Assessing Deadwood Using Harmonized National Forest Inventory Data

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Abstract: Deadwood plays an important role in forest ecological processes and is fundamental for the maintenance of biological diversity. Further, it is a forest carbon pool whose assessment must be reported for international agreements dealing with protection and forest management sustainability. Despite wide agreement on deadwood monitoring by national forest inventories (NFIs), much work is still necessary to clarify definitions so that estimates can be directly compared or aggregated for international reporting. There is an urgent need for an international consensus on definitions and agreement on harmonization methods. The study addresses two main objectives: to analyze the feasibility of harmonization procedures for deadwood estimates and to evaluate the impact of the harmonization process based on different definitions on final deadwood estimates. Results are reported for an experimental harmonization test using NFI deadwood data from 9,208 sample plots measured in nine European countries and the United States. Harmonization methods were investigated for volume by spatial position (lying or standing), decay classes, and woody species accompanied by accuracy assessments. Estimates of mean plot volume based on harmonized definitions with minimum length/height of 1 m and minimum diameter thresholds of 10, 12, and 20 cm were on average 3, 8, and 30% smaller, respectively, than estimates based on national definitions. Volume differences were less when estimated for various deadwood categories. An accuracy assessment demonstrated that, on average, the harmonization procedures did not substantially alter deadwood observations (root mean square error 23.17%). For. Sci. 58(3):269–283.

Keywords: reference definitions, bridging functions, deadwood attributes, biodiversity indicator, carbon pool

Deadwood is acknowledged to be a critical ecological factor that plays a fundamental role in forest ecosystems (e.g., Christensen et al. 2005, Lombardi et al. 2010). It is one of the most relevant components of forest biodiversity, and it represents an important forest carbon pool (Stokland et al. 2004, Woodall et al. 2009). Dead trees, stumps, and fine and coarse woody debris (CWD) are essential to forest ecosystem dynamics by providing food and habitat for taxa such as fungi, arthropods, birds, insects, and epiphytic lichens (Sippola and Renvall 1999, Bowman et al. 2000, Ferris et al. 2000, Siitonen et al. 2000, Similä et al. 2003, Jonsson et al. 2005, Odor et al. 2006, Londsale et al. 2008, Winter and Möller 2008). Approximately 20–25% of forest species depend on decaying wood (Boddy 2001, Siitonen 2001), although decayed material is often viewed as a limited habitat resource for some organisms (Hagen and Grove 1999).

Deadwood is also considered to be an important indicator for assessing sustainable forest management and conservation of forest biodiversity (Ferris and Humphrey 1999, Hahn and Christensen 2004, Travaglini et al. 2007, Fischer et al. 2009). Deadwood was recognized as a biodiversity indicator for sustainable forest management by Forest Europe, the former Ministerial Conference on the Protection of Forests in Europe (2003), and the Montréal Process (Montréal Process 2005) and as one of 26 indicators selected for the Streamlining European 2010 Biodiversity Indicators initiative to track temporal biodiversity changes in the context

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of the 2010 European target to halt the loss of biodiversity (European Environment Agency [EEA] 2007).

Deadwood is one of the five forest carbon pools defined by the Good Practice Guidance for Land Use, Land-Use Change and Forestry of the Intergovernmental Panel on Climate Change (Penman et al. 2003). For signatories to the United Nations Framework Convention on Climate Change, timely assessments of deadwood changes are essential for preparation of the required annual reports on greenhouse gas inventories (Cienciala et al. 2008, Woodall et al. 2008).

The main source of information on the large-scale quantities and characteristics of deadwood are national forest inventories (NFIs) which, in recent decades, have incorporated assessments of deadwood because of its relevance for biodiversity and for carbon pool monitoring (Puumalainen et al. 2003, Stokland et al. 2004, Böhl and Brändli 2007). Because deadwood surveys have most often been developed for local conditions (Woldendorp et al. 2004, Travaglini et al. 2006), NFIs have adopted different definitions and inventorying methods. The result is that deadwood estimates are generally not comparable for different countries.

Estimation of reliable and comparable deadwood volumes at cross-country levels may be achieved using two possible approaches, standardization or harmonization. Köhl et al. (2000) described standardization as a top-down approach that requires adoption of common international standards. The harmonization approach is, instead, a bottom-up approach based on the use of bridges to convert estimates based on national definitions to estimates based on international reference definitions (Ståhl et al. 2012).

This article presents the results of experimental investigations conducted by Working Group 3 (WG3) of COST Action E43 (Chirici et al. 2011), which dealt with harmonized assessments of forest biodiversity using NFI data. One component of these investigations focused on deadwood, in particular, on developing and testing bridges for the harmonized assessment of multiple deadwood variables using NFI sample data voluntarily contributed by 10 countries: Belgium (BE), Switzerland (CH), Czech Republic (CZ), Germany (DE), Denmark (DK), Spain (ES), Finland (FI), Italy (IT), Sweden (SE) and the United States of America (USA). The harmonization tests are based on the assumption that the adopted reference definition for deadwood (Table 1, reference 1) is equivalent, except for the minimum diameter threshold, to the definitions adopted by individual NFIs. The impacts on deadwood estimates of different minimum diameter thresholds in the reference definitions are reported, and problems related to the implementation of the proposed harmonization bridges are discussed.

