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Estimating Dead Wood During National Forest Inventories: A Review of Inventory Methodologies and Suggestions for Harmonization

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Abstract Efforts to assess forest ecosystem carbon stocks, biodiversity, and fire hazards have spurred the need for comprehensive assessments of forest ecosystem dead wood (DW) components around the world. Currently, information regarding the prevalence, status, and methods of DW inventories occurring in the world's forested landscapes is scattered. The goal of this study is to describe the status, DW components measured, sample methods employed, and DW component thresholds used by national forest inventories that currently inventory DW around the world. Study results indicate that most countries do not inventory forest DW. Globally, we estimate that about 13% of countries inventory DW using a diversity of sample methods and DW component definitions. A common feature among DW inventories was that most countries had only just begun DW inventories and employ very low sample intensities. There are major hurdles to harmonizing national forest inventories of DW: differences in population definitions, lack of clarity on sample protocols/estimation procedures, and sparse availability of inventory data/reports. Increasing database/estimation flexibility, developing common dimensional thresholds of DW components, publishing inventory procedures/protocols, releasing inventory data/reports to international peer review, and increasing communication (e.g., workshops) among countries inventorying DW are suggestions forwarded by this study to increase DW inventory harmonization.

Keywords Inventory · Standing dead wood · Downed dead wood · Harmonization · Forest

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Introduction

Dead Wood (DW) is typically defined as all non-living tree biomass (excluding duff and litter), including woody debris that is standing or lying along with stumps (FAO 2006). Although the definition of DW components varies around the world, they may be broadly assigned to the following individual components: standing dead trees, down dead wood (DDW), fine woody debris (FWD), stumps, and residue piles. The difference in DDW and FWD is a diameter threshold above which the larger downed and dead wood pieces are considered DDW, while the smaller downed dead wood pieces are considered FWD. Stumps can be broadly defined as standing dead trees where the majority of the bole has been removed. Finally, residue piles can be defined as an accumulation of downed, dead woody material assembled in a pile-like shape.

DW assessments are increasingly being included in national-scale forest inventories (NFI's) for three broad scientific pursuits: carbon accounting, forest fire risk assessment, and biodiversity assessment. Carbon sequestration is becoming an increasingly important estimate derived from NFI's because it is possible to store carbon in biomass, soil, and dead organic matter (dead wood and litter) to mitigate climate change (Brown and others 1996a, 1996b; Goodale and others 2002; IPCC 2003). In 1992, 150 countries signed the United Nations Framework Convention on Climate Change that requires annual reports of greenhouse gas inventories, including C in forests. In 2006, approximately 11 percent of all greenhouse gas emissions in the United States were sequestered annually in forests and forest products (Smith and others 2004; US EPA 2006). In the U.S., 35 percent of the total forest C pool is in live vegetation, 52 percent in the soil, and 14 percent in dead organic material (excluding fine woody debris) (Heath and others 2003). Therefore, accurately estimating baseline forest DW carbon stocks and monitoring stock changes over time is essential especially in the face of climate change (Woodall and Liknes 2008). Even so, estimates of DW have been omitted from some large-scale C assessments (Goodale and others 2002; Woodall and others 2008) due to the lack of sufficient inventory data.

Concerns over the increase of forest fire occurrences at national scales have brought attention to the critical role that DW plays in large-scale fire hazards. Estimates of DW are integral to numerous fire behavior models (for examples see Albini 1976; Burgan and Rothermel 1984; Finney 1998; Reinhardt and others 1997; Rothermel 1972). Dead wood NFI's can be used to estimate fuel loads and fire dangers at national scales (for example see Woodall and others 2005).

