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Biomass and carbon attributes of downed woody materials in forests of the United States

C.W. Woodall [a,*], B.F. Walters [a], S.N. Oswalt [b], G.M. Domke [a], C. Toney [c], A.N. Gray [d]

[a] USDA Forest Service, Northern Research Station, St. Paul, MN, United States
[b] USDA Forest Service, Southern Research Station, Knoxville, TN, United States
[c] USDA Forest Service, Rocky Mountain Research Station, Missoula, MT, United States
[d] USDA Forest Service, Pacific Northwest Research Station, Corvallis, OR, United States

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ABSTRACT

Due to burgeoning interest in the biomass/carbon attributes of forest downed and dead woody materials (DWMs) attributable to its fundamental role in the carbon cycle, stand structure/diversity, bioenergy resources, and fuel loadings, the U.S. Department of Agriculture has conducted a nationwide field-based inventory of DWM. Using the national DWM inventory, attributes (e.g., carbon stock totals and biomass density) were summarized by state and common tree species along with evaluations of residue pile metrics and relationships between DWM and other stand attributes (e.g., live tree biomass, relative density, and climate). Results indicate that DWM are ubiquitous in US forests with individual components (e.g., fine woody debris and piles) varying by region as influenced by endemic ecosystem dynamics and management practices. Eastern forests, particularly in the southeast, have fine woody debris and residue piles biomass densities that often exceed those of west coast forests. Rocky Mountain forests have coarse woody biomass densities approaching those of west coast forests, which have the largest amounts nationally. There is a complex relationship between the standing dead, standing live, and down dead wood biomass densities per unit area in the context of changing stand relative densities and average annual precipitation/minimum temperatures. As evidenced by this initial exploration, a publicly available national dataset comprised of DWM attributes may inform decision makers with objective estimates of DWM resources and facilitate further DWM dynamics research.

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1. Introduction

Down and dead woody materials (DWMs) could be considered one of the most enigmatic components of forest ecosystems. Historically, DWM was considered un-utilized woody material that hindered stand management activities or was a fire hazard. Only during recent decades (Harmon et al., 1986) has the ecological importance of DWM emerged as a central component of wildlife habitat (Freedman et al., 1996), a controlling factor of forest nutrient cycles (Graham and Cromack, 1982; Finér et al., 2003), facilitator of tree regeneration (Hagan and Grove, 1999; Weaver et al., 2009), a store of carbon (C) (Janisch and Harmon, 2002; Harmon et al., 2004; Gough et al., 2007; Woodall et al., 2008), and determinant of wildfire behavior (Rothermel, 1972). Contrary to being termed "dead," DWM may affect most biotic processes in forest ecosystems (Harmon et al., 1986; Stokland et al., 2012). With the recent emergence of C/bioenergy economies, the attributes of DWM and associated roles in forest C/biomass cycles are facing even greater scrutiny (MCCS, 2010; Lippke et al., 2011; Gunn et al., 2012). The role of DWM in contemporary forest management is dichotomous (Hagan and Grove, 1999). On one hand, the combustibility of DWM promulgates its removal from forests to reduce fire hazards and/or to capture said energy through bioenergy industries (Malmsheimer et al., 2008; McKinley et al., 2011). On the other hand, because DWM facilitates numerous ecosystem processes critical to ecosystem services (e.g., C stocks, tree regeneration, and wildlife habitat) there is impetus to maintain and/or increase DWM in some ecosystems (Campbell et al., 2012). Perhaps at no other time in the course of forest science have objective assessments of the DWM resources and associated dynamics been so critical to a wide breadth of scientists, policy makers, and stakeholders.

Assessments of DWM have largely focused on the unique characteristics of detritus in individual forest types or regions. In North America, there is an abundance of DWM studies in ecosystems ranging from boreal to temperate (Gough et al., 2007; Hall et al., 2006) to sub-tropical using an equally abundant diversity of sample designs. Given the costs and logistics necessary to develop a

* Corresponding author. Address: 1992 Folwell Avenue, St. Paul, MN 55108, United States. Tel.: +1 651 649 5141; fax: +1 651 649 5140.
E-mail address: cwoodall@fs.fed.us (C.W. Woodall).

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consistent national-scale DWM inventory, most Nations do not have a systematic field-based inventory of DWM (Woodall et al., 2009), with only a handful of European countries having conducted a national inventory prior to 2000 (e.g., Fridman and Walheim, 2000). A focus on holistic assessments of forest ecosystems (e.g., C stocks, biodiversity, and social constructs), due to the advent of efforts such as the Montreal Process Criteria and Indicators helped initiate the sampling of indicators of forest health in nations like the US (Smith, 2002; Woodall et al., 2011). As the U.S. Department of Agriculture's Forest Inventory and Analysis (FIA) program is authorized by the U.S. Congress to inventory forest resources of the Nation (Smith, 2002), the FIA initiated a national inventory of DWM in 2001. Thus far, most interim analyses of this emerging dataset have been regional in nature (Chojnacky et al., 2004), only examined initial stand-level dynamics (Woodall and Liknes, 2008a,b), or lacked stratified population estimates using the full dataset (Woodall et al., 2008). The current DWM inventory in the US is nearing completion. Thus, an opportunity exists to present the first statistically rigorous analysis of this unique dataset at a national scale. Analogous to a national DWM analysis in Sweden (Fridman and Walheim, 2000), empirical examination of a Nation's DWM attributes can inform not only resource policy but also detrital dynamics. The opportunity exists to extend the foundational work of Fridman and Walheim (2000) by examining the attributes of DWM across the diverse forest biomes and climatic gradients (e.g., coastal Alaska to southern Florida) found in the US. Additionally, given the considerable investment to inventory dead wood attributes in concert with associated stand attributes (e.g., standing live and dead trees) across such a relatively large landscape, this study is meant to introduce a diversity of ecological applications of this dataset which is freely available to the public for further exploration.

The goal of this study was to assess the biomass/C attributes of downed woody materials across forests of the United States and highlight potential applications of an emerging dataset using FIA's nationwide inventory with specific objectives including:

(1) Estimate C population totals and biomass density (with associated sampling errors) by state across the US by DWM components (e.g., fine and coarse woody debris),
(2) Estimate distribution of CWD biomass by decay and large-end diameter class for the top 25 tree species in terms of nationwide total biomass,
(3) Estimate the frequency and biomass attributes of residue piles across US by classes of total pile volume,
(4) Examine the relationship (stand-level) between standing live/dead tree biomass and DWM across the US by classes of relative density, stand age, and climate information, and
(5) Propose future research directions for this newly released public dataset that is a component of the US's 2013 National Greenhouse Gas Inventory.

2. Methods

2.1. Field sample protocols

The USDA Forest Service's Forest Inventory and Analysis (FIA) program is the primary source for information about the extent, condition, status, and trends of forest resources in the United States (Smith et al., 2009). FIA applies a nationally consistent sampling protocol using a systematic design covering all ownerships across the US using a 3-phase inventory (Bechtold and Patterson, 2005). The FIA sampling design is based on a tessellation of the United States into hexagons approximately 2428-ha in size with at least one permanent plot established in each hexagon (i.e., national base sample intensity). In phase 1, the population of interest is stratified (e.g., forest canopy cover classes) and plots are assigned to strata to increase the precision of estimates. Remotely sensed data may also be used to determine if plot locations have forest cover; only forested land is included in the inventory and it is defined as areas at least 10% stocked with tree species, at least 0.4 ha in size, and at least 36.6 m wide (Bechtold and Patterson, 2005). In phase 2, tree and site attributes are measured for plots established in the 2428-ha hexagons. FIA inventory plots established in forested conditions consist of four 7.32-m fixed-radius subplots spaced 36.6 m apart in a triangular arrangement with one subplot in the center (USDA Forest Service, 2007a; Woudenberg et al., 2010). All trees (live and standing dead) with a diameter at breast height of at least 12.7 cm are inventoried on forested subplots. A standing dead tree is considered DWM when the lean angle of its central bole is greater than 45° from vertical (USDA Forest Service, 2007b). Within each sub-plot, a 2.07 m microplot offset 3.66 m from subplot center is established where only live trees with a d.b.h. between 2.5 and 12.7 cm are inventoried.

