a transect diameter ≥0.01 cm and <7.62 cm. CWD and FWD are sampled on transects radiating from each FIA subplot center (Woodall and Williams, 2005; USDA Forest Service, 2005) (Fig. 1).

Information collected for every CWD piece intersected on the three horizontal 7.32-m transects (established at arbitrarily selected azimuths of 30°, 150°, and 270°) on each FIA subplot are transect diameter, length, small-end diameter, large-end diameter, decay class, species, evidence of fire, and presence of cavities. Transect diameter is the diameter of a down woody piece at the point of intersection with the sampling transect. Length is the length of each CWD piece between the small-end and large-end diameters. Decay class is a classification variable representing the amount of decay present in an individual piece. Classes of decay are based on visual appraisal of the structure (i.e., cylindrical shape or mound of rot) and texture (i.e., solid wood or brown, crumbly rot present) of each CWD piece. Decay class one is the least decayed (freshly fallen or cut piece), while decay class five is an extremely decayed log typically consisting of a pile of brown, cube-shaped rot. The species of each down piece is identified through examination of species-specific bark, branching, bud, and wood composition attributes (excluding decay class five CWD pieces). If a CWD piece is too decomposed to identify its species, a hierarchy of species identification is followed: species, species group, conifer or hardwood, or unknown (for CWD sample protocol details, see Waddell, 2002; Woodall and Monleon, 2008; USDA Forest Service, 2005).

FWD is sampled on each subplot (arbitrarily established on the 150° transect) (Fig. 1). Two sizes of FWD – with transect diameters less than or equal to 0.61 and from 0.62 to 2.54 cm – were tallied separately on a 1.83-m slope-distance transect (4.27 m to 6.09 m on the 150° transect) for a total of 7.2 m of transect for a fully forested FIA plot. It should be noted that although FWD with a transect diameter less than 0.61 cm is tallied on the transect, it is not included in this analysis. Forest floor samples (litter and FWD less than 0.61 cm in diameter) are collected for laboratory analysis by the soils phase 3 inventory, which includes this category of FWD (O'Neill et al., 2005). FWD with transect diameters of 2.55–7.59 cm (100-hr fuels category) was tallied on a 3.05-m slope-distance

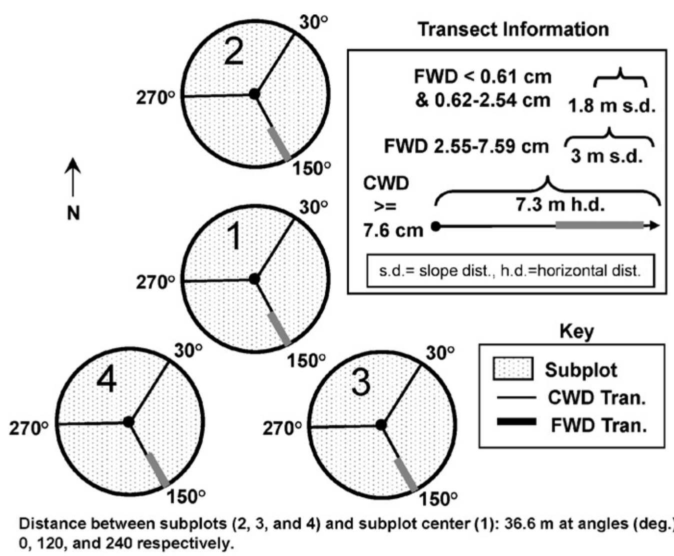

Fig. 1. Sampling design for the down woody materials indicator of the USDA Forest Service Forest Inventory and Analysis program (although fine woody debris less than or equal to 0.61 cm was measured on the transect, in this study, those pieces were assumed to be part of the forest floor).

transect (4.27–7.32 m on the 150° transect) for a total of 12.2 m per fully forested FIA plot (for more information on FWD class definitions, see Deeming et al., 1977). Details of the FWD sampling methods on FIA plots are discussed in Woodall and Monleon (2008). To assess measurement variable repeatability, a subset (<10% nationally) of DDW plots is blindly remeasured by independent field crews each year.