Dead wood components, such as standing dead and DDW, increase a forest's structural heterogeneity and serve as critical habitat for numerous flora and fauna (Lonsdale and others 2008). Flora use the microclimate of moisture, shade, and nutrients provided by DDW to establish regeneration (Harmon and others 1986). Both standing and DDW provide a diversity (e.g., stages of decay, size classes, and species) of habitat for fauna (ranging from large mammals to invertebrates) (Bull and others 1997; Heilmann-Clausen and Christensen 2005; Harmon and others 1986; Maser and others 1979; Siitonen 2001). Due to the possibility of dwindling habitat for many native species across many countries, inventories of DW are important for habitat assessments and wildlife conservation efforts (for examples see Ohmann and Waddell 2002; Tietje and others 2002). Volume of standing and DDW has also been adopted as a pan-European indicator for sustainable forest management related to forest biodiversity (MCPFE 2002). Due to the importance of assessing forest sustainability/diversity indicators at scales exceeding the political boundary's of countries, efforts have recently emerged to "harmonize" NFI's (McRoberts and others 2009). The effort of "harmonizing" NFI's includes finding common ground among a wide array countries on measurement variable definitions, estimation procedures, and forest health indicators. The identification of countries inventorying DW and comparison of their DW sample methods has been largely unexplored at a global scale, but could provide a basis for future inventory harmonization efforts among countries.

Given the importance of DW NFI's, the goal of this article is to broadly describe the current DW NFI methods used around the world and suggest opportunities for harmonization. Specific goals include: (1) to describe the current status (e.g., year of first inventory, number of plots/transects, publicly available data) of DW NFI's, (2) to describe the attributes of inventoried DW components (e.g., standing dead trees or FWD) in current DW NFI's, (3) to briefly describe the DW sample techniques (e.g., fixed area plots or line-intersect transects) used in NFI's, and (4) to suggest opportunities for international harmonization of DW NFI's.

Survey Methods

A DW inventory questionnaire was developed and sent to a selection of countries in 2006. The questionnaire consisted of 21 questions in spreadsheet format grouped into four sections: (1) current status of inventory, (2) DW components inventoried, (3) inventory methods, and (4) DW component attribute thresholds (e.g., FWD maximum diameter) (Fig. 1). In an attempt to increase survey participation, the survey questions were brief with opportunities for respondents to insert their own comments. Additionally, a completed survey for the United States was developed and included in the questionnaire packet as an example for other countries.

At the onset of this study, it was postulated that attempting to identify a national DW inventory expert in over 200 countries was impractical. Therefore, countries were grouped according to their likelihood of having a DW survey based on expert knowledge (Table 1). A guiding principle of this grouping was that countries with nationwide forest inventories were likely to have DW inventories, whereas countries lacking national forest inventories were unlikely. Furthermore, only a subset of all nations unlikely to have a DW inventory were surveyed. Contacts for each country were based on advice from forestry colleagues and a list of participants in the FAO's Global Forest Resource Assessment (FAO 2006). The response rate for countries likely to have a DW inventory was 85 percent. For countries unlikely to have a DW inventory, they were not only queried for their country's DW inventory prospects, but were also asked to forward any information they may have

National Forest Inventory Dead Wood Inventory Methods Survey
Respondee: Please try to fill out the following fields to the best of your ability. Please add comments as necessary to clarify your responses, refer to example sheet for United States.

Current Status of your National Dead Wood Inventory
Year national inventory began?
Number of plots sampled?
Frequency of remeasurement?
Is data publicly available?
National analysis/report produced?
Comments:

Dead Wood Components Measured
Standing dead trees
Down and dead trees
Stumps
Logging residue piles
Fine woody debris (diameter < 7 cm)
Comments:

Dead Wood Sample Methods by component
Standing dead trees
Down and dead trees
Stumps
Logging residue piles
Fine woody debris (diameter < 7 cm)
Comments:

Dimension Thresholds
Standing dead trees
Down and dead trees
Stumps
Logging residue piles
Fine woody debris (diameter < 7 cm)
Number of DDW decay classes
Comments:

Fig. 1 Example dead wood inventory questionnaire

had regarding DW inventories in other countries within their region/continent. The response rate of "unlikely" countries was 15 percent with only one indicating a basic DW inventory. A total of 65 countries were contacted across "likely" and "unlikely" categories. The most difficult component of the survey was handling non-responses. Because only one country out of 27 within the "unlikely" category indicated having conducted a DW survey, it was assumed that the overwhelming majority of non-respondents and the remaining non-surveyed countries do not conduct DW inventories. Therefore, despite the best attempts by the authors to accurately estimate the prevalence of DW sampling around the world, the results of this study's survey most likely underestimate the intensity of global DW sampling.