For the purposes of this study, population definitions of DWM components were based on those used by FIA (Woodall and Monleon, 2008) which roughly follow global convention (Woodall et al., 2009). Down woody materials were defined as detrital components of forest ecosystems comprising fine and coarse woody debris, along with coarse woody debris that may be assembled in a pile due to logging activities. Coarse woody debris (CWD) were pieces, or portion of pieces, of down dead wood with a minimum small-end diameter of at least 7.62 cm at the point of intersection with a sampling transect and a length of at least 0.91 m. CWD pieces must be detached from a bole and/or not be self-supported by a root system with a lean angle more than 45° from vertical (Woodall and Monleon, 2008). Fine woody debris (FWD) were pieces, or portion of pieces, of DWM with a diameter less than 7.62 cm at the point of intersection with a sampling transect excluding dead branches attached to standing trees, dead foliage, bark fragments, or cubicle rot. Residue piles (alternatively referred to as slash piles) were defined as spatial assemblages of CWD into piles that can be delineated in terms of size and piece density.

DWM were sampled on a subset of phase two inventory plots during the third phase of FIA's multi-scale inventory sampling design (Woodall and Monleon, 2008). The national base sample intensity for phase three is 1/16th of phase two plots or approximately 38,848 ha (Woodall et al., 2011). CWD were sampled on transects radiating from each FIA subplot center (at angles 30°, 150° and 270°, respectively). Each subplot had three 7.32 m transects, totaling 87.8 m for a fully forested inventory plot. Information collected for every CWD piece intersected by transects included transect diameter, length, small-end diameter, large-end diameter, decay class, and species. Transect diameter was the diameter of a down woody piece at the point of intersection with a sampling transect. Decay class was a subjective determination of the amount of decay present in an individual log. Decay class 1 is the least decayed (freshly fallen log), while decay class 5 is an extremely decayed log (cubicle rot pile). The species of each fallen log was identified through determination of species-specific bark, branching, bud, and wood composition attributes (excluding decay class 5). FWD with transect diameters less than 0.61 cm (small FWD) and 0.62 cm to 2.54 cm (medium FWD) were tallied separately on a 1.83-m slope distance transect (4.27–6.09 m on the 150° transect). FWD with transect diameters of 2.55–7.59 cm (large FWD) were tallied on a 3.05-m slope-distance transect (4.27–7.32 m on the 150° transect). Finally, if CWD were found in piles (regardless if the result of a natural occurrence or harvesting activity) with the pile center coinciding with a subplot then pile sampling protocols were used in lieu of sampling transects. Field crews assigned the pile a shape category, measured its dimensions, and visually assessed the pile in terms of the density of CWD within the defined shape (i.e., packing ratio) (Hardy, 1996; Woodall and Monleon, 2008).

2.2. Data and analysis

Field data (USDA Forest Service, 2007a,b) for this study were taken entirely from the FIA database (Woudenberg et al., 2010; Woodall et al., 2010) sampled from 2002 to 2010 using the forest inventory in 46 states (Wyoming, Nevada, New Mexico, Hawaii, and interior Alaska absent from study due to insufficient sample intensity or lack of an annual inventory) for a total of 27,000 unique inventory plot conditions (Fig. 1). As DWM inventories were initiated at varying times from 2002 to 2010, sample intensities vary by state. In addition, states and regions of the US have the opportunity to increase the sample intensity of both phase 2 and phase 3 plots. In some states, the sample intensity of DWM plots was increased from 1/16th of phase 2 plots to the same intensity as phase 2 plots (west Texas, Washington, Oregon, and California). Furthermore, states/regions also had the opportunity to increase the size of the fixed-area sample plots from 7.32 m to 17.95 m, with a commensurate increase in the length of CWD transects. Changes in both fixed-area subplot size and CWD sampling transects were incorporated into estimation procedures to allow seamless comparison across the entire US, although the precision of DWM population estimates should be higher in states with greater sample intensities and/or longer transects. In a manner similar to phase 2 population estimation (e.g., forest land area estimation; Bechtold and Patterson, 2005), no outliers in the DWM dataset were removed during analytical procedures. The associated field data are available for download at the following site: http://fiatools.fs.fed.us (FIA Datamart, USDA, 2011).

The volume and C content of FWD and CWD were determined through application of estimators detailed in Woodall and Monleon (2008). Briefly, the volume of FWD is estimated per unit area, and then converted to an estimate of biomass using a bulk density and decay reduction factor based on forest type. An estimate of FWD C was then derived by reducing the biomass estimate by 0.5. For CWD the volume was determined for every CWD piece then used in an estimator to estimate per unit area volume (Woodall and Monleon, 2008). Volume was converted into biomass and C through the use of decay reduction factors, bulk density, and C conversion based on a piece's unique species and decay class (Harmon et al., 2008). For decay class 5 CWD pieces that have no species assignment (i.e., species code = 999), a national default initial wood density (specific gravity = 0.52) and decay reduction (decay reduction factor = 0.42) were applied. For details and examples please refer to Woodall and Monleon (2008). Estimates associated with both individual FIA plots and domains of interest (e.g., states), along with sampling errors for each domain, were calculated using estimators detailed in Woodall and Monleon (2008). As this study highlights the application of a national DWM inventory towards a limited set of biomass/carbon research questions, readers are encouraged to both replicate this study and/or explore their own research initiatives using this publicly available dataset (http://fiatools.fs.fed.us). In addition, numerous additional tables of DWM population estimates by common forest type groups of the US (Woudenberg et al., 2010) are presented as supplementary material in Appendix A.

In order to examine the dynamics between numerous components of total stand biomass and stand/site attributes, the mean proportion of three stand components (standing live trees, standing dead trees, and DWM) relative to total stand biomass (standing live trees + standing dead trees + DWM) was determined by classes of stand relative density (Woodall et al., 2005) and climatic attributes (average annual precipitation and maximum/minimum temperature; PRISM, 2006).

3. Results

Based on this initial assessment, the total U.S. C stock of DWM was approximately 2194 Tg (Table 1) with the omission of four states. Coarse woody debris comprised the largest percentage of