2.1.1. DDW C estimation procedures

CWD and FWD C contents were estimated using a combination of line-intersect volume per unit area estimators and conversion factors for biomass and carbon (Woodall and Monleon, 2008). Line-intersect sampling estimators were used to determine volume per unit area estimates for sample plots based on DDW sub-plot transects (Brown, 1974). These volume per unit area estimators are simply equations to determine the volume that a given sample of CWD pieces represent for an entire area of interest. The shorter the sample transect or CWD piece the larger the volume that piece represents on a per unit area basis. Estimates of volume were first converted to biomass and then to C using conversion constants (Birdsey, 1992; Waddell, 2002; Woodall and Monleon, 2008). Carbon storage in CWD (C_{CWD}) (g C ha^{-1}) was calculated using Eq. (1):

$$C_{CWD} = \sum_{i=1}^{n} (c_i G_i) \left[\left(\frac{\pi}{2L} \right) \left(\frac{V_i}{l_i} \right) f \right] \quad (1)$$

where n is the number of pieces, c_i is the proportion of C in the mass of the ith piece, f is the conversion factor for unit-area values (10,000), G_i is the estimated bulk density (g m^{-3}) of the ith piece reduced by a modeled decay reduction factor, L is the total length of the transect corrected for slope (m), V_i is the volume of the ith CW piece (m^3), and l_i is the length of the ith piece in meters (Woodall and Monleon, 2008). Birdsey (1992) provides mean conversion factors (c) for both softwood (0.521) and hardwood species (0.491). Waddell (2002) provides decay reduction factors for various CWD decay stages for reducing the specific gravity of CWD pieces based on the state of decay.

Carbon storage in FWD (C_{FWD}) (g C ha^{-1}) was calculated using Eq. (2):

$$C_{FWD} = \sum_{i=1}^{n} \frac{(G_i a_i c_i s k)}{L} t_i \bar{d}_i^2 \quad (2)$$

where n is FWD size class (medium or large), G_i is the bulk density (g m^{-3}) of the ith class, a_i is the nonhorizontal lean angle correction factor for ith class, c_i is the proportion of C in the ith class, s is the slope correction factor because FWD is measured along a slope-distance transect, k is a constant representing both unit conversion and a constant for FWD piece lengths (1.234), L is the slope length of the transect (m), t_i is the number of pieces of FWD in the ith size class, and d_i is the mean diameter (cm) of pieces within size class i. Because species data are not collected for FWD, values of G, c, and a were based on the forest type assessed during phase 2 measurements (Woodall and Monleon, 2008). Carbon storage for the smallest FWD size class was not included in plot totals be-cause this stock is included in forest floor measurements.

2.1.2. DDW inventory data and analysis

Between 2001 and 2004, the FIA program measured 4643 forest inventory plots across the nation for DDW with variables measured to estimate C. In addition, the FIA program (blindly) remeasured 86 plots during these field seasons to assess measurement variable repeatability.

US states were assigned to regions identical to previous national forest C reports (except for the Pacific Northwest region) (Smith et al., 2004b) (Fig. 2). Additionally, all plots were assigned to 4° latitude classes. The mean and standard error for CWD and FWD C stocks were determined for each US region and latitude class based on constituent plots. Extreme outliers in plot-level estimates of DDW C stocks were excluded using the criterion of discarding plots outside 10 times the interquartile range (>51.80 Mg ha^{-1} for CWD and >30.40 Mg ha^{-1} for FWD). Plots discarded as outliers totaled 111 out of 4643 plots nationwide (2.4%), with fewer plots discarded in more recent data as the protocols became more familiar to field crews thus reducing measurement error. Finally,