Because an international standard definition for deadwood does not exist, adoption of reference definitions was indeed a critical step. For the purposes of this study, reference definitions were defined on the basis of the discussions in COST E43 after a detailed analysis of national local definitions. More information related to the discussion and the general work program followed in COST E43 is detailed in Chirici et al. (2011). The reference definitions adopted are described in Table 1. In particular, deadwood volume at the plot level is defined as the sum of the volumes of standing and lying dead trees and coarse woody debris. The harmonization process we adopted is implemented at two different levels: for single deadwood elements and at aggregated plot level.

The process was repeated for three different deadwood reference definitions based on different minimum diameters (10, 12, and 20 cm). The results are presented using comparisons of deadwood volume estimates based on the original NFI definitions and estimates resulting from the harmonization process, accompanied by an error estimation performed by assessing the quality of bridges.

Table 1. Deadwood references adopted for the harmonization test.

Reference no.	Deadwood elements	Reference definitions
1	Living and dead stems	A living stem has active or dormant cambium; otherwise the stem is dead.
2	Standing and lying stems	A lying stem is the main stem that is not self-supporting with the majority of its length lying on the ground; otherwise it is a standing stem.
3	Decay classes	Four decay classes (A, B, C, and D) are considered on the basis of the percentage of hard texture wood present in the deadwood volume. Wood is considered "hard texture" if a knife cannot be penetrated more than 2 cm. Class A: hard texture ≥90% (not decayed, completely hard) Class B: hard texture 90–60% (slightly decayed, most part still hard) Class C: hard texture 60–30% (decayed, most part soft) Class D: hard texture ≤30% (very decayed, completely soft)
4	Stem volume of dead trees	The stem volume of dead trees is the aggregated aboveground volume of all dead stems, standing or lying, over a specified area. Included are volumes—from the stump height to a top diameter of 10 cm—of dead stems with a dbh of >10 cm. Branches are excluded.
5	Piece of coarse woody debris	A piece of coarse woody debris is a downed (not suspended) piece of deadwood lying on ground, with sections coarser than 10 cm (over bark) of at least 1 m in length (as proposed among COST E43 recommendations). Lying dead stems, including attached branches, are excluded. (The definition was not yet agreed as a reference among COST Action E43.)
6	Volume of coarse woody debris	The volume of coarse woody debris is the aggregated aboveground volume of all pieces of coarse woody debris over a specified land area. Included are those sections of the coarse woody debris pieces that are coarser than 10 cm (over bark) on a length of at least 1 m.

The final aim of this contribution is 2-fold: to demonstrate that the aggregation at the international level of deadwood volume estimates acquired at the country level based on different definitions led to possible inaccuracies and to demonstrate that the harmonization of deadwood volume estimates on the basis of international common reference definitions is possible and feasible, even without the acquisition of new field data. The solutions we propose are limited by types of data we acquired within the framework of COST Action E43. We expect that our results will motivate future development of optimized harmonization techniques that can be operationally applied by the countries using their own NFI data.

For some countries, plot data were acquired within the framework of local forest inventories that are not formally national. For simplicity, we refer to all the data used in the test as from NFIs, even if they were sometimes acquired and provided by different authorities.

Materials

Methods and definitions adopted by the 10 countries involved in this study for assessing different deadwood components were acquired through questionnaires developed by WG3 of COST Action E43 (Winter et al. 2008). The responses are summarized for the following deadwood features: sampling methods, spatial position (lying or standing), decay classes, woody species, and volume calculation.

Sampling Methods

Deadwood elements are sampled in the field using plots or linear transects. When plots are used, all deadwood elements satisfying a specific definition and located within an area of predefined size, shape, and spatial location are measured. The transect approach (line intersect sampling [LIS]), which is adopted only for lying deadwood, consisted of measuring pieces that satisfy a specific definition and that intersected a sampling line of given length, origin, and direction (Warren and Olsen 1964, Van Wagner 1968, De Vries 1986).

Spatial Position

Eight countries adopted the lying and standing classes for classifying deadwood elements. Two countries used more complex systems of nomenclature with four or five classes to produce a more detailed description of the lying/standing condition of deadwood.

Decay Classes

Information on deadwood decomposition stage was available for nine countries. These countries used multiple decay classes ranging between 3 and 9 mainly based on deadwood color, texture, and softness.

Woody Species

Six countries determined the species of the deadwood; the others recorded only whether the element was from a coniferous or broadleaved tree. Some countries used a specific code such as "other" or "unidentified" for pieces for which the identification of the species was impossible because of advanced decomposition.

Volume

National definitions and methods for calculating volumes of sampled deadwood elements were analyzed separately on the basis of two factors: sampling rules and volume estimation procedures.

First, sampling rules are aimed to determine whether a deadwood element satisfies the adopted definition; if so, it is included in the sample, otherwise it is not considered for volume estimation. NFI field procedures are generally based on minimum diameter and length (or height) thresholds (Table 2) and are applied to elements inside a sampling unit (plot) or intersecting a line transect (LIS).

For standing deadwood, national minimum diameter thresholds varied between 4 and 20 cm, whereas minimum height was always the height at which diameter is measured. For eight countries, minimum height was 1.3 m aboveground, for Belgium minimum height was 1.5 m, and for the United States minimum height was 1.37 m (4.5 ft).