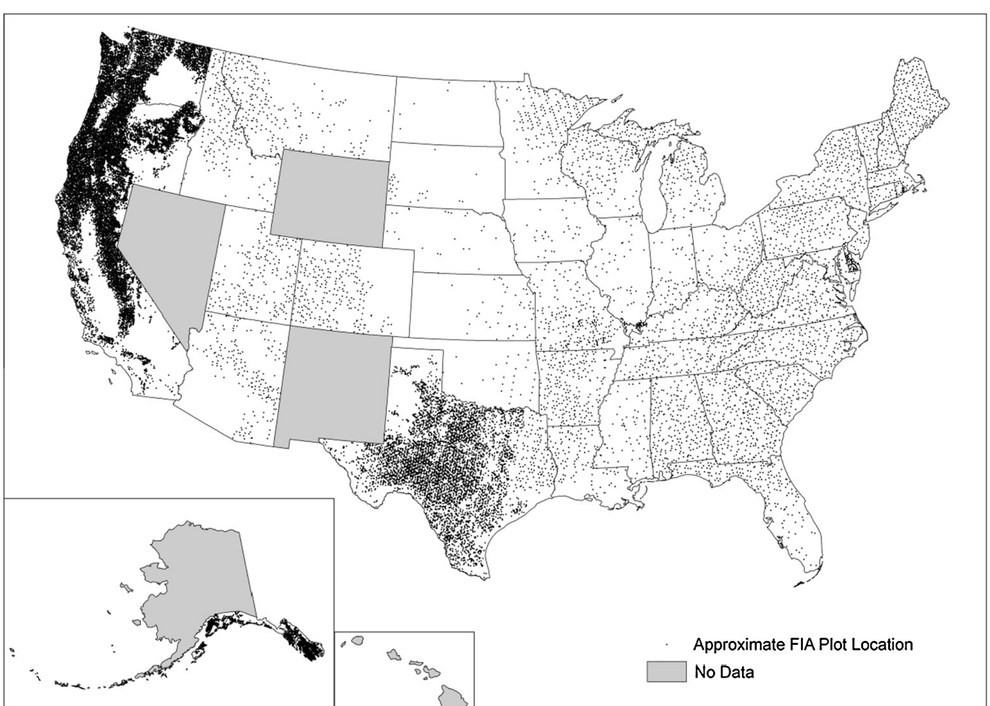

Fig. 1. Approximate down woody materials inventory plot locations across the United States, 2002–2010.

this total stock, followed by fine woody debris and piles, 54%, 28%, and 18%, respectively. Among FWD classes, large FWD was three times greater than medium FWD (445 vs 148 Tg C), while small FWD was a very minor stock at 19 Tg C nationally. As it stands to reason, the states with the largest DWM C stocks tended to be the states with the most forest land areas. Washington, Oregon, Texas, California, and Montana were the top five states in terms of total DWM C stocks. Among DWM components there was one important diversion from this trend. Texas, Tennessee, Alabama, and Florida were four southern states that were in the top 5 nationally in terms of pile C stocks with Texas having twice as much pile C as the 2nd ranked state.

To further discern trends in DWM biomass/C population trends among states, the relationship between aboveground standing tree biomass (live and dead) and DWM in the context of a state's total forest land was assessed (Fig. 2). There is a general trend of a state's DWM biomass increasing linearly with increases in standing tree biomass. The national ratio of DWM to standing tree biomass was 0.16. There are notable exceptions to this trend with Texas having 312 Tg of DWM biomass compared to 849 Tg for standing trees which results in a ratio of 0.37. In contrast, Georgia had 72 Tg of DWM biomass compared to 962 Tg for standing trees resulting in a ratio of 0.07. There was a general trend in increasing total DWM biomass with increasing state forest land area with some notable exceptions. Some states, such as Utah, Arizona, South Carolina, Louisiana, and Wisconsin have moderate quantities of forest land area but relatively small quantities of DWM biomass. In contrast, other states such as Washington, Montana, Idaho, Tennessee, and Alabama have relatively high quantities of DWM biomass while still only having moderate acreages of forest land areas in the US. For example, Washington only has 11% more forest land area than Arizona but has 670% more DWM biomass.

The density of forest land DWM biomass (biomass per unit area; Mg/ha) across states of the US (Table 2) diverges somewhat from trends seen in state totals (Fig. 2). In terms of FWD, a number of eastern states (Indiana, New York, and Connecticut) have some of the highest biomass densities (>6 Mg/ha), albeit some of the highest sampling errors (Table 2). In contrast, it is the northern

Table 1
Estimates of downed woody material carbon stocks (Tg) and associated sampling errors (SE; percent) by component for all inventoried US states, 2001–2010.

State	Small FWD	SE	Medium FWD	SE	Large FWD	SE	CWD	SE	Residue Pile	SE
AL	0.77	12.4	4.88	8.6	14.71	9.4	18.74	13.3	39.91	68.0
AK[a]	0.45	13.6	2.00	13.9	5.95	12.0	78.24	14.3	0.00	
AZ	0.39	10.7	1.96	8.8	7.13	13.4	19.32	15.0	1.20	64.7
AR	0.41	6.3	4.06	6.4	14.23	6.9	17.79	13.4	24.46	99.3
CA	1.18	1.7	7.93	3.1	22.24	1.9	91.43	2.0	5.60	17.8
CO	0.75	7.1	3.85	6.6	12.47	8.7	39.11	9.8	0.83	100.7
CT	0.07	20.5	0.56	22.0	1.98	27.2	4.48	49.6	0.00	
DE	0.01	11.8	0.09	12.7	0.24	14.7	0.43	17.9	0.06	105.5
FL	0.40	10.7	4.20	11.7	9.54	16.8	12.44	18.9	33.38	63.5
GA	0.67	6.5	5.66	8.4	15.14	17.6	10.99	11.0	3.65	43.1
ID	0.84	7.7	4.57	15.4	19.83	12.3	66.57	8.6	0.00	
IL	0.14	14.5	2.22	28.5	3.54	13.9	5.81	14.3	0.00	
IN	0.18	16.0	1.40	12.9	4.49	15.3	10.07	17.4	0.00	
IA	0.06	13.9	0.85	15.4	1.70	20.2	5.70	21.4	0.00	
KS	0.04	21.7	0.55	21.7	2.04	27.8	1.87	22.6	1.62	106.0
KY	0.28	11.6	2.98	13.1	11.30	14.3	18.58	13.3	0.82	76.1
LA	0.18	10.2	2.16	10.1	6.10	12.8	10.49	31.8	17.12	85.3
ME	0.81	4.7	4.81	4.8	14.77	5.2	35.96	7.3	0.04	98.6
MD	0.09	20.8	0.75	28.0	2.31	23.0	3.28	25.2	0.00	
MA	0.13	21.5	0.85	18.9	2.29	18.5	3.75	21.0	0.00	
MI	0.47	8.3	4.83	6.1	12.39	6.4	34.29	8.1	0.21	96.6
MN	0.45	7.3	4.01	6.0	9.09	8.5	30.57	8.0	3.88	62.9
MS	0.31	9.6	4.46	12.3	14.35	12.8	19.17	21.6	15.55	66.5
MO	0.39	16.1	3.75	6.4	10.59	8.0	21.36	14.2	0.38	100.0
MT	0.82	6.9	4.12	7.3	14.02	7.8	79.14	7.7	3.28	86.3
NE	0.03	35.1	0.37	41.4	1.32	39.4	1.50	45.2	0.00	
NH	0.17	9.4	1.03	10.0	4.15	18.9	7.61	16.1	0.00	
NJ	0.05	21.1	0.41	21.2	0.76	25.4	0.85	37.5	0.00	
NY	1.00	9.2	5.96	7.5	16.44	6.8	33.56	8.0	2.50	66.4
NC	0.53	8.8	5.37	8.6	14.11	7.6	25.79	10.3	3.51	52.3
ND	0.01	45.4	0.16	44.9	0.46	48.7	0.38	66.4	0.00	
OH	0.25	7.7	1.89	8.8	6.92	9.6	12.87	15.5	3.16	80.3
OK	0.28	21.8	3.09	36.3	8.45	34.0	11.19	41.8	11.01	61.5
OR	1.15	1.6	8.06	2.1	25.42	1.9	137.16	1.6	13.00	17.4
PA	0.52	9.4	4.89	14.7	14.65	11.7	28.45	10.8	6.67	62.1
RI	0.02	43.2	0.14	49.3	0.59	48.6	0.55	50.8	0.00	
SC	0.24	7.0	2.16	11.1	8.40	8.3	9.47	13.4	5.75	62.3
SD	0.02	34.5	0.39	31.4	1.20	26.2	2.01	29.6	0.00	
TN	0.37	13.2	3.98	10.8	10.98	8.6	18.59	9.7	50.80	83.8
TX	0.96	3.8	8.67	8.1	29.91	15.6	17.49	7.9	100.52	22.6
UT	0.64	6.8	4.60	8.5	10.16	10.3	22.81	13.7	0.08	67.3
VT	0.16	10.6	1.08	9.7	3.54	11.7	11.02	17.4	0.00	
VA	0.41	7.6	5.26	9.6	13.05	8.1	24.80	16.4	10.17	61.5
WA	1.05	2.6	5.98	2.1	21.78	3.0	139.59	2.0	35.27	50.2
WV	0.36	6.4	2.68	6.2	10.54	7.1	22.50	10.7	1.09	62.2
WI	0.36	7.2	4.04	6.2	9.49	8.4	17.95	9.0	1.21	77.1
Total	18.87		147.71		444.76		1185.72		396.73	

[a] Coastal Alaska.