All submitted surveys were summarized broadly such that individual countries were not identified as promised to some individual respondents to increase survey participation. For the purposes of this study, DW was defined as dead wood that was standing or downed including all sizes. Because many countries define individual DW components (e.g., DDW and FWD) with varying definitions, for the purposes of this study FWD was defined as downed and dead woody debris with a diameter less than 7 cm as a starting point for the survey. The relatively broad and inclusive definitions of DW components allowed questionnaire respondents to provide their own definition for the purposes of this study's survey.

Table 1 Countries contacted and responses to DW inventory questionnaire grouped by likelihood; countries that were unlikely to have a DW inventory were asked to identify any other countries in their region that might have a DW inventory

Likely		Unlikely/regional contact	
Country	Responded	Country	Responded
Albania	No	Argentina	Yes
Australia	Yes	Bahamas	No
Austria	Yes	Brazil	Yes
Belarus	Yes	Chile	No
Belgium	Yes	China	No
Bosnia and Herzegovina	Yes	Croatia	No
Britain	Yes	Fiji	No
Bulgaria	No	Guatemala	No
Canada	Yes	Iceland	No
Czech Republic	Yes	India	No
Denmark	No	Indonesia	No
Estonia	Yes	Israel	Yes
Finland	Yes	Japan	No
France	Yes	Jordan	No
Germany	Yes	Macedonia	No
Greece	Yes	Mexico	Yes
Hungary	Yes	Moldova	No
Ireland	No	Myanmar	No
Italy	Yes	Nepal	No
Latvia	Yes	Pakistan	No
Lithuania	Yes	Saudi Arabia	No
Luxembourg	Yes	Seychelles	No
Netherlands	Yes	South Korea	No
New Zealand	Yes	Turkey	No
Norway	Yes	Venezuela	No
Poland	Yes	Vietnam	No
Romania	Yes	Zimbabwe	No
Portugal	No		
Russia	Yes		
Serbia	Yes		
Slovakia	Yes		
Slovenia	No		
Spain	Yes		
Sweden	Yes		
Switzerland	Yes		
Ukraine	Yes		
United Kingdom	Yes		
United States	Yes		

The lack of response from individual countries does not denote an unwillingness to participate, rather it may be due to language barriers or incorrect mailings

Results

Current Status of Dead Wood National Inventories

This survey identified only 30 countries that currently inventory DW, albeit this study's questionnaire was only sent to 66 out of the world's 229 countries (FAO 2006). This represents only 13 percent of the world's countries (FAO 2006), yet these countries possess over 41 percent of the world's forest land area. Given the non-response of many countries, these proportions should be considered a conservative underestimate. Of countries that responded to the survey and indicated an active DW inventory program, DW inventories were described as relatively recent phenomenon (Fig. 2a). Over 77 percent of DW inventories identified in this study were initiated since 2000. The sample intensity (number of forested hectares in any country divided by the number of DW inventory plots) varied widely with most countries having an intensity greater than one plot per 10,000 forested ha (Fig. 2b). Almost all countries had an interval between plot remeasurement less than or equal to 10 years (Fig. 2c). Approximately 80 percent of countries have not publicly released their DW inventory data, while nearly 87 percent have not summarized the inventory in an official report focused on DW resources. Overall, it appears that the majority of the world's forests are not inventoried for DW. In almost all countries where there is a history of forest inventories (e.g., Austria, Finland, Russia and Sweden), DW is inventoried. There is quite a range of analysis, dissemination, and review of DW inventories. For some countries, such as Switzerland and the United States (Böhl and Brändli 2007; Woodall and Monleon 2008), there is an abundant amount of information regarding domestic DW inventories. In contrast, there are a number of countries around the world with a lack of publicly available DW inventory data and summary reports.

Dead Wood Components Measured in National Forest Inventories

Almost all countries that had a DW inventory compiled information on both standing dead and down dead trees (e.g., fine woody debris). Of countries that had a DW inventory, 60 percent inventoried stumps, 73 percent inventoried residue piles, and 47 percent inventoried FWD (Fig. 3a,b). Almost all countries measured the species and decay class of DW. Notably, 68 percent of countries had a four or five decay class rating system for DW. Overall, it appears that most DW inventories sample DDW, standing dead, stumps, and residue piles. Only a minority of countries with a DW inventory sampled FWD. The lack of FWD inventories may due to: being inventoried as part of