For lying deadwood, national thresholds included minimum diameter and minimum length. For lying stems, minimum diameter referred to the diameter measured at 1.3 m from the thicker end and varied from 7.5 to 12 cm; for lying deadwood pieces, minimum diameter referred to the diameter measured at the thinner end and varied from 6.4 to 20 cm. In the United States, which uses LIS, a minimum diameter of 7.6 cm is used for the point at which the line intersects the deadwood piece. Minimum lengths varied between 0.1 and 1.3 m.

Second, for volume estimation procedures, national definitions vary with respect to the particular part of deadwood elements considered to estimate volume. Thus, even if two NFIs adopt the same sampling rules, the method used to estimate plot-level deadwood volume may differ, with the result that plot-level estimates may vary considerably.

The main differences among the 10 countries are reported in Tables 3 and 4.

The Common NFI Database

A common NFI database (DB) was populated with raw NFI deadwood data contributed from 4,842 plots from Europe and 4,366 plots from the United States. Each country was responsible for the selection of plots for which data were contributed (Figure 1). The percentages of European plots by country are as follows: BE, 400 plots (8%); CH, 401 plots (8%); CZ, 302 plots (6%); DE, 790 plots (16%); DK, 1,458 plots (30%); ES, 775 plots (16%), FI, 336 plots (7%); IT, 192 plots (4%); and SE, 188 plots (4%).

The DB includes data for 9,208 plots, although deadwood was observed and measured on only 4,985 plots. For the remaining plots, deadwood was not present or deadwood elements did not satisfy local sampling rules. For all plots together, more than 23,000 deadwood pieces were observed and measured. All countries measured dbh and height for standing deadwood. However, consistency was

Table 2. **Sampling rules used to identify deadwood pieces to be included in the field sample.**

	Standing deadwood				Lying deadwood			
Country	Type of deadwood	Type of diameter	Minimum diameter	Minimum height	Type of deadwood	Type of diameter	Minimum diameter	Minimum length
BE	Standing trees	dbh[1]	6.4 cm	1.5 m	Lying trees and pieces of deadwood	Thinner end	6.4 cm	1 m
	Broken snags	At half height	6.4 cm	1.5 m				
CH	Standing trees and broken snags	dbh	12 cm	not used	Lying trees	Thinner end	12 cm	not used
CZ	Standing trees and broken snags	dbh	5 cm	1.3 m	Lying trees and pieces of deadwood	Thinner end	7 cm	0.1 m
DE	Standing trees and broken snags	dbh	20 cm	1.3 m	Lying trees and pieces of deadwood	Thinner end	20 cm	0.1 m
DK	Standing trees and broken snags	dbh	4 cm	1.3 m	Lying trees and pieces of deadwood	Thinner end	10 cm	1.3 m
ES	Standing trees and broken snags	dbh	7.5 cm	1.3 m	Lying trees	Thinner end	7.5 cm	1.3 m
					Lying pieces of deadwood	Thinner end	7.5 cm	0.3 m
FI	Standing trees	dbh	10 cm	1.3 m	Lying trees and pieces of deadwood	Thinner end	10 cm	1.3 m
	Broken snags	Top diameter[2]	10 cm	1.3 m				
IT	Standing trees and broken snags	dbh	4.5 cm	1.3 m	Lying trees and pieces of deadwood	Thinner end	9.5 cm	0.1 m
SE	Standing trees and broken snags	dbh	10 cm	1.3 m	Lying trees	Thinner end	10 cm	1.3 m
					Lying pieces of deadwood	Thinner end	10 cm	1.3 m
USA	Standing trees and broken snags	dbh[3]	12.7	1.3 m	Lying trees and pieces of deadwood	Diameter at the line intersection point	7.6 cm	0.9 m

[1] dbh for BE is measured at a height of 1.5 m.
[2] dbh in the USA is measured at a height of 1.37 m (4.5 ft).
[3] The height is measured if the tree is broken under the (top) diameter of 10 cm.

lacking for measurements of other deadwood attributes. One country did not record the height/length for standing snags (broken standing dead stem) and another country measured circumference at half the snag height. Measures for lying deadwood were for whole deadwood pieces for some countries but only for portions for other countries (Figure 2).

Methods

Overview

Bridges are methods for converting estimates based on national definitions to estimates based on reference definitions (Ståhl et al. 2012). Three types of bridges, depending on data availability relative to the reference definition and its thresholds, are used to make these conversions. When the scope of the data collected using national definitions is greater than the scope required by the reference definitions, a reductive bridge that discards some of the national data is used. When the scope of the data collected using national definitions is the same as that required by the reference definition, a neutral bridge is appropriate. Finally, when the scope of the data collected using the national definitions is less than that required by the reference definition, an expansive bridge is necessary. Expansive bridges are the most difficult to construct because a procedure for acquiring additional information is necessary.

For the deadwood harmonization investigations, bridges were applied at two levels: calculation of volume for individual deadwood pieces and per plot estimates by lying/standing classes, decay classes, and woody species. In addition, plot-level bridges were necessary because of different plot-level volume estimation procedures. Reductive and neutral bridges were used at the level of individual deadwood pieces. Data were then aggregated at the plot level, and expansive bridges were applied when needed. The procedure was repeated for reference definitions corresponding to three minimum diameter thresholds: 10, 12, and 20 cm, labeled, respectively, Ref_{10}, Ref_{12}, and Ref_{20} (Table 5).

To evaluate the accuracy of the harmonization process, deadwood volumes based on country definitions were compared with volumes predicted using bridges. The procedure was possible only for the subsample of plots for which the diameter threshold for the local deadwood definition completely was less than that for the reference definition. Results are reported for aggregations by spatial position.