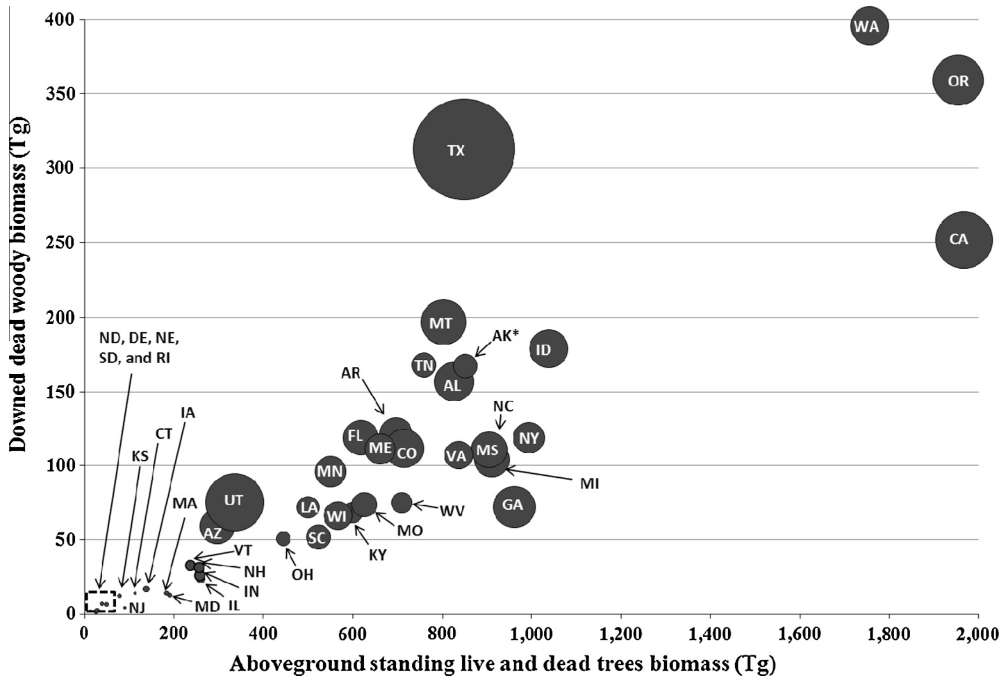

Fig. 2. Total down woody materials and standing tree (live and dead) biomass (Tg) by state with data points scaled to total forest land area in each state relative to all states, 2002–2010. (Note: Alaska is only southeastern coastal forests).

Rocky and west coast states (Washington, Coastal Alaska, Oregon, Montana, and Idaho) that have the highest CWD biomass density (>14 Mg/ha). The biomass density of piles was dominated by southern states (Tennessee, Alabama, Florida, and Texas) with estimates in excess of 7 Mg/ha. Divergences in CWD, FWD, and pile proportions of total DWM biomass become apparent when viewing biomass densities across distinct regions of the US (Fig. 3). Although regions such as the west coast and northern Rockies have some of the highest DWM biomass densities, they are primarily dominated by the CWD component. Although other regions of the eastern US may have less DWM biomass density, they differ in their proportion of other components constituting DWM. Eastern forests tended to have higher proportions of FWD while southeastern and south central forests have some of the highest proportions of piles.

The species diversity of DWM is most easily assessed by examining the attributes of CWD across the US (Note: decay class 5 CWD pieces cannot have their species identified thus are excluded from this assessment). When viewing the top 25 species in terms of total CWD biomass across the US, Douglas-fir (*Pseudotsuga menziesii*) dominates the list at 246 Tg (Table 3). Coarse woody pieces of unidentifiable species were second at 167 Tg nationally. Overall, western softwood tree species accounted for most of the top ten tree species (e.g., western hemlock, Lodgepole pine, ponderosa pine). Hardwood tree species that were in the top twenty were quaking aspen, sugar maple, northern red oak, and red maple. Nationally, CWD decay class distribution was dominated by pieces in moderate stages of decay with decay class 3 accounting for 692 Tg biomass, nearly twice that of its nearest competitor (decay class 2, 352 Tg). The large-end diameter distribution of CWD pieces was overwhelmingly dominated by relatively small-sizes (76% <57.62 cm). There are exceptions to these general national trends outside of the top 25 species. Redwood (*Sequoia sempervirens*) had 46% of its large-end diameters larger than 62.62 cm. When examining trends in CWD attributes among regions of the US, not only do west coast forests have some of the highest biomass densities of CWD, but they are also dominated by moderately decayed large sized pieces (Fig. 4). In contrast, the Plains and Great Lakes regions have moderate quantities of DWM biomass dominated by small-sized pieces. Differences in proportions of CWD biomass by decay class were less evident; however, southeastern CWD appeared to have the least amount of biomass in the freshest decay classes of 1 and 2.

Given the sparse sample intensity of the DWM inventory coupled with the infrequent occurrence of piles (i.e., high sample errors), piles were examined at a national scale by classes of pile volume (Table 4). Pile frequency (number per forest land area) is overwhelming dominated by small piles ($\leqslant 25\ m^3$) at a rate of approximately 0.6 piles per forest land hectare. Despite their rate of occurrence, the biomass and C content of these piles is minor averaging 1.7 and 0.9 Mg/ha nationally, respectively. The biomass and C content of piles does not constitute an appreciable amount when compared to other components such as standing live trees until volume exceeds $100\ m^3$ with C content averaging over 19 Mg/ha. Despite such a C stock, the frequency of such piles occurring is slightly above 0.01 per forest land hectare.

Trends among the live and detrital forest components in the context of selected stand and climate attributes were examined (Fig. 5a–c). As a stand's relative density (RD) of live trees increases, there are increases in total stand biomass (standing live/dead trees and DWM) from approximately 25 Mg/ha when RD was <0.1 to over 400 Mg/ha when RD was >0.9 (Fig. 5a). The proportion of DWM that constituted the total biomass in stands was highest (>0.35) when RD was <0.1. This proportion decreased sequentially across classes of RD until reaching <0.1 when RD was >0.9. Standing dead trees had a similar, although muted trend. The proportion of DWM or standing live/dead tree constituting total stand biomass did not appear to vary according to classes of average annual precipitation, although it appeared to influence total stand biomass from a mean of approximately 50 Mg/ha when average annual precipitation was <30 cm to a high of nearly 300 Mg/ha when precipitation was over 270 cm (Fig. 5b). The proportions of stand components constituting total stand biomass were irregular across classes of average annual maximum and minimum temperature

Table 2
Estimates of downed woody material biomass density (Mg/ha) and associated sampling errors (SE; percent) by component for all inventoried US states, 2001–2010.