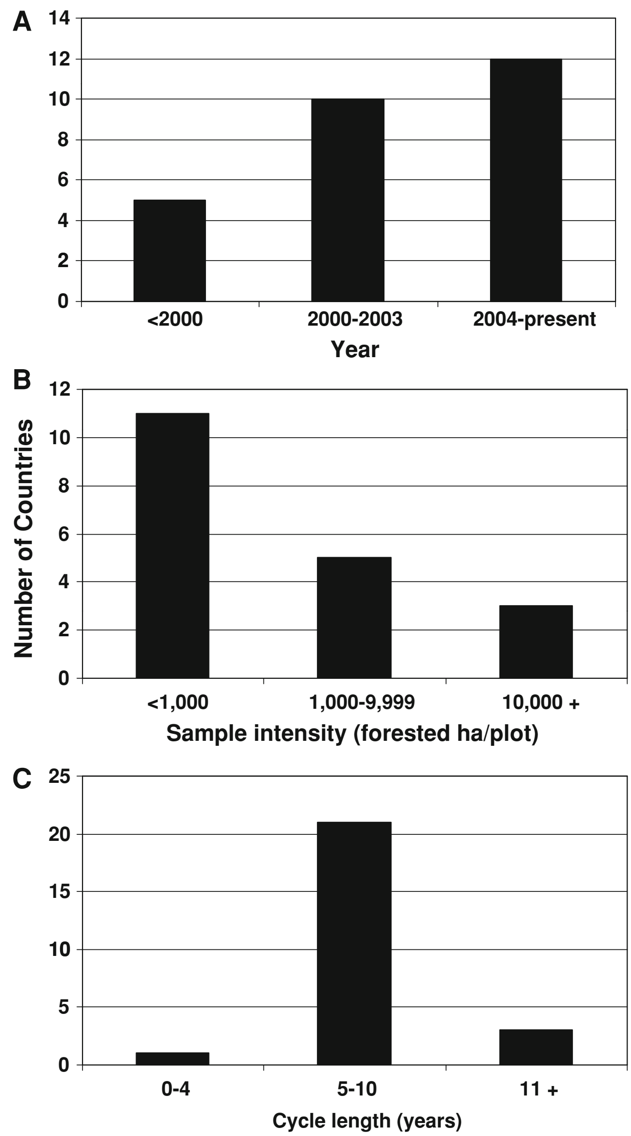

Fig. 2 Dead wood inventory attributes by number of survey respondents that conduct dead wood inventories **a** start date of last dead wood inventory cycle, **b** dead wood inventory sample intensity, and **c** dead wood inventory cycle length

the forest floor, its minor contribution to total forest biomass, and/or its cost/benefit ratio being relatively high.

Dead Wood Sample Methods and Attribute Thresholds

Almost all countries used fixed-area plots for inventorying standing dead trees, but sample methods for downed DW were more varied (Fig. 4). Sixty three percent of countries used fixed-area plots for DDW and 19 percent used line-intersect sampling. The remainder of countries used variable-radius plots or ocular estimation (i.e., expert observation/classification). The sample technique for FWD was evenly split between fixed-area plots (quadrat or fixed-

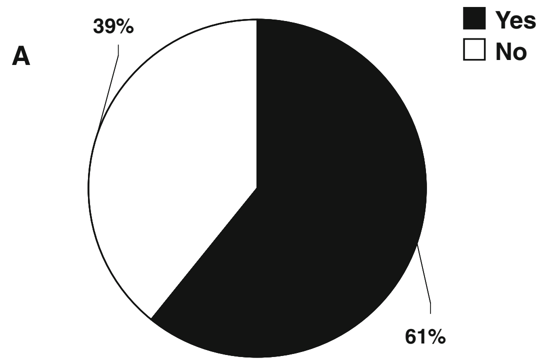

Fig. 3 Percentages of countries inventorying **a** stumps, **b** residue/slash piles, or **c** fine woody debris if the country conducts a standing dead or downed dead wood inventory

radius) and line-intersect sampling. At the country-level, fixed-area plots were the most common DW inventory method, irregardless of DW component. However, in terms of global forestland area, nearly 16 percent of the world's forest DDW are inventoried using line-intersect sampling techniques. In contrast, only approximately 3 percent of the world's forest DDW are inventoried using fixed-area plots. It appears that in countries with relatively large expanses of forest area and where DW fuels pose substantial fire hazards (e.g., Canada and the United States) line-intersect sampling is the method of choice.