Spatial Position

Neutral and reductive bridges were used to harmonize categories of spatial position into two categories: standing or lying. On the basis of the data available in the common DB, the bridge did not alter national definitions, because

Table 3. National definitions for deadwood volume estimation.

Country	Standing	Lying
BE	Stem volume from the stump height to a top diameter of 7 cm of standing trees and snags with diameter at 1.50 m from the ground ≥6.4 cm	Stem volume of the portion of lying trees and pieces of deadwood having a minimum diameter ≥6.4 cm and a length ≥1 m
CH	Stem volume from the stump height to the stem top of standing trees and snags with dbh ≥12 cm	Stem volume from the stump height to the stem top of lying trees with diameter at 1.30 m from the base ≥12 cm
CZ	Stem volume from the stump height to a top diameter of 7 cm of standing trees and broken snags with dbh ≥5 cm and height ≥1.30 m	Stem volume of the potion of lying trees and pieces of deadwood with diameter ≥7 cm and length ≥0.1 m
DE	Stem volume from the stump height to the stem top of standing trees and snags with dbh ≥20 cm and height ≥1.30 m	Stem volume of lying trees and pieces of deadwood with a diameter at the thicker end ≥20 cm and a length ≥0.1 m; volume of the stumps with diameter at felling height ≥60 cm and height ≥0.50 m
DK	Stem volume from the stump height to the stem top of standing trees and snags with dbh ≥4 cm and height ≥1.30 m	Stem volume of lying trees and pieces of deadwood with a diameter at thicker end ≥10 cm and a length ≥1.3 m
ES	Stem volume from the stump height to a top diameter of 7.5 cm of standing trees and snags with dbh ≥7.5 cm and height ≥1.30 m	Stem volume from the stump height to a top diameter of 7.5 cm of lying trees with dbh ≥7.5 cm and length ≥1.30 m; volume of the portion of pieces of deadwood with diameter ≥7.5 cm and length ≥0.30 m
FI	Stem volume from the stump height to a top diameter of 10 cm of standing trees and snags with dbh ≥10 cm and height ≥1.30 m	Stem volume of the portion of lying trees and pieces of deadwood with a diameter ≥10 cm and a length ≥1.3 m
IT	Stem volume from the stump height to a top diameter of 5 cm of standing trees and snags with dbh ≥4.5 cm and height ≥1.30 m	Stem volume of the portion of lying trees and pieces of deadwood with a diameter ≥9.5 cm and a length ≥0.1 m
SE	Stem volume from the stump height to the stem top of standing trees and snags with dbh ≥10 cm and height ≥1.30 m	Stem volume from the stump height to the stem top of lying trees with dbh ≥10 cm and height ≥1.30 m; volume of whole pieces of deadwood with a diameter at thicker end ≥10 cm and a length ≥1.3 m
USA	Stem volume from the stump height to the stem top of standing trees and snags with dbh ≥12.7 cm and height ≥1.30 m	Volume of the portion of lying trees and pieces of deadwood with a diameter ≥7.6 cm and a length ≥0.9 m

Table 4. Methods for volume estimation for deadwood elements.

	Deadwood elements				
Volume function	Standing trees	Standing snags	Lying trees	Lying pieces of deadwood	Other
Country volume tables (from stump height to stem top, top diameter = 0)	CH, DE, DK, SE, USA	CH, DE, DK, SE, USA	CH, SE		
Country volume tables, volume functions, and taper curve models (from stump height to top diameter)	BE, CZ, ES, FI, IT	CZ, ES, FI	ES		
Smalian's formula (Loetsch et al. 1973)			FI	ES, FI, SE, USA	
Huber's formula (Loetsch et al. 1973)		BE	BE, CZ, DE, DK	BE, CZ, DE, DK	DE (stump)
Frustum of cone				IT	
Half volume of cylinder with d = dbh		IT			

they were essentially equivalent to the reference definition (Table 1). For eight countries, the bridges were neutral, whereas for two countries they were reductive. Thus, dead trees and deadwood pieces recorded in the DB were assigned to either a standing or lying spatial position.

Decay Classes

Neutral and reductive bridges were used to harmonize categories of decay classes by reassigning them from national decay classes to reference classes (Table 1, reference 3). The bridges were neutral for four countries and reductive for six countries and were applied to all the dead trees and deadwood pieces.

Woody Species

Harmonization was conducted to assign all the deadwood pieces to one of three classes: coniferous, broadleaved, and not available.

Volume Calculation

Harmonization of deadwood estimates was conducted in two steps: intermediate harmonized volume estimates were calculated for each deadwood piece using NFI measurements in the DB for each of Ref_{10}, Ref_{12}, and Ref_{20} and the piecewise volume estimates from the first step were aggregated at the plot level and a second harmonization step was conducted using expansive bridges to obtain aggregated