State	Small FWD	SE	Medium FWD	SE	Large FWD	SE	CWD	SE	Residue pile	SE
AL	0.17	11.9	1.06	8.0	3.19	8.9	4.06	13.2	8.55	68.0
AK*	0.15	10.6	0.68	10.2	2.01	11.1	25.44	14.0	0.00	0.0
AZ	0.09	9.9	0.48	8.2	1.74	13.0	4.58	14.8	0.29	65.3
AR	0.11	6.0	1.04	6.2	3.65	6.8	4.59	13.4	6.20	99.3
CA	0.18	1.6	1.19	3.1	3.35	1.9	13.39	2.0	0.83	17.7
CO	0.16	6.4	0.83	5.8	2.70	8.1	8.23	9.3	0.18	101.9
CT	0.19	13.6	1.55	16.5	5.48	23.0	12.54	47.0	0.00	0.0
DE	0.14	9.2	1.15	10.8	3.07	13.5	5.51	16.8	0.76	106.3
FL	0.10	10.0	1.03	11.2	2.34	16.4	3.05	18.4	8.16	62.0
GA	0.13	6.0	1.12	7.9	2.99	17.2	2.15	11.0	0.71	42.9
ID	0.19	7.4	1.01	14.7	4.38	11.7	14.19	8.6	0.00	0.0
IL	0.14	12.0	2.29	25.9	3.65	12.3	6.09	14.0	0.00	0.0
IN	0.19	14.1	1.53	10.3	4.93	13.3	11.22	15.5	0.00	0.0
IA	0.09	10.4	1.33	13.0	2.68	17.9	9.13	18.3	0.00	0.0
KS	0.08	19.4	1.07	19.4	3.97	24.8	3.71	20.9	3.10	106.7
KY	0.11	10.5	1.16	12.3	4.40	13.4	7.32	13.1	0.31	76.2
LA	0.07	9.3	0.82	9.3	2.30	12.1	3.96	31.9	6.39	85.3
ME	0.22	4.6	1.34	4.7	4.10	5.1	9.79	7.2	0.01	101.6
MD	0.16	17.8	1.41	26.4	4.34	20.2	6.19	22.6	0.00	0.0
MA	0.22	18.8	1.44	15.5	3.86	15.3	6.37	19.6	0.00	0.0
MI	0.12	7.9	1.17	5.6	3.01	6.0	8.30	7.6	0.05	97.4
MN	0.13	6.7	1.12	5.4	2.53	8.0	8.52	7.6	1.07	66.0
MS	0.07	8.8	1.02	11.5	3.27	12.4	4.33	21.1	3.51	66.3
MO	0.13	15.1	1.22	5.5	3.46	7.3	7.09	13.4	0.12	112.9
MT	0.15	6.9	0.77	7.2	2.62	7.7	14.22	7.9	0.61	85.1
NE	0.09	31.5	1.09	37.8	3.87	35.5	4.49	42.4	0.00	0.0
NH	0.18	8.0	1.07	8.9	4.31	17.5	7.85	14.4	0.00	0.0
NJ	0.13	15.0	1.00	16.1	1.86	22.1	2.10	33.0	0.00	0.0
NY	0.27	9.0	1.62	6.9	4.48	6.2	9.18	7.5	0.67	64.6
NC	0.13	8.3	1.35	8.4	3.53	7.3	6.39	10.0	0.87	52.3
ND	0.09	27.0	1.44	26.7	4.09	28.0	3.38	54.6	0.00	0.0
OH	0.16	6.4	1.17	7.6	4.28	8.4	8.08	14.9	1.93	80.3
OK	0.11	18.4	1.22	31.8	3.34	29.9	4.50	42.3	4.30	61.5
OR	0.19	1.6	1.33	2.0	4.19	1.9	21.78	1.6	2.12	17.2
PA	0.16	9.3	1.51	14.7	4.51	11.8	8.88	10.3	2.03	61.7
RI	0.24	20.9	1.79	31.6	7.43	30.6	6.95	32.9	0.00	0.0
SC	0.09	6.7	0.77	11.1	3.00	8.3	3.34	13.1	2.03	62.5
SD	0.05	30.4	1.01	29.2	3.11	20.7	5.07	27.7	0.00	0.0
TN	0.13	12.9	1.39	10.5	3.83	8.3	6.47	9.6	17.51	83.9
TX	0.07	3.1	0.67	7.9	2.33	15.7	1.36	4.0	7.74	17.5
UT	0.15	5.8	1.11	7.4	2.45	9.7	5.34	13.4	0.02	68.2
VT	0.17	9.7	1.20	8.6	3.92	11.0	12.21	16.8	0.00	0.0
VA	0.12	6.9	1.60	9.3	3.97	7.7	7.56	16.2	3.06	61.4
WA	0.23	2.6	1.32	2.0	4.81	2.9	29.65	1.9	7.69	50.4
WV	0.15	5.9	1.10	5.7	4.33	6.5	9.37	10.3	0.44	60.6
WI	0.11	6.7	1.24	5.6	2.92	7.8	5.54	8.7	0.37	78.2
National	0.14		1.09		3.29		8.62		2.91	

Note: Alaska is only southeastern coastal forests.

(Fig. 5c). The proportion of standing dead tree biomass did appear to decrease gradually as both maximum and minimum temperatures increased. Total stand biomass and the proportions of live tree and DWM had no clear trends across classes of maximum and minimum temperature.

4. Discussion

Down woody materials are ubiquitous throughout the forests of the US with state/regional variations suggesting a complex interaction between ecological processes (e.g., Fraver et al., 2002), climate (e.g., Erickson et al., 1985), and management/disturbance (e.g., Klutsch et al., 2009) that shape their unique characteristics. Some regions may have endemic ecological processes that largely govern DWM attributes and dynamics such as the arid intermountain west where low stand productivity combined with frequent fire occurrences serve to reduce DWM quantities (Covington and Sackett, 1984). Other regions such as the Pacific Northwest may have unique climatic conditions (i.e., temperate rainforest of Olympic peninsula, Washington) that facilitate tremendous stores of DWM biomass/C (Busing and Fujimori, 2005) and concomitant lower wildfire occurrence where climate serves as a regulator of forest productivity (i.e., DWM accretion) and decay processes (i.e., DWM depletion). Still further, DWM dynamics may be predominantly governed by stochastic disturbance events (i.e., ice storms and wind throw events) and management activities in regions across the eastern US (Everham and Brokaw, 1996).

The amount and size of DWM across the Nation's forests was directly related to the amount and size of live tree biomass. Forests of the Pacific Northwest, for example, possess tremendous stocks of DWM C exceeding 100's of Tg in states such as Washington and Oregon, a result documented in past regional studies (Spies et al., 1988; Busing and Fujimori, 2005). The DWM C stocks within this region are dominated by abundant and relatively large CWD. Forests of the northern Rockies had stocks of DWM biomass/C nearly equivalent to those of the Pacific Northwest, but with FWD representing a greater proportion of total DWM. Fire can reduce the DWM biomass in these forests (Brown and See, 1981); however, the cold and/or dry environments of the northern Rockies may