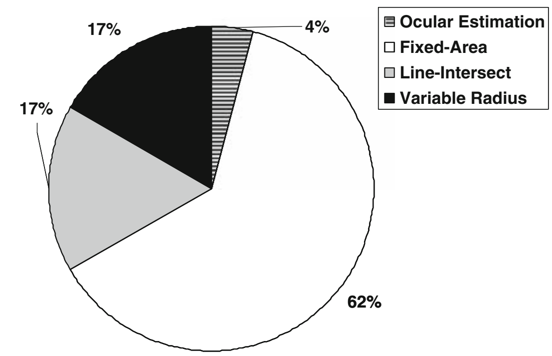

Fig. 4 Dead wood sampling techniques by survey respondents that conduct dead wood inventories

The definitions of DW variables, predominantly defined by measurement thresholds, varied among countries that inventory DW. Common minimum diameters at breast height for standing dead trees were 5, 7, 10, and 12 cm (Fig. 5a). A minimum diameter of 10 cm was the most common minimum diameter at 19 percent of all countries. For DDW, 33 percent of countries inventoried DDW with a minimum diameter of 7 or 7.6 cm (Fig. 5b). However, 10 cm was still a frequent minimum diameter with 27 percent of countries utilizing that threshold. The threshold of 7 or 7.6 cm relates to a common break point between FWD and DDW. A diameter of 7.6 cm is close to the English measurement unit of 3 inches, which is used to differentiate between fine and heavy fuels in fuel and fire behavior models (Deeming and others 1977). For countries that had dimensional thresholds for inventorying standing and dead downed trees, minimum heights/lengths were overwhelmingly (>70 percent) either 1 or 1.3 meters. Dimensional thresholds for stumps were the most varied with minimum diameters appearing to be larger than for the standing and downed dead trees (Fig. 5c). Some countries that had a minimum diameter of 12 cm for standing dead trees had a minimum stump diameter of 30 cm. This result could indicate that since stumps contain less biomass per cm of diameter than standing dead trees, a larger stump diameter is needed to justify the effort to measure it. Most countries (53 percent) did not inventory FWD or even define it as a separate component of DW. As mentioned previously, the minimum diameter for DDW often defines the maximum diameter for FWD. Thus, 7 and 7.6 cm was the most common maximum diameter for FWD. Just a few countries specified minimum diameters for FWD, often 1.5 or 2.5 cm. Overall, the thresholds for DW components appear in most cases to be based on the relationship between sampling efficiency and the relative contribution of the DW component to overall stand biomass. Because standing dead trees are both a major contributor to stand biomass and can be sampled efficiently, the population