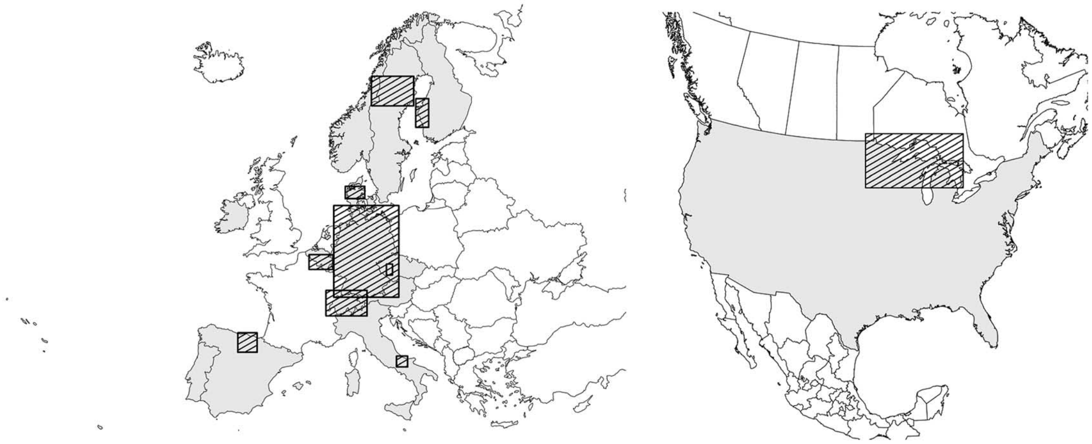

Figure 1. Geographic location of the 9,208 plots used in the deadwood harmonization test.

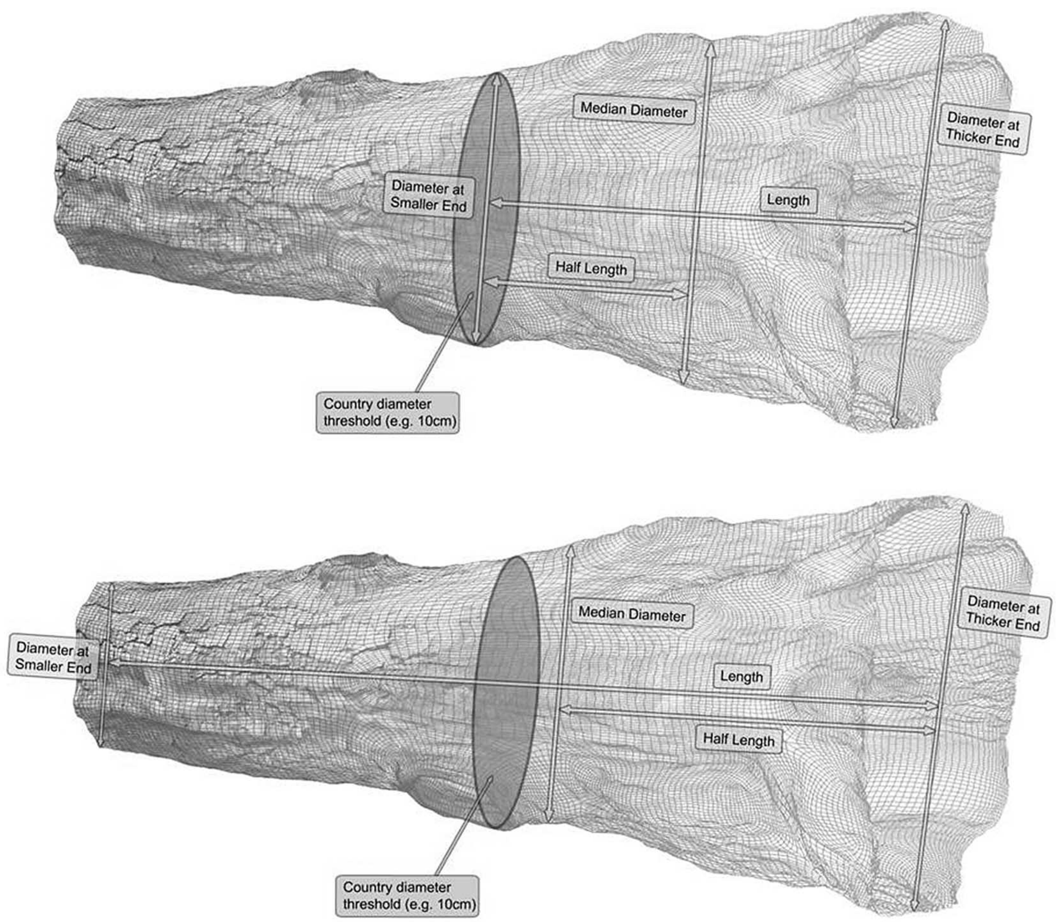

Figure 2. Example of measures referred to the whole piece of lying deadwood (bottom) and referred to a part of it (top).

plot-level volume estimates because of differences in minimum diameter and minimum length thresholds between national and reference definitions.

Per Piece Harmonization

Bridges were developed to estimate volumes of individual deadwood elements corresponding to the three reference definitions using data collected according to national definitions. Reductive bridges were developed for use when the national thresholds were less than reference thresholds. These bridges are in the form of reduction factors (*Rf*) with values between 0 and 1 and are applied to reduce the piecewise deadwood volumes provided by the countries. Values of *Rf* are calculated differently for different deadwood components and are described in detail below.