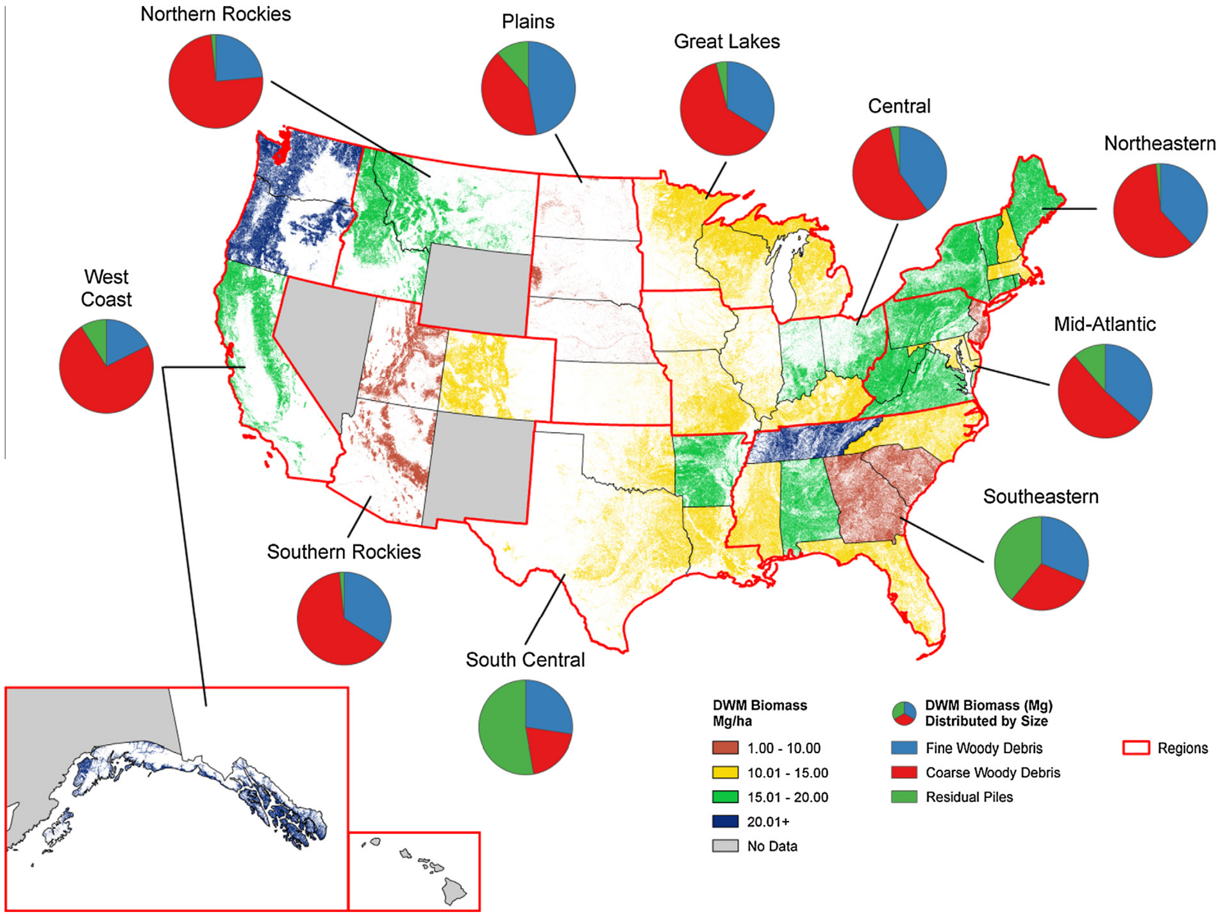

Fig. 3. Estimates of down woody material biomass density (Mg/ha) on forest land by state with the proportion (pie charts) of total DWM represented by fine woody debris, coarse woody debris, and piles by region of the US (outlined in red), 2002–2010. (Note: coastal Alaska is included in the West Coast region).

Table 3
Estimates of coarse woody debris biomass (Tg) by classes of decay and large-end diameter for top 25 tree species in the US by total national biomass, 2001–2010.

Species	Total biomass	Decay class				Large-end diameter class (cm)				
		One	Two	Three	Four[a]	⩽32.62	32.63–57.62	57.63–82.62	82.63–107.62	>107.62
Douglas fir	246.10	15.29	61.31	106.73	62.77	69.08	66.86	49.98	33.30	26.89
Unknown	166.69	0.26	0.61	6.78	5.42	66.50	53.61	24.37	10.11	12.10
Western hemlock	146.53	12.05	35.93	72.73	25.82	33.60	43.52	41.81	20.63	6.97
Lodgepole pine	111.96	7.70	42.89	45.54	15.82	79.23	27.28	4.12	1.04	0.29
Unknown hardwood	104.83	5.08	11.48	47.41	40.85	68.48	24.65	8.41	1.16	2.13
Unknown softwood	85.88	0.61	7.34	43.18	34.75	33.99	28.12	15.98	4.06	3.72
Ponderosa pine	80.84	10.68	21.95	37.40	10.81	31.05	25.89	14.54	5.32	4.04
Western red cedar	60.82	1.39	7.04	40.73	11.67	10.08	18.21	14.91	8.88	8.74
Subalpine fir	52.24	5.17	15.88	22.99	8.20	28.86	20.14	2.87	0.16	0.22
Quaking aspen	48.92	5.69	17.76	18.32	7.15	32.72	14.01	2.15	0.04	0.00
Loblolly pine	48.49	3.16	7.29	25.40	12.64	34.62	13.45	0.43	0.00	0.00
Sugar maple	48.09	4.84	14.44	23.88	4.94	28.39	15.10	3.92	0.68	0.00
Engelmann spruce	43.84	5.18	11.30	18.29	9.07	13.73	17.77	9.64	2.50	0.20
Northern red oak	42.55	7.87	11.93	20.40	2.34	20.19	19.79	2.57	0.00	0.00
Red maple	42.14	7.64	13.38	17.58	3.54	31.17	8.56	2.40	0.00	0.00
Oak spp.	36.53	0.00	6.73	22.94	6.86	21.85	12.51	2.17	0.00	0.00
White oak	33.59	8.89	7.81	14.64	2.25	19.18	11.39	3.02	0.00	0.00
Balsam fir	32.92	4.21	7.55	16.48	4.69	29.49	3.44	0.00	0.00	0.00
Black oak	32.44	4.49	4.24	22.22	1.50	18.35	12.16	1.93	0.00	0.00
Water oak	31.26	8.72	4.88	13.87	3.79	12.18	5.82	5.42	4.18	3.67
Grand fir	28.98	1.71	8.14	14.30	4.83	15.05	11.28	1.78	0.76	0.11
White fir	27.87	2.28	9.44	10.70	5.45	9.90	10.10	4.40	1.94	1.51
Virginia pine	22.94	1.12	4.55	11.72	5.55	18.01	4.46	0.48	0.00	0.00
Northern white-cedar	21.80	2.69	7.01	10.35	1.75	12.53	6.86	2.40	0.00	0.00
Sitka spruce	21.45	0.79	11.03	7.12	2.51	4.74	5.67	5.55	2.69	2.80
National	1619.70	127.51	351.91	691.70	294.97	742.97	480.65	225.25	97.45	73.39

[a] Species is not recorded for decay class five pieces (i.e., unknown), therefore the national estimate for the biomass of decay 5 pieces is 153.62 Tg.