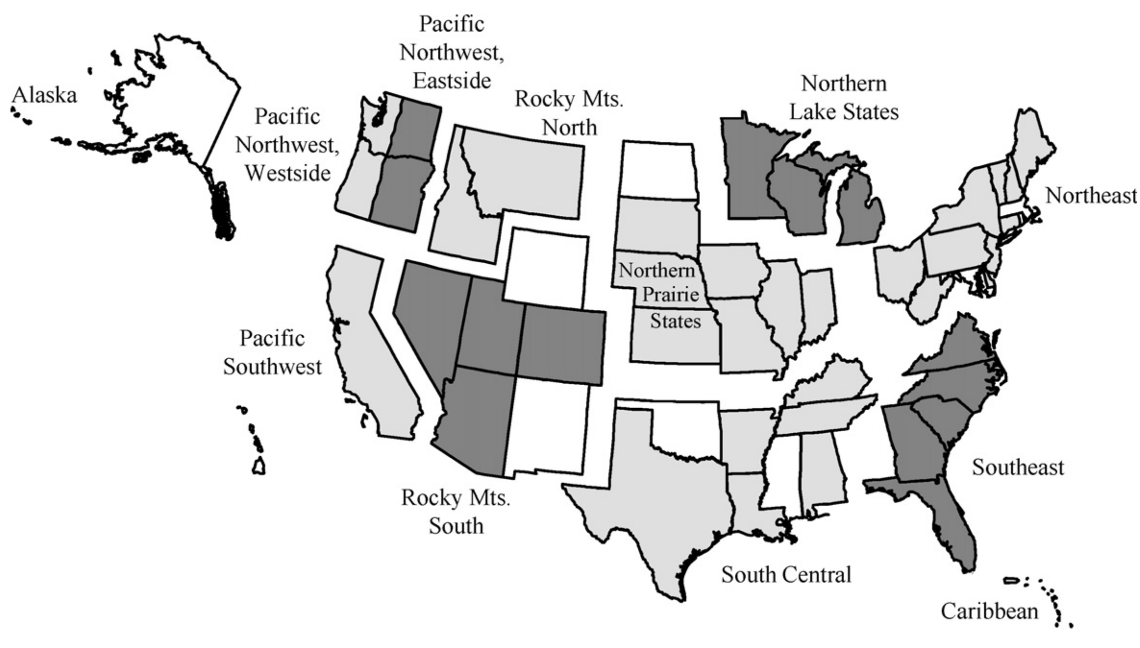

Fig. 2. US regional carbon stock estimation reporting regions. Shading is used to highlight the different regional groupings of states. States colored white have little or no DDW measurements as of 2005.

Table 1
Means and associated standard errors for forest CWD and FWD carbon stocks for regions of the US based on a national field inventory

Region	n	CWD carbon		FWD carbon	
		Mean (Mg ha^{-1})	Standard error	Mean (Mg ha^{-1})	Standard error
Northeast	884	4.27	0.19	3.67	0.11
Northern Lake States	586	4.59	0.25	3.44	0.14
Northern Prairie States	399	3.72	0.33	2.93	0.15
Pacific Southwest	224	5.74	0.59	3.29	0.21
Pacific Northwest	330	11.35	0.66	4.17	0.22
Rocky Mtns. (North)	145	7.14	0.66	2.77	0.19
Rocky Mtns. (South)	528	2.73	0.22	2.13	0.10
South Central	726	2.16	0.19	2.82	0.12
Southeast	654	2.73	0.21	3.13	0.11

Regional State groupings – Northeast: Maine, New Hampshire, Vermont, New York, Connecticut, Rhode Island, Massachusetts, New Jersey, Delaware, Maryland, Ohio, West Virginia, Kentucky, Pennsylvania. Northern Lake States: Minnesota, Michigan, Wisconsin. Northern Prairie States: North and South Dakota, Kansas, Nebraska, Iowa, Illinois, Indiana, Missouri. Pacific Southwest: California, Hawaii. Pacific Northwest: Washington and Oregon. Rocky Mtns. (North): Idaho, Montana. Rocky Mtns. (South): Wyoming, Colorado, Nevada, Utah, Arizona, New Mexico. South Central: Texas, Oklahoma, Arizona, Louisiana, Mississippi, Alabama, Tennessee. Southeast: Virginia, North Carolina, South Carolina, Georgia, Florida.

the percentage of measurements of DDW variables within measurement tolerances on independently remeasured plots was determined. Tolerances are defined in the DDW national inventory field manual (USDA Forest Service, 2005).