Per Piece Harmonization of Standing Dead Stems

According to the reference definitions (Table 1), standing dead stem volume is the volume from the stump height

Table 5. **Bridges used for deadwood harmonization at single-piece level (reductive and neutral bridges) and at plot level (expansive bridges).**

	Reductive bridges	Neutral bridges	Expansive bridges
Standing stems (whole trees and broken snags)			
dbh (Ref_{10})	BE, DK, IT, CZ, ES	FI, SE	CH, DE, USA
dbh (Ref_{12})	BE, DK, IT, CZ, ES, FI, SE	CH,	DE, USA
dbh (Ref_{20})	BE, DK, IT, CZ, ES, FI, SE, CH, USA	DE	
Height		CH, CZ, FI, IT, SE, USA, DK, ES, DE	BE
Lying stems (whole trees) (only for SE, ES, and CH)			
Diameter at 1.30 m (Ref_{10})	ES	SE	CH
Diameter at 1.30 m (Ref_{12})	ES, SE	CH	
Diameter at 1.30 m (Ref_{20})	ES, SE, CH		
Length		CH, ES, SE	
CWD (no data for Switzerland) and lying stems			
Diameter (Ref_{10})	BE, CZ, ES, USA, IT	DK, SE	DE, FI
Diameter (Ref_{12})	BE, CZ, ES, USA, IT, DK, SE, FI		DE
Diameter (Ref_{20})	BE, CZ, ES, USA, IT, DK, SE, FI	DE	
Length	BE, CZ, DE, ES, USA, IT		DK, SE, FI

to a top over-bark diameter of 10 cm for stems with dbh of at least 10, 12, or 20 cm, depending on the reference definition used. When volume for individual standing dead stems is calculated, harmonization is necessary because of differences between national and reference definitions for both minimum dbh and minimum top diameter. When the national minimum dbh is smaller than the reference minimum dbh, a reductive bridge is used by selecting only standing dead stems in the DB whose dbhs are greater than the reference minimum dbh. When the national and reference minimum dbhs are equal, the harmonization is through a neutral bridge used to convert values between different data formats. When the national minimum dbh is greater than the reference minimum dbh, an expansive bridge is necessary and is developed for application at the plot level. For Ref_{10}, five reductive, two neutral, and three expansive bridges were necessary, for Ref_{12}, seven reductive, one neutral, and two expansive bridges were necessary, and for Ref_{20}, nine reductive bridges and one neutral bridge were necessary.

The reference definition specifies a minimum top diameter of 10 cm (Table 1). Only one country adopted a national definition with a minimum top diameter threshold that was equal to that of the reference definition; in this case, as already made for the minimum dbh, a neutral bridge was used. For the other nine countries, reductive bridges in the form of reduction factors were used because their minimum top diameter thresholds were less than the reference threshold of 10 cm. Stem volume from stump height to top diameter d, $Vtop_d$, can be defined as

$$Vtop_d = Rf_d * Vtop_0. \quad (1)$$

where $Vtop_0$ is total stem volume, $Vtop_d$ is stem volume to top diameter d, and Rf_d is the reduction factor.

Rf_d in Equation 1 can be calculated from the estimation system developed by Corona and Ferrara (1992) on the basis of the simple bole model proposed by Ormerod (1973):

$$Rf_d = 1 - [(H - 1.3)/H]^{2b+1} \times (d/dbh^{(2b+1)/b}). \quad (2)$$

where Rf_d is the reduction factor, H is the total height of the stem, b is the exponent estimated for each tree, and d is the top diameter. The exponent b is estimated using an algorithm that modifies an initial estimate iteratively until the change between iterations is less than the prescribed amount (Figure 3). Stem volume to a reference top diameter, $Vtop_{ref}$, is then defined as

$$Vtop_{ref} = Rf_{ref-d} * Vtop_d. \quad (3)$$

where ref is the minimum threshold for the reference definition, $Vtop_{ref}$ is stem volume to the reference top diameter, and Rf_{ref-d} is the reduction factor from $Vtop_d$ to $Vtop_{ref}$.

Stem volumes for different top diameters were first estimated using Equation 1 with data available in the DB. Once $Vtop_{10}$ corresponding to the minimum top diameter of 10 cm for the reference definition was obtained using Equation 1, Rf_{ref-d} was calculated to convert stem volumes with minimum top diameters of 5, 7, and 7.5 cm to stem volumes with minimum top diameters of 10 cm (Rf_{10-5}, Rf_{10-7}, and $Rf_{10-7.5}$). The relationship between Rf_{ref-d} and dbh was described using an equation of the form:

$$Rf_{ref-d} = 1 - (a * b^{dbh}). \quad (4)$$

The resulting equations (Figure 4) were then applied to individual standing dead stems in the DB to calculate the reference volume, $Vtop_{ref}$, using Equation 3 and data collected according to national definitions (Table 3). The Rf_{ref-d} estimates obtained using Equation 4 were compared to the available measured Rf_{ref-d} to assess the accuracy of the models (Figure 5).

Per Piece Harmonization for Lying Deadwood

For purposes of calculating volume, the shape of a lying deadwood piece was assumed to be a frustum of a cone defined by maximum diameter (D_{max}), minimum diameter (D_{min}), and length (L) as the linear distance between D_{max} and D_{min}. The volume of such pieces (Figure 6), according