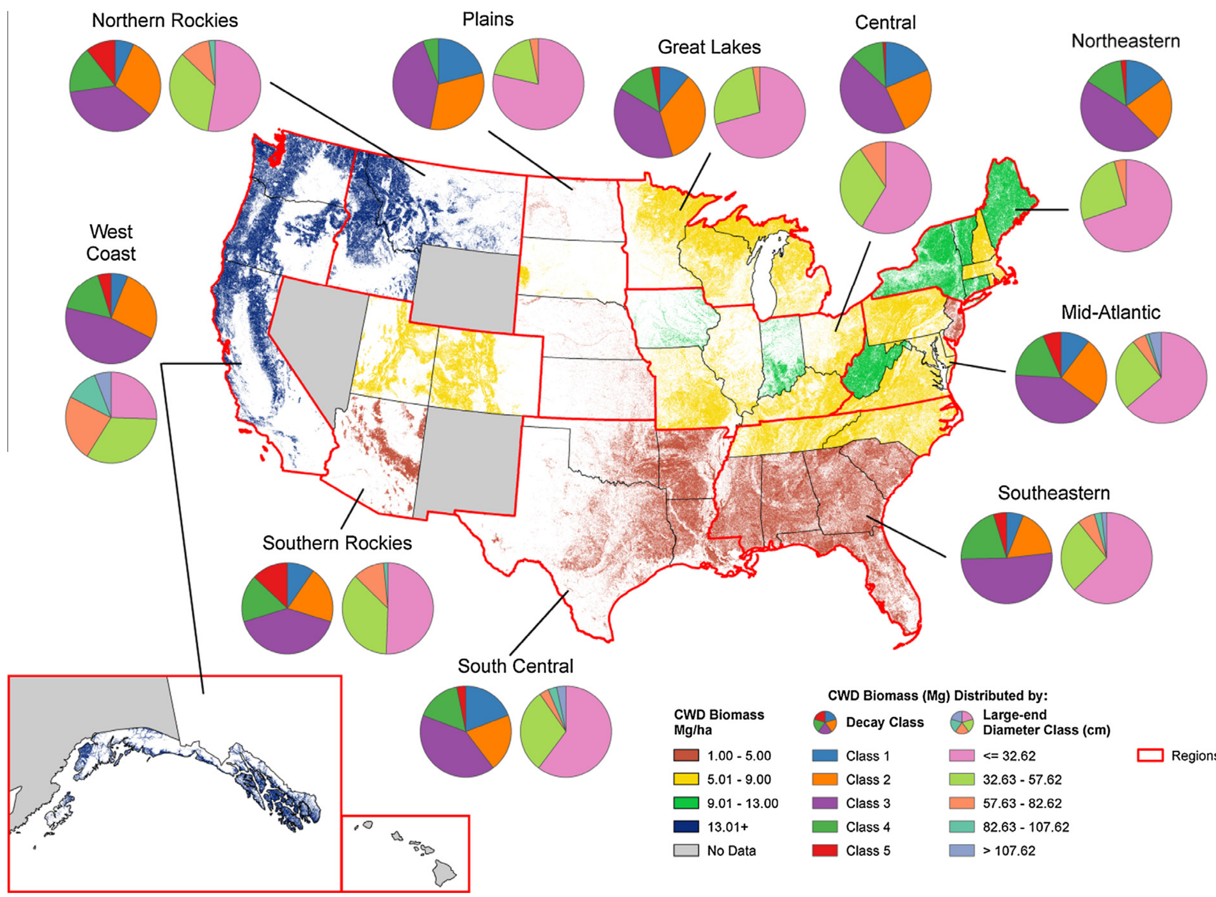

Fig. 4. Estimates of coarse woody material biomass density (Mg/ha) on forest land by state with the proportion (pie charts) of coarse woody debris total biomass represented by classes of decay and large-end diameter (cm) by region of the US (outlined in red), 2002–2010. (Note: coastal Alaska is included in the West Coast region).

Table 4
Estimates of mean biomass/carbon and frequency by classes of total pile volume, 2001–2010.

Volume class (m^3)	Dry biomass (Mg)	Carbon (Mg)	Frequency (# per forest land ha)	Frequency sampling error (%)
⩽25.0	1.718	0.869	0.622	1.705
25.1–50.0	11.685	5.913	0.029	5.569
50.1–100.0	20.906	10.578	0.010	8.186
100.1–150.0	38.331	19.395	0.013	8.088
>150.1	165.620	83.804	0.012	7.976

slow decomposition allowing CWD accumulation (Kueppers et al., 2004). Recent mortality in this region due to drought and beetle infestation (Klutsch et al., 2009) may be reflected in this study's estimates of DWM for this region. Forests of the Great Lakes and New England all appeared to have moderate amounts of DWM biomass/C balanced across DWM components. Due to the continental climate in this region (Woodall and Liknes, 2008a), slow decay rates perhaps alter the balance between fine and coarse woody debris (Woodall and Liknes, 2008b). Forest floor components were not examined in this study, although undoubtedly the gradual decay of DWM in this region adds to their substantial humic components (Woodall et al., 2012). Stochastic disturbances such as ice/wind storms can have a considerable effect on DWM components in this region (Everham and Brokaw, 1996; Woodall and Nagel, 2007); hence, large DWM biomass/C stocks might be found at local scales. The southern US had reduced amounts of DWM; however, they were more disproportionately represented by piles. The "timber basket" of the south (Hodges et al., 2012) with its concomitant levels of harvest activity most likely leads to less dispersed CWD (Carnus et al., 2006) with a higher occurrence of harvest residue piles. In states such as Alabama, the biomass/C in piles was almost twice that of all other DWM components. Despite the occurrence of piles in this region, it has been suggested that even-aged management may result in less options for DWM retention (Cimon-Morin et al., 2010) with piles typically containing small-diameter CWD pieces that rapidly decay (Fraver et al., 2002). Finally, forests of the southwestern US (e.g., Arizona and Utah) have some of the lowest quantities of DWM most likely owing to wildfire regimes (Covington and Sackett, 1984) and lower forest productivity (Erickson et al., 1985).

A surprising result of this study was the contribution of piles to DWM biomass/C stocks. Many examinations of DWM do not include piles as part of their population of interest. One exception, Heath and Chojnacky (2001) found piles to be a substantial component of the DWM population in Maine's timberlands. It appears that relatively small piles (<25 m^3) may occur at a moderate