2.2. Simulating DDW C as reported in the current US NGHGI

The NGHGI requires annual C change estimates beginning with 1990. US forests and forest products are sequestering C at a net annual rate of 205 Mg C yr^{-1} (US EPA, 2005). Of the 146 Mg C yr^{-1} net C change in forests, 9% is attributed to dead wood. This increase in dead wood means that more dead wood C is transferred into the pool (for instance, from harvests) than is emitted through decay. For more information about reporting details of the NGHGI, see Houghton et al. (1997) and Penman et al. (2003). The dead wood C pool in the US NGHGI (US EPA, 2005) is the sum of C in standing dead trees and down dead wood. Down dead wood is defined as pieces of dead wood greater than 7.5 cm diameter at transect intersection and not attached to live or standing dead trees. Because FIA started the DDW survey in only the last few years, an older simulation approach (FORCARB) is currently used to estimate C in dead wood.

In the early-to mid-1990s, electronically available FIA data were limited. A US C budget model, FORCARB (Plantinga and Birdsey, 1993; Heath and Birdsey, 1993), had been developed and linked to a USDA Forest Service timber modeling projection system used for national planning in the US (Mills and Kincaid, 1992; Ince, 1994; Haynes, 2003). FORCARB used the traditional forest inventory information from ATLAS (a timber inventory projection system; Mills and Kincaid, 1992), converting volumes to tree C and area to soil C based on forest type, region, productivity, and regeneration type of the management units through a projection period of 1990–2040, with inventory information reported at 10- or 5-year increments. FORCARB calculated C change by providing C stock estimates and then calculating an average annual change between consecutive years. The projection period for newer versions of the modeling system is 2000–2050. A newer version of the C budget model, FORCARB2 (Smith and Heath, 2004), includes additional pools, including standing dead tree and DDW. In FORCARB2, dead standing trees and DDW are assumed to decay following decay rates in Turner et al. (1995). DDW is added to existing pools as logging residue from harvests, the predominant disturbance in US forests. Because the timber modeling system is based on net growth, mortality is already considered by assuming it was captured and emitted before becoming DDW.

The early US NGHGI for forests (e.g., US EPA, 1995) used the C stocks and average annual net C changes from this modeling system. The system was used as late as 2004 (US EPA, 2004) for projecting the last C stock in calculations for all C pools. Currently, the NGHGI for forest C pools of the United States is based on FIA data, augmented by information from ecological studies and C conversion factors (Smith et al., 2004a,b; US EPA, 2005). Live tree C pools in the NGHGI are based on FIA data converted to C and summarized from field plots. Standing dead tree C is still calculated based on ratios in a modeling approach until FIA's standing dead tree inventory is fully developed in the near future. Average ratios of dead standing trees to live standing trees and ratios of down dead wood to live standing trees are calculated by forest type and region from this modeling system. Standing dead tree C and down dead wood C ratios are applied to live tree C pools on a plot-by-plot basis and summarized by appropriate category. It is clear that this approach does not capture the variability in DDW. For instance, a plot of zero live tree C multiplied by any ratio may in reality be covered by down dead wood, but our approach would estimate the down dead wood C as zero for the plot.

3. Results

3.1. National field-based DDW inventory

The Pacific Coast region of the US has the highest forest DDW stocks on average exceeding 15 Mg ha^{-1} (Table 1, Fig. 2). Forest land in the Northern Rockies, Pacific Southwest, Northern Lakes, and Northeast regions of the US had DDW stocks around 8 Mg ha^{-1}, while the remaining regions of the US had substantially

Table 2
Means and associated standard errors for forest CWD and FWD carbon stocks for latitude classes across the US based on a national field inventory

Latitude class (°)	n	Mean CWD C (Mg ha^{-1})	Standard error	Mean FWD C (Mg ha^{-1})	Standard error
$<$33	615	1.72	0.22	2.41	0.12
$\geq$33 and $<$37	923	2.64	0.16	2.99	0.09
$\geq$37 and $<$41	1103	3.90	0.19	3.08	0.09
$\geq$41 and $<$45	811	4.89	0.27	3.62	0.13
$\geq$45	768	7.35	0.32	3.42	0.12

Table 3
Repeatability of DDW measurement variables based on blind-remeasured DDW inventory plots

Variable	*n*	Tolerance	Percentage within tolerance[a]
CWD decay class	523	±1 class	93.1
CWD species	491	0	69.0
CWD transect diameter	510	±7.6 cm	98.6
CWD total length	523	±20%	72.5
CWD total plot count	86	±2 pieces/5%	89.5
Medium FWD count	385	±20%	34.5
Large FWD count	385	±20%	56.4

[a] Differences between actual variable measurement and blind remeasurement that are within defined tolerance.

less DDW C stocks on average. For all regions except the Southeast, Caribbean, and South Central, CWD C stocks exceeded FWD C stocks on average.