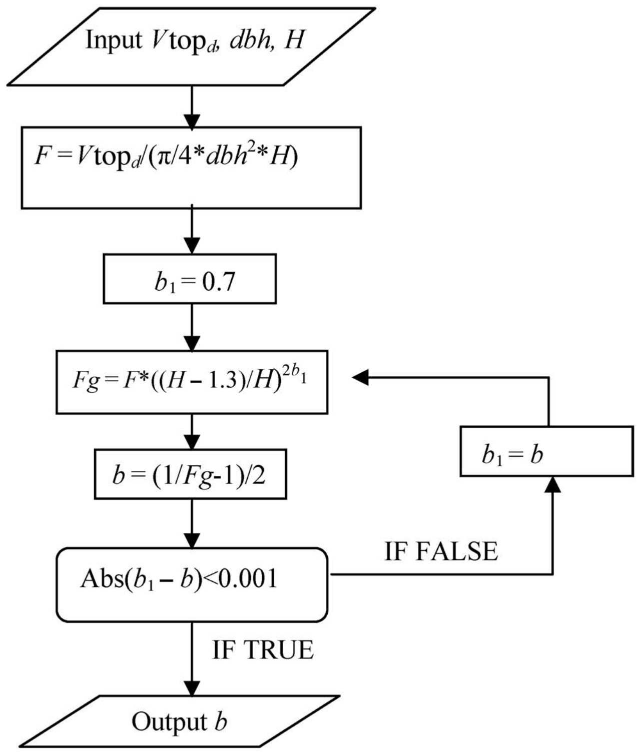

Figure 3. The algorithm for the calculation of the exponent *b* of equation 2. For the meaning of $Vtop_0$, dbh, and *H* we refer to equations 1 and 2. [Abs ($b_1 - b$) means "absolute value" of the difference ($b_1 - b$)]. Adapted from Corona and Ferrara (1992).

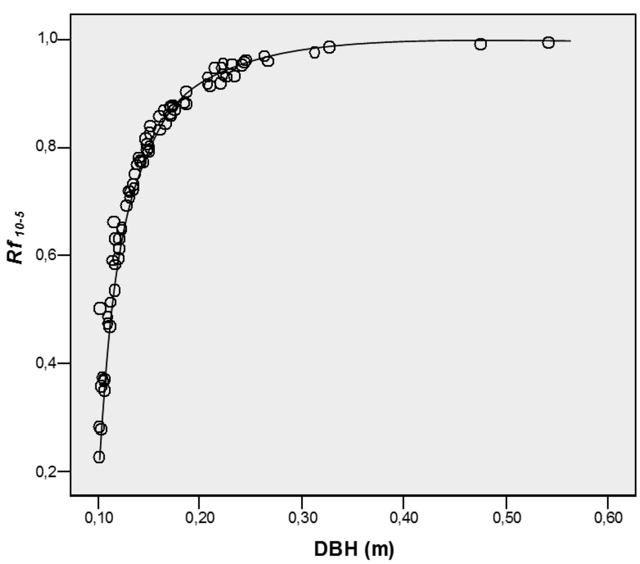

Figure 4. Example of the function from equation 4 used for local minimum top diameters of 5 cm (Rf_{10-5}).

to the adopted reference definitions, is the volume of the portions of a piece of lying deadwood with a minimum diameter ≥10 cm (or 12 or 20 cm) and having at least 1-m length (V_{CWDref}). Volumes for lying deadwood components with diameters less than the reference definition threshold and equal to or greater than the reference threshold were calculated using the following procedure. Two cases had to be analyzed, depending on the availability of end diameters of the pieces of wood considered.

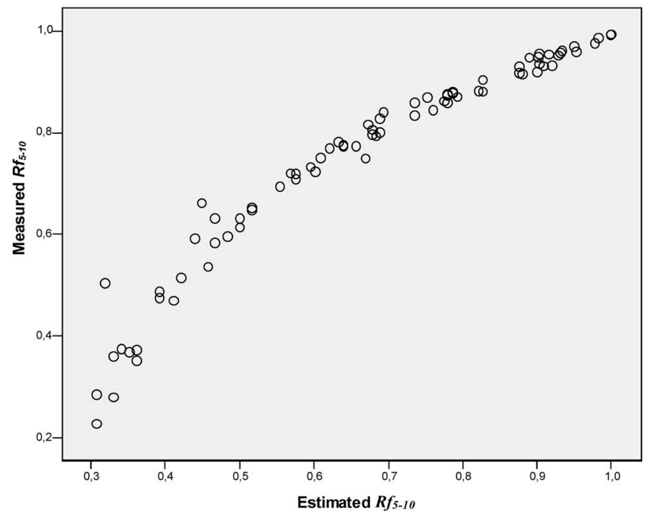

Figure 5. Example of the regression found for reduction factor Rf_{5-10}) and its estimation made throughout the regression in Figure 4.

If the countries provide D_{min} and D_{max}, they are used to calculate a tapering rate R expressed as follows:

$$R = \frac{D_{\mathrm{max}} - D_{\mathrm{min}}}{L}. \quad (5)$$

The rate is used to estimate the lengths of components with diameters less than the reference diameter and the lengths of components with diameters greater than or equal to the reference diameter. From those lengths and the two diameters, volumes are estimated using the Smalian formula (Loetsch et al. 1973, Rondeux 1999b). The reduction factor r is then calculated as the ratio of two volumes: the volume of the component with diameter greater than or equal to the reference diameter and the total volume:

$$r = \frac{V_{D_{\mathrm{min}} \geq 10}}{V_{D_{\mathrm{min}} \geq 10} + V_{D_{\mathrm{min}} < 10}}. \quad (6)$$

The volume of the piece of wood corresponding to the reference definition is the product of the reduction factor r (Equation 6) and the volume of the piece provided by the NFI.