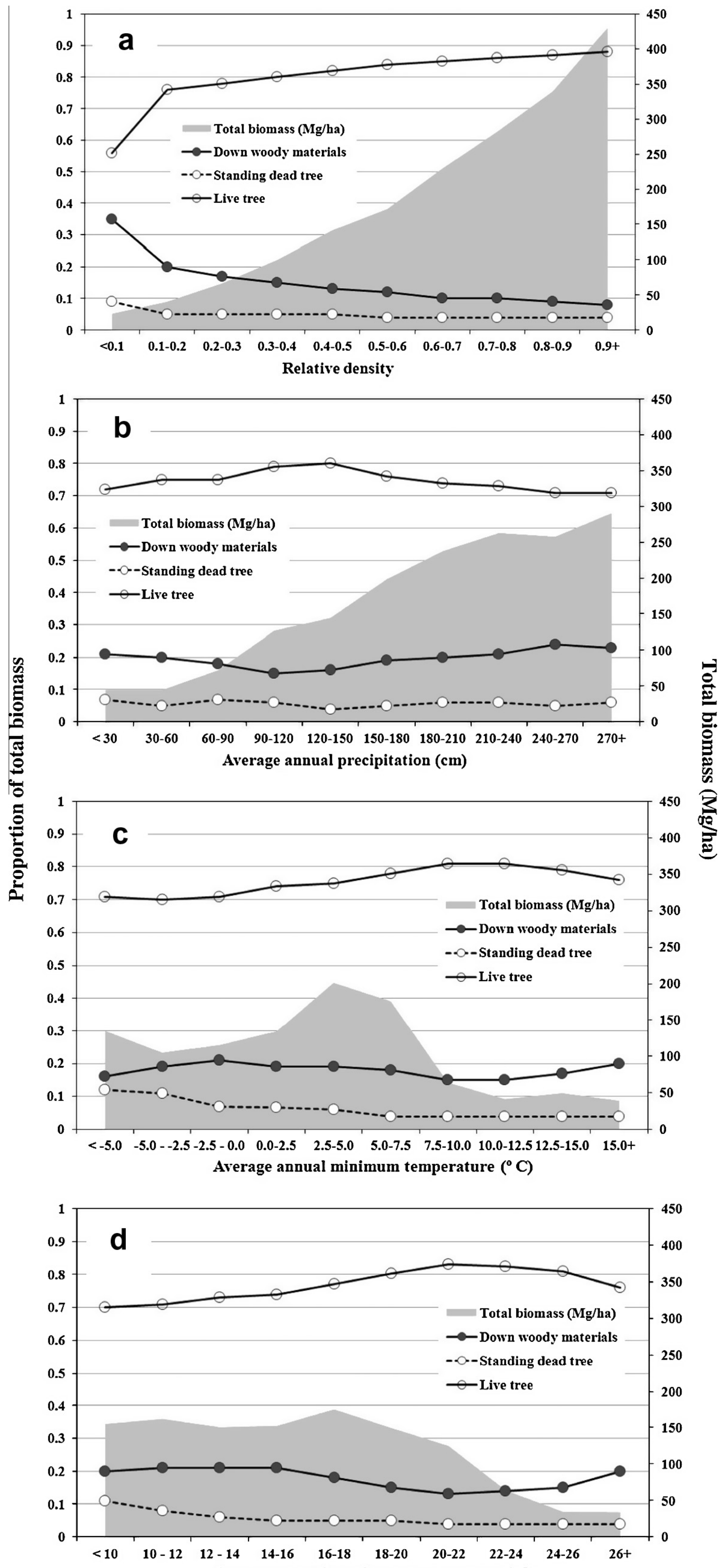

Fig. 5. Mean total biomass (downed dead and aboveground standing live/dead) and mean proportion of downed dead wood, aboveground live tree, and aboveground standing dead tree biomass as proportion of total biomass by classes of (a) relative density (Woodall et al., 2005), (b) average annual precipitation, (c) average annual minimum temperature, and (d) average annual maximum temperature.

frequency (0.5 per forest land ha) across the US, especially in actively managed forest lands. In some states such as Washington, there were infrequent but very large piles that resulted in tremendous population estimates owing to the relatively spare sample intensity of FIA's DWM inventory. Future examinations of CWD biomass/C attributes, especially in managed forest land areas, should consider the sampling of piles.

Given the costs associated with sampling DWM populations and the interest in refining understanding of forest stand biomass/C dynamics, numerous studies have sought to establish links between DWM and the more widely measured and understood standing tree and site attributes (Harmon et al., 1986; Sturtevant et al., 1997; Martin et al., 2005). If DWM attributes were closely correlated with stand/site attributes then traditional management/assessment activities could be more easily aligned with DWM management. It has been suggested that DWM accumulation, such as CWD over stages of stand development, is "U" shaped over time where stands have the most DWM when they are young or old (Harmon et al., 1986). The results of this study suggest that such a close correlation does not exist, especially for the numerous managed forests included in this comprehensive inventory. A hypothesis that mature forests highly stocked with living trees also have concomitant stocks of DWM biomass/C (Smith et al., 2006) could not be supported by the initial results of this study. At the national-scale the opposite was found, as a proportion of total stand biomass (standing live/dead and DWM), DWM constituted the largest proportion when the stand was least "stocked" with live trees. It should be noted that relative density was used as a surrogate for stocking (Woodall et al., 2005) which is largely independent of site quality and stand age. In absolute terms, perhaps fully-stocked mature forests (with self-thinning and concomitant understory re-initiation; Oliver and Larson, 1996) on highly productive sites with relatively slow decay rates may have the most DWM biomass/C. It can also be hypothesized that looking at a variety of stands across the US in unison (i.e., no single chronosequence) may obscure stand development dynamics (e.g., Taylor et al., 2007) thus reducing trends to large-scale fundamentals. However, the role of under-stocked and/or young forests in the maintenance of DWM should not be overlooked especially in light of the contribution of residue piles to DWM. Although climatic variables, in particular average annual precipitation, may govern live tree growth as evidenced by trends in total biomass (live and dead), there were no evident trends in standing dead or DWM biomass as a proportion of total biomass by precipitation or temperature. Perhaps climate equally affects live and dead biomass through growth/decay processes such that the proportion of each forest component is invariable across a variety of climates. Establishing correct paradigms in the standing live/dead and DWM matrix could transform and/or reduce the uncertainty associated with our modeling and forecasting of DWM components in the future.

Beyond examination of FIA's DWM estimates themselves, the estimates of DWM components can be refined through research into their sampling/estimation. Many assumptions are used to estimate FWD attributes such as initial wood density (i.e., species composition), decay reduction factor, and quadratic mean diameter. Initial exploration of potential improvements has yielded no definitive direction (Fasth et al., 2010). There is concern that approximating FWD quadratic mean diameter (Woodall and Monleon, 2010) could be underestimating small FWD biomass given the high variability in FWD biomass across small spatial scales (Keane et al., 2012). Piles of CWD are another DWM component that is difficult to efficiently sample. The visual assessment of the density of wood within subjectively delineated pile shapes, in concert with selection of wood density and decay attributes, is a substantial hurdle. The sampling of piles could benefit from increased sample intensity and/or refined field protocols as visual assessments of pile CWD content is difficult to repeat (Westfall and Woodall, 2007). Implementation of a national inventory of DWM has already facilitated development of new sampling and estimation techniques (e.g., FWD quadratic mean diameters, Woodall and Monleon, 2010), though more undoubtedly will emerge through a process of continuous refinement.

As this study serves as an introduction to the analysis of a publicly available dataset that took hundreds of field crew nearly a decade to sample, there are numerous opportunities to continue exploration of some of this study's findings. The role of DWM in forest ecosystem biomass/C dynamics is an emerging field (Evans and Finkral, 2009; Campbell et al., 2012) which could be illuminated by data such as presented in this study. Stratified estimates of empirically derived DWM components should inform assessments of forest biomass and greenhouse gas inventories at regional and national scales. It is hoped that the digital release of all field data and compiled plot/population estimates will facilitate research and the verification of a component of the US's National Greenhouse Gas Inventory (Domke et al. 2013). Data presented in this study also represent a significant step forward in providing comprehensive fuel loading information needed to support future fire management applications (Keane, 2012). Classification and mapping of fuel attributes are especially critical to fire management and research for simulating fire dynamics spatially, assessing risk, and estimating fire effects (Keane et al., 2001; Reinhardt et al., 2001; Reeves et al., 2009), but such efforts have been hindered in part by a lack of quality fuels data across all ecosystems of the USA (Lutes et al., 2009; Rollins, 2009). Since one of the first examinations of a nation's DWM resources (Fridman and Walheim, 2000), the breadth of interest has increased from biodiversity to include topics of interest to a wide breadth of the public (e.g., C stocks and bioenergy) where national DWM assessments may provide an objective starting point for policy/management discussions.

5. Conclusions

An inventory of the US's DWM in forest ecosystems suggests their ubiquitous presence with regional differences in DWM components (e.g., CWD and piles) attributable to ecosystem processes and management/disturbance events that are regionally unique. Initial estimates suggest DWM biomass/C is a larger component of total forest ecosystem aboveground biomass (standing live/dead and DWM) than standing dead trees, an attribute potentially invariant of climate. Continued research using this publicly available dataset, especially in concert with long-term research plots, may refine not only the sampling/estimation process itself, but also the role of DWM in forest ecosystems and larger questions regarding the management of forest DWM biomass/C resources.

Appendix A. Supplementary material

Presents FIA tables of DWM population estimates (core tables 60, 61, 62, 63, 64, 65) by forest type group for entire US. Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2013.05.030.

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