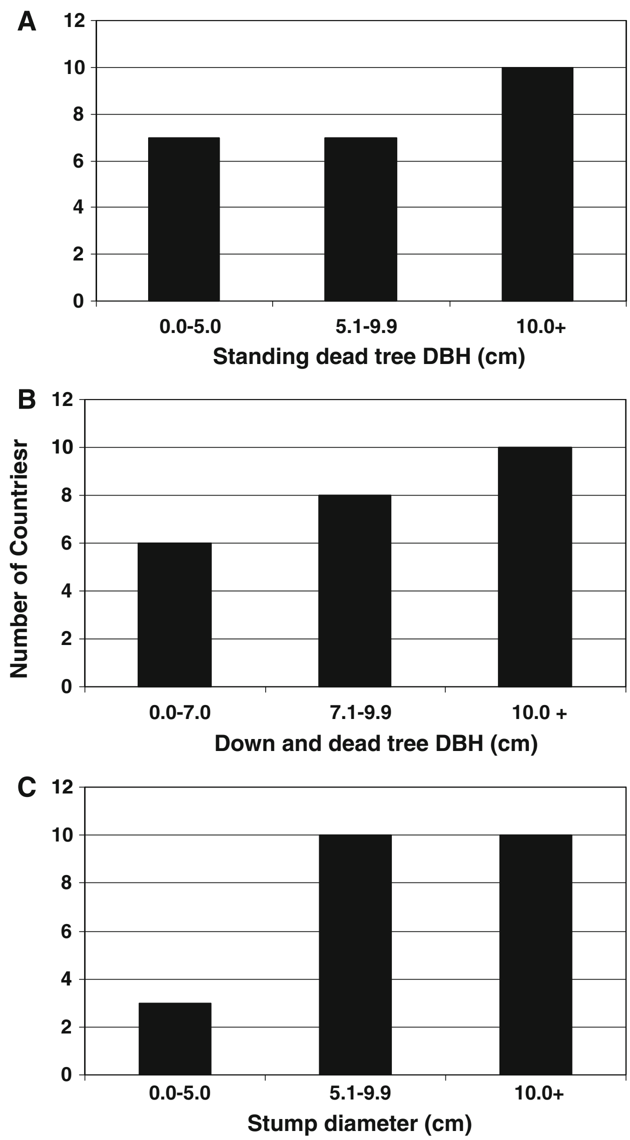

Fig. 5 Minimum diameter thresholds for **a** standing dead wood, **b** down dead wood (including all sizes of woody debris), and **c** stumps by number of survey respondents that conduct dead wood inventories

definition was the most inclusive (i.e., smallest minimum diameter). In contrast, either FWD was often not measured or its population was narrowly defined.

Discussion

It must be acknowledged that assumptions were made with this study's survey design such that non-response countries were assumed to have no DW inventory. It is felt that the benefits gained from globally examining DW resource inventories exceed any possible bias from this study's assumptions. Caveats aside, this study found numerous similarities among DW NFI's. First, standing dead and downed trees are often measured in unison. Rarely does a country inventory standing dead trees, but not downed trees. However, nearly all countries do not measure standing DW limbs and/or coarse roots (a substantial contributor to dead wood carbon pools). Some countries have found the difficulties in measuring coarse roots to be ameliorated through modeling efforts using broad stand attributes (e.g., stand age and forest type) (Smith and others 2004). The modeling of coarse roots might be ameliorated through the addition of DW measurement variables such as standing dead wood decay class or diameter. Second, the size, species, and decay class of dead trees are ubiquitously measured. Most countries recognize the need to measure these parameters in order to more accurately estimate dead tree attributes such as volume, biomass, or carbon. Third, most countries have only recently started inventorying DW. This phenomenon can be most likely attributed to the relatively recent focus on national forest carbon stocks and indicators of biodiversity related to international agreements (e.g., Kyoto Protocol, the Montreal Process, Ministerial Conference on the Protection of Forests in Europe) and their requirements on reporting DW for greenhouse gas emissions and biodiversity. Fourth, fixed-radius sampling techniques were the most common technique for inventories of both standing and downed dead trees. Fixed-radius techniques were most likely adopted as efficient/logical extensions of fixed-radius techniques commonly used to inventory standing live trees. Fifth, most countries conducting DW inventories have neither publicly released their data nor summarized findings in a national report. These DW inventories are a recent activity for many countries, so it is likely that datasets are not complete and/or analytical expertise has not yet been developed. Finally, the remeasurement periods for DW NFI's is almost always 10 years or less, indicating the intention of countries to maintain DW resource monitoring.

Despite the broad similarities among countries that inventory DW, even slight differences can cause problems with combining and comparing estimates in a regional/global context such as those required by global greenhouse gas offset accounting programs. The most prominent difference that can inhibit DW estimate comparison among countries is that of DW component population definitions. If countries use separate minimum diameters for either standing or downed dead trees then their resulting estimates are for different populations. There are at least two solutions: common thresholds and database/estimation flexibility. Another apparent discrepancy was that of the number of DW components measured. Not all countries that inventory standing and downed dead trees also inventory stumps, residue piles, or FWD. Thus, national DW estimates may be incomparable. Total DW resource estimates may only be compared if the same DW components are measured or a common reporting framework is explicitly defined. The inherent nature of DW resources is that of decay and transition from standing dead, to DDW, to soil organic matter. Not only are dimensional thresholds (i.e., minimum diameter) important to define DW populations, defining the transition from standing dead to downed dead is important as well, for example: how close to horizontal does a standing dead tree need to lean to be considered a downed dead tree? Another component to DW resource estimation that hinders cross-country compilation is DW volume/biomass/carbon equations. There is a dearth of adequately validated and documented methods for converting DW diameter measurements into biomass/carbon estimates (Woodall and others 2008; Harmon and others 2008; Sandström and others 2007). Finally, the force that may be driving DW inventories in different directions is the diversity of user groups demanding DW inventory information. For some countries, the main purpose of a DW inventory may be to assess fuel loadings, while in other countries it may be carbon accounting or biodiversity assessment. If inventory sample protocols are a reflection of inventory objectives, then the diversity of DW sample protocols reflects diversity in budgetary constraints and inventory objectives.