As is obvious from the regional analysis results, the latitude of forests across the US may influence the DDW C stocks because of the influence of climate on decay. Indeed, when forests are examined by latitude classes, as latitude increases so does the total forest DDW on average; forests located above 45° latitude having nearly 11 Mg ha^{-1} of DDW C on average (Table 2). In contrast, forests below 33° latitude approximately 4 Mg ha^{-1} of DDW on average. Another trend was that mean CWD C stocks increased by nearly 325% between the lowest and highest latitude classes, while mean FWD C stocks increased only by approximately 40%, although both increases were still substantial. Latitude as an indicator of decay rates has much more of an effect on CWD C stocks than on FWD C stocks.

There was adequate repeatability of measurements from blindly remeasured DDW plots (Table 3). Nearly 90% of measurements were within defined tolerances for the following variables: CWD decay class, CWD transect diameter, and CWD piece total plot count. Poor repeatability was found for the following DDW measurement variables: CWD species, CWD total length, and FWD counts.

3.2. Simulated DDW estimates in US NGHGI

The most recent national model simulations estimate that DDW C stocks range from 2.5 Mg C yr^{-1} in the northern Rocky Mountains to 15.5 Mg C yr^{-1} in the subregion Pacific Northwest, west of the Cascades (US EPA, 2005) (Table 4). This approach estimates FWD as part of the forest floor, so we are not able to explicitly report it. However, standing dead tree C stock is estimated. The regions in the western US have more standing dead tree C than DDW, while the eastern regions (including the Northern Prairie States) have less standing dead tree C than DDW. Table 5 displays the dead wood pool estimates by latitude class. As expected, dead wood is higher in the northern latitudes and lower in the southern latitudes. Carbon changes are calculated by forest type in the NGHGI, so knowing information about C by forest type is critical (Table 6). Usually the forest type is broken down by region, but for this study C by forest type was averaged for forests across the US.

4. Discussion

4.1. Comparison of simulated and field-based DDW C inventories

Simulated mean DDW C stock estimates in the past NGHGI and current field-based DDW inventory estimates are very close in some regions, but nearly 45% different in other regions, most likely because of the lack of extensive field data used in model development. The trends across latitude classes are similar. Standing dead tree C is larger than FWD in all regions except South Central. This indicates that standing dead tree and CWD C stocks constitute more sizeable C stocks than FWD.

An unexpected result in our study was that the standing dead wood tree C of the NGHGI appeared more similar to the CWD C from the DDW inventory than the simulated DDW C stock. The higher DDW in the Southern regions in Table 4 was particularly noticeable. This high estimate may be due to using ratios from a modeling system that projects increasing harvests in the future,

Table 4
Mean and associated standard error of forest standing dead and down dead wood carbon for regions of the US used in the NGHGI (US EPA, 2005)

Region	*n*	Standing dead tree carbon		DDW carbon	
		Mean (Mg ha^{-1})	Standard error	Mean (Mg ha^{-1})	Standard error
Northeast	13440	5.04	0.017	5.85	0.028
Northern Lake States	22187	4.30	0.013	4.86	0.022
Northern Prairie States	7349	3.94	0.017	5.07	0.037
Pacific Southwest	2445	9.86	0.161	8.50	0.203
Pacific Northwest (Eastside)	1759	7.91	0.126	6.51	0.157
Pacific Northwest (Westside)	2001	15.49	0.238	15.08	0.307
Rocky Mtns. (North)	1383	8.73	0.135	4.99	0.123
Rocky Mtns. (South)	9551	3.57	0.054	2.52	0.034
South Central	19602	2.25	0.009	4.31	0.021
Southeast	24706	2.49	0.011	4.18	0.020

Regional State groupings as for Table 1, except – Pacific Northwest (Eastside): Washington and Oregon (east of Cascade Range crest). Pacific Northwest (Westside): Washington and Oregon (west of Cascade Range crest).

Table 5
Means and associated standard errors for forest standing dead tree and down dead woody material carbon stocks used in the US NGHGI by latitude class (US EPA, 2005)

Latitude class (°)	*n*	Standing dead tree carbon		Down dead woody material carbon	
		Mean (Mg ha^{-1})	Standard error	Mean (Mg ha^{-1})	Standard error
<33	18793	1.95	0.01	3.49	0.02
≥33 and <37	26485	2.61	0.02	3.99	0.02
≥37 and <41	19939	4.81	0.04	5.00	0.04
≥41 and <45	18842	6.77	0.04	6.47	0.05
≥45	20364	8.14	0.05	6.64	0.05

Table 6
Means and associated standard errors of forest standing dead and down dead wood carbon for major forest types of the coterminous US used in the NGHGI (US EPA, 2005)

Forest type	Example species[a]	*n*	Standing dead tree carbon		DDW carbon	
			Mean (Mg ha^{-1})	Standard error	Mean (Mg ha^{-1})	Standard error
Aspen/Birch	*Populus tremuloides*, *Betula papyrifera*	6968	5.2	0.038	3.9	0.033
California Mixed Conifer	*Abies* spp., *Picea* spp., *Pinus* spp.	673	14.8	0.271	14.0	0.344
Douglas-fir	*Pseudotsuga menziesii*	2335	11.0	0.139	10.5	0.228
Elm/Ash/Cottonwood	*Ulmus* spp., *Fraxinus* spp., *Populus deltoids*	4888	4.6	0.030	4.6	0.055
Fir/Spruce/Mt. Hemlock	*Abies* spp.	2019	15.7	0.149	10.0	0.179
Hemlock/Sitka spruce	*Tsuga heterophylla*, *Picea sitchensis*	320	21.3	0.702	18.0	0.787
Loblolly/Shortleaf pine	*Pinus taeda*, *P. echinata*	11284	1.4	0.008	3.6	0.024
Lodgepole pine	*Pinus contorta*	1101	6.6	0.105	5.2	0.121
Longleaf/Slash pine	*Pinus palustris*, *P. elliotii*	3732	0.7	0.007	2.7	0.035
Maple/Beech/Birch	*Acer* spp., *Fagus grandifolia*, *Betula* spp.	10906	5.7	0.017	6.2	0.031
Oak/Gum/Cypress	*Nyssa* spp., *Quercus* spp., *Liquidambar styraciflua*	5620	3.6	0.019	5.3	0.049
Oak/Hickory	*Quercus* spp., *Carya* spp.	27110	3.3	0.007	5.3	0.019
Oak/Pine	*Quercus* spp., *Pinus* spp., *Juniperus virginiana*	7667	2.4	0.014	4.1	0.032
Pinyon/Juniper	*Pinus edulis*, *Juniperus* spp.	4771	0.4	0.013	0.8	0.011
Ponderosa pine	*Pinus ponderosa*	1962	3.8	0.034	5.1	0.082
Redwood	*Sequoia sempervirens*	50	16.1	0.678	25.9	3.313
Spruce/Fir	*Abies* spp., *Picea* spp.	4660	5.2	0.036	4.9	0.048
Tanoak/Laurel	*Lithocarpus densiflorus*, *Kalmia* spp.	168	11.6	0.554	6.1	0.375
Western Larch	*Larix occidentalis*	84	10.4	0.494	6.2	0.549
White/Red/Jack pine	*Pinus strobus*, *P. resinosa*, *P. banksiana*	3002	4.4	0.031	5.5	0.058

[a] Species constituting the plurality/majority of stocking in stands.

which could produce more logging residue and therefore greater amounts of DDW. Clearly, more work is needed in estimating standing dead tree C using FIA data.

As the FIA DDW inventory becomes completely available by being linked to the P2 data, the data will become more usable for estimating C change in national or state inventories. Because the field-based DDW survey provides a sample of actual changes in DDW C stocks, there will be a shift toward including field-based estimates of DDW C stocks in future NGHGIs. Therefore, refining field-based DDW inventories is critical to future NGHGIs.