Forest DW inventories have expanded tremendously around the world during the past decade. Although there are numerous similarities that bespeak a basis on ecological fundamentals (e.g., DW components of standing dead and DDW) and extensions of historic standing live tree inventories (e.g., fixed-radius sample protocols), it is the inventory details that confound attempts to efficiently compare and combine DW resource estimates among countries. We feel that differences in sample intensity, remeasurement period length, or sample technique (e.g., fixed-radius or line intersect) are not the major culprits in restricting global assessments. Almost all countries with DW inventories based the inventory design on generally accepted sample techniques. It is the differences in population definitions, lack of sample protocol/estimation procedure clarity, and sparse availability of comprehensive inventory data/reports that are the largest hurdles to harmonization of DW NFI's. Possible solutions to these problems include: (1) increasing database/estimation flexibility to accommodate varying population definitions, (2) developing common dimensional thresholds of DW components, (3) publishing inventory procedures/protocols (many countries may post information on the web, but less officially publish this information in English), (4) releasing inventory data/reports to international peer review, and (5) increasing communication (e.g., workshops or initiatives such as COST Action E43 in Europe) among countries inventorying DW. Given the substantial progress with DW inventories during the past years, there is little doubt that, with more effort/communication, these inventories may be more closely harmonized in the future.

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References

Albini FA (1976) Estimating wildfire behavior and effects. Gen. Tech. Rep. INT-30. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, p 92

Böhl J, Brändli UB (2007) Deadwood volume assessment in the third Swiss National Forest Inventory: methods and first results. European Journal of Forest Research 126:449–457

Brown S, Sathaye J, Cannell M (1996a) Management of forests for mitigation of greenhouse gas emissions. In: Watson RT, Zinyowera MC, Moss RH (eds) Impacts, adaptation and mitigation of climate change: scientific-technical analyses. Contribution of WG II to the Second Assessment Report of the IPCC. Cambridge University Press, Cambridge, pp 773–797

Brown S, Sathaye J, Cannell M, Kauppi PE (1996b) Mitigation of carbon emssions to the atmosphere by forest management. Commonwealth Forestry Review 75:80–91

Bull EL, Parks CG, Torgersen TR (1997) Trees and logs important to wildlife in the Interior Columbia River Basin. Gen. Tech. Rep. PNW-391. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, p 55

Burgan RE, Rothermel RC (1984) BEHAVE: fire behavior prediction and fuel modeling system—FUEL subsystem. Gen. Tech. Rep. INT-167. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, p 126

Deeming JE, Burgan RE, Cohen JD (1977) The national fire-danger rating system. Res. Pap. INT-226. USDA Forest Service. Intermountain Forest and Range Experiment Station, Ogden, UT. p 17

FAO (2006) Global Forest Resources Assessment, 2005. Food and Agricultural Organization of the United Nations. Forestry Paper, Rome, Italy, p 147

Finney MA (1998) FARSITE: fire area simulator—model development and evaluation. Res. Pap. RMRS-RP-4. Fort Collins, CO U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, p 47

Goodale CL, Apps MJ, Birdsey RA, Field CB, Heath LS, Houghton RA, Jenkins JC, Kohlmaier GH, Kurz WA, Liu S, Nabuurs GJ, Nilsson S, Shvidenko AZ (2002) Forest carbon sinks in the northern hemisphere. Ecological Applications 12:891–899

Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR, Lienkaemper GW, Cromack K Jr, Cummins KW (1986) Ecology of coarse woody debris in temperate ecosystems. Advanced Ecology Research 15:133–302

Harmon ME, Woodall CW, Fasth B, Sexton J (2008) Woody detritus density and density reduction factors for tree species in the United States: a synthesis. USDA Forest Service, Gen. Tech. Rep. 29, Northern Research Station, p 65