4.2. Challenges and opportunities for improving a national DDW C inventory

Examination of the US national DDW inventory in the context of a NGHGI indicates that efficient sampling of DDW C stocks may be incorporated seamlessly with a standard national forest inventory. In the case of the US and other nations (Patenaude et al., 2003), DDW C stocks are not as sizeable as standing live tree or soils C stocks. However, DDW still represent a considerable C stock, especially in northern forests. Since the US DDW inventory began in 2001, numerous ideas for possibly improving a national DDW inventory have emerged and are apparent at all levels of a national inventory, from field implementation to data distribution/reporting.

First, the most important step to improving national DDW inventories is to catch errors in the field before they enter national databases. Although nearly 99% of blindly remeasured CWD transect diameters were within tolerance, mismeasurement of a few plots across the nation necessitated the exclusion of plot outliers in this study's analysis. It appears that on less than 2% of plots, field crews accidentally measured CWD diameters to the same precision as standing live trees, 0.25 cm. Simple decimal place errors with even one CWD piece measurement can result in an extreme outlier, thus skewing regional or national estimates of DDW (a 15-cm CWD piece would be recorded as a 150-cm piece). To maintain field crews in an efficient and economic manner, DDW is typically sampled by field crews that spend the majority of their time sampling standing tree attributes. Switching from standing live to DDW inventories, together with their varying measurement precisions for different variables, results in measurement mistakes. Developing appropriate range checks on portable data recorders used by field crews may eliminate numerous data errors (Woodall and Westfall, 2008).

Second, DDW inventory precision standards and blind remeasurement data used to evaluate those standards may need to be revisited (Westfall and Woodall, 2007). Originally, there was little existing information on which to base the precision standards; data from the inventories could now be used in an analysis to set standards. Because of the poor repeatability of FWD counts and the known factor that FWD can change relatively rapidly, blind remeasurements should be scheduled as soon as possible following the original survey. Additionally, because logging residue piles (slash piles) are an infrequent occurrence, no blind remeasurement data are available. A study by Heath and Chojnacky (2001), in conjunction with the FIA, found that C in residue piles accounted for nearly 25% of the total DDW C stocks in the state of Maine. This estimate varied greatly depending on the underlying assumptions about percentage airspace in the pile and the effect of decay class on a pile's mass.

Third, given limited national forest inventory budgets, there are trade-offs between having longer transects on fewer inventory plots or having shorter transects on more inventory plots. It has been shown in various studies/simulations that longer transect lengths increase CWD estimation precision (Pickford and Hazard, 1978; Harmon and Sexton, 1996; Woldendorp et al., 2004); however, this does not resolve the national inventory issue as to whether gains in the precision of population level estimates is worth the sacrifice in plot-level estimate precision with more numerous but shorter transects. As found in one simulation study (Williams, personal communication, 2005, mathematical statistician, USDA Forest Service, Rocky Mountain Research Station, Ft. Collins, CO), although increasing transect lengths on individual plots may reduce sampling error, sampling DDW on shorter transects on more plots may better estimate DDW attributes at large scales. Additional simulation studies are needed to resolve this inventory issue whose answer is most likely highly dependent on the heterogeneity of forest conditions across a nation.

Fourth, the selection of CWD volume estimation procedures is integral to the entire DDW inventory. Pickford and Hazard (1978) demonstrated that the sampling of irregularly tapered CWD pieces can greatly affect the variance associated with line intersect estimates. Measuring additional CWD dimensions (e.g., length and end diameters) may increase the precision of CWD estimates. Some estimators (DeVries, 1986) allow for use of Smalian's log rule (total length, small-end, and large-end diameter of CWD pieces; see Husch et al., 1972) to facilitate population estimation of CWD attributes. In contrast, other estimators (Van Wagner, 1964) allow for using only the transect diameter of CWD pieces to estimate DDW C stocks. Although Smalian's log rule (Smalian's log rule, see Husch et al., 1972; DeVries, 1986) may more accurately estimate CWD populations when log dimensions are accurately measured, in reality field crews measure small-end, large-end, and total lengths of CWD pieces less accurately than CWD transect diameter. Blind measurement data indicated that nearly 99% of remeasured transect diameters were within tolerance, while total length and end-point diameters had much worse remeasurement results. Because of the decayed and disturbed nature of CWD pieces, poor measurement repeatability of dimensional variables and possible Smalian log rule bias may negate any possible benefit from their measurement. Measuring just the transect diameter of CWD pieces may just as accurately estimate CWD population attributes as using Smalian's log rule and should be explored further.