Heath LS, Smith JE, Birdsey RA (2003) Carbon trends in U.S. forest lands: a context for the role of soils in forest carbon sequestration. In: Kimble JM, Heath LS, Birdsey RA, Lal R (eds) The potential of US forest soils to sequester carbon and mitigate the Greenhouse effect. CRC Press LLC, Boca Raton, FL, pp 35–45

Heilmann-Clausen J, Christensen M (2005) Wood-inhabiting macrofungi in Danish beech-forests—conflicting diversity patterns and their implications in a conservation perspective. Biological Conservation 122:633–642

IPCC (2003) Good practice guidance for land use, land-use change and forestry. IPCC national greenhouse gas inventories programme. Institute for Global Environmental strategies for the IPCC, Hayama, Kanagawa

Lonsdale D, Pautasso M, Holdenrieder O (2008) Wood-decaying fungi in the forest: conservation needs and management options. European Journal of Forest Research 127:1–22

Maser C, Anderson RG, Cromack Jr K, Williams JT, Martin RE (1979) Dead and down woody material. In: Thomas JW (ed) Wildlife habitats in managed forests: the Blue Mountains of Oregon and Washington. Agric. Handb. 553. U.S. Department of Agriculture, Forest Service, Washington, DC, pp 78–95

MCPFE (2002) Improved pan-European indicators for sustainable forest management as adopted by the MCPFE expert level meeting 7–8 October 2002, Ministerial Conference on the Protection of Forests in Europe, Liaison Unit Vienna, Vienna, Austria

McRoberts RE, Tomppo E, Schadauer K, Vidal C, Göran G, Chirici G, Lanz A, Cienciala E, Winter S, Smith WB (2009) Harmonizing national forest inventories. Journal of Forestry 107:179–187

Ohmann JL, Waddell KL (2002) Regional patterns of dead wood in forested habitat of Oregon and Washington. In: Laudenslayer, WFG Jr, Shea PJ, Valentine BE, Weatherspoon CP, Lisle TE (eds) Proceedings of the symposium on the ecology and management of dead wood in western forests. 1999 November 2–4; Reno, NV. Gen. Tech. Rep. PSW-GTR-181. Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture, Albany, CA

Reinhardt ED, Keane RE, Brown JK (1997) First order fire effects model: FOFEM 4.0, user's guide. Gen. Tech. Rep. INT-344. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, p 65

Rothermel RC (1972) A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, p 40

Sandström F, Petersson H, Kruys N, Stahl G (2007) Biomass conversion factors (density and carbon concentration) by decay classes for dead wood of *Pinus sylvestris*, *Picea abies* and *Betula spp.* in boreal forests of Sweden. Forest Ecology and Management 243:19–27

Siitonen J (2001) Forest management, coarse woody debris and saproxylic organisms: Fennoscandian boreal forests as an example. Ecological Bulletins 49:11–41

Smith JE, Heath LS, Woodbury PB (2004) Forest carbon sequestration and products storage. In: U.S. Agriculture and Forestry Greenhouse Gas Inventory, Tech. Bull. 1907. Global Change Program Office, Office of the Chief Economist, U.S. Department of Agriculture, pp 80–93

Tietje WD, Waddell KL, Vreeland JK, Bolsinger CL (2002) Coarse woody debris in oak woodlands of California. Western Journal of Applied Forestry 17:139–146

US EPA (2006) Inventory of U.S. Greenhouse gas emissions and sinks: 1990–2004. EPA 430-R-06-002. Available at http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublications GHGEmissionsUSEmissionsInventory2006.html (13 June 2006)

Woodall CW, Liknes GC (2008) Relationships between forest fine and coarse woody debris carbon stocks across latitudinal gradients in the United States as an indicator of climate change effects. Ecological Indicators 8:686–690

Woodall CW, Monleon VJ (2008) Sampling protocols, estimation procedures, and analytical guidelines for down woody materials indicator of the Forest Inventory and Analysis Program, 2nd edn. USDA Forest Service, Gen. Tech . Rep. 22, Northern Research Station, p 68

Woodall CW, Charney JJ, Liknes GC, Potter BE (2005) What is the fire danger now? Linking fuel inventories with atmospheric data. Journal of Forestry 103:293–298

Woodall CW, Heath LS, Smith JE (2008) National inventories of dead and downed forest carbon stocks in the United States: opportunities and challenges. Forest Ecology and Management 256:221–228