Fifth, very few countries have the necessary finances to conduct a national forest inventory, let alone measure additional forest C stocks such as DDW. For the very few nations that may plan or conduct a national DDW inventory, usually the inventory is on a subset of standard forest inventory plots, as currently done in the US. However, the infrequency of sampling DDW among diverse ecosystem conditions means that rare DDW events (e.g., CWD in an infrequent forest type) may not be sampled at an appropriate intensity to allow for reasonably precise population estimates. Additionally, there are sampling alternatives to line-intersect sampling that may be more efficient. A more rapid method for measuring CWD, perpendicular distance sampling (PDS) and its derivatives/extensions have been discussed as a possible efficient technique for measuring CWD resources at large scales (Williams and Gove, 2003). Although PDS and other related techniques have not been thoroughly tested or employed as a technique for sampling CWD in a national inventory, DDW inventories may someday benefit from new sampling technologies that allow for rapid and unbiased estimation of DDW attributes.

Sixth, the robust management of DDW inventory data is critical to meshing DDW C estimates with other C stocks (e.g., soil and standing live tree) in national assessments. The US national DDW survey does not explicitly measure stumps; however, if the DDW inventory is properly linked to the standing tree inventory, then using tree removals for stump C estimation is possible. McWilliams et al. (2000) found that the magnitude of stump C stocks in northern US forests was notable enough to include in large-scale analyses. To facilitate rapid data dissemination to the public and efficient analysis among diverse ecosystem components measured using differing sample protocols, a National Information Management Systems (NIMS) has been developed to manage newer forest inventory data used in the US NGHGI (Alerich et al., 2005). Without a documented and robust data management system, inventorying and reporting on national DDW in concert with other forest attributes would be difficult and prone to error. Additionally, hindering the dissemination of DDW C stocks to public review disallows critical research that may in turn benefit the inventory itself. A country wishing to conduct its own DDW inventory may easily conduct the field portion of the inventory only to find more effort and resources required to manage the data and disseminate it to the public.

Seventh, another major concern in a national DDW inventory is that of trampling impacts. FWD is especially vulnerable to trampling impacts which increase decay rates. CWD may even be subject to trampling impacts, due to field crews stepping on or over CWD pieces, inadvertently breaking CWD pieces or scuffing off bark/wood pieces. Little research has been conducted on the impacts of trampling on DDW decay rates; however, forest recreation research has indicated that FWD may be reduced by as much as 25% in areas impacted by repeated trampling (Hall and Farrell, 2001). Additionally, trampling might be affecting the repeatability of field measurements (e.g., FWD counts and CWD total length).

Finally, the most obvious challenge to the national DDW inventory in the US is that the inventory measures the size of DDW, not the C content. Carbon content is modeled from DDW volumes using both mass and C conversion constants. A 10% variation in the specific gravity and decay class reduction factor of CWD can cause more than a 4% variation in estimates of CWD mass (weight per unit area; Woodall and Lutes, 2005). Little research has been done on defining specific gravity of live tree wood, much less the reduction in specific gravity that occurs as dead wood decays at species-specific rates. In terms of the C conversion constants, little research has been conducted to provide refined constants for estimating DDW stocks for all the hundreds of tree species across the US rather than one constant used for hardwood and softwoods in the US (Waddell, 2002). The accuracy of DDW C estimates may be greatly enhanced through more research on DDW decay reduction factors and C content.

5. Conclusions

The current forest DDW C inventory in the US provides the opportunity to explore efficient and effective ways to conduct national DDW C inventories. The current inventory provides estimates of DDW C pools across the nation using a statistically defensible sample design and repeatable application of many measurement protocols. However, initial results indicate that numerous aspects of the DDW inventory could be improved. Given the limited budgets of national forest inventories, DDW inventories should focus on measurement variables that are repeatable with corresponding widely acceptable estimators. Additionally, the lack of information on decay reduction factors and C conversion constants of DDW hinders refining national DDW estimates. Although many great steps have occurred during the past few years to inventory the frequently ignored forest resource of DDW, reporting requirements for the NGHGI have presented the opportunity to refine DDW inventories using new science and technologies.

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