If the countries do not provide D_{min} and D_{max} because only the diameter in the middle of every piece of wood is measured (D_{mid}), R cannot be calculated. Therefore, $\Delta D = D_{\mathrm{max}} - D_{min}$ must be estimated using data from other countries that measure both D_{max} and D_{min}. Several possibilities exist to solve this problem, for example, using D_{mid} as an explanatory variable of R. We preferred a linear regression model of the form, $\Delta D = a + b \times L$ (Figure 7), constructed to estimate ΔD for every piece of wood of a given length L. For coniferous species, the model and its coefficient estimates are $\Delta D = 0.0202 + 0.0018L$, where ΔD and L are expressed in m, with $r^2 = 0.5272$ and root mean square error (RMSE) = 54%. For broadleaved species, the model and its coefficient estimates are $\Delta D = 0.0367 - 0.0122\ L$, with $r^2 = 0.5107$ and RMSE = 47%.

These linear models were then applied to pieces for which D_{max} and D_{min} were not provided as a means of

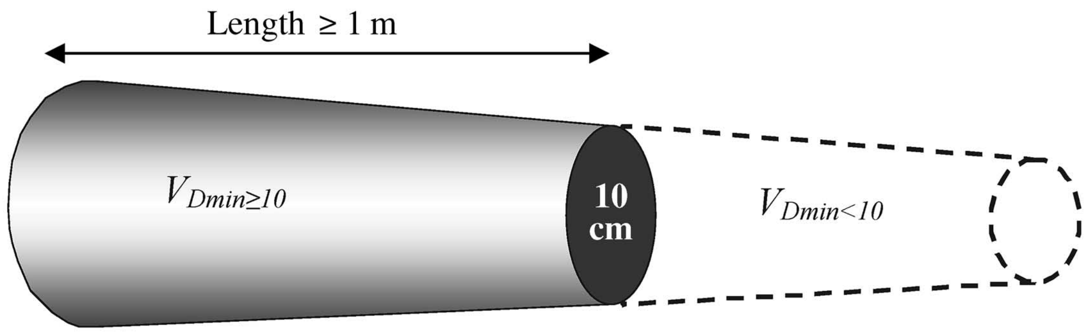

Figure 6. Schematic diagram of the division of a lying piece of deadwood in two components on the basis of the reference definition with a minimum diameter of 10 cm. The right part has a minimum diameter <10 cm; its volume is $V_{D_{min} \geq 10}$. The left part has a minimum diameter ≥10 cm; its volume is $V_{D_{min} \geq 10}$. The proportion of $V_{D_{min} \geq 10}$ when the left side part has a length ≥1 m is used to calculate the reference volume V_{CWD10}.

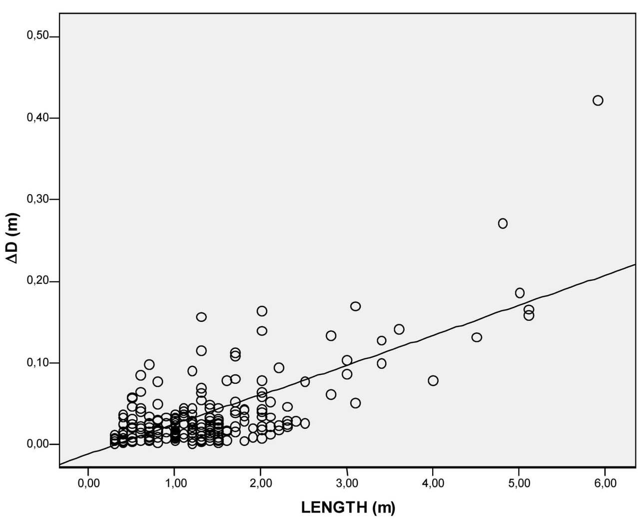

Figure 7. Example of the linear regression found for the category "Conifers" ($\Delta D = D_{max} - D_{min}$).

estimating R (Equation 5). Therefore, D_{max} and D_{min} can be estimated as follows:

$$D_{max} = D_{mid} + R * L/2.$$

$$D_{min} = D_{mid} - R * L/2.$$

The same steps presented in the case of countries where D_{max} and D_{min} were measured were then used.

Per plot harmonization

Per plot harmonization was needed for countries whose minimum diameter, minimum height, or minimum length used in the selection of the deadwood elements to be measured in the field were greater than the reference definition thresholds (Table 4). In these cases, expansive bridges are needed to estimate the portion of deadwood volume not measured in the field using national definitions.

Per plot harmonization was necessary for six countries for Ref_{10}, five for Ref_{12}, and three countries for Ref_{20} (Table 5). For countries not requiring expansive bridges, the harmonized estimate of deadwood volume per plot is the sum of the harmonized volumes of all the deadwood pieces expressed on a per ha basis.

Per plot harmonization was accomplished by constructing plot-level models of the relationship between the national deadwood volumes (V_{NFI}) and the volumes estimated using the reference definitions (V_{ref}). Using NFI data for a sample of plots from Czech Republic, Italy, and Spain, the relationship between V_{NFI} and V_{ref} was modeled as

$$V_{ref} = f(V_{NFI}). \quad (7)$$

Data for these three countries were used because their national deadwood thresholds were less than the reference thresholds. Linear models of the form

$$V_{ref} = a * V_{NFI} + b, \quad (8)$$

were constructed for different deadwood components according to local definitions. A total of 16 models were used (Table 6).

Accuracy Assessment

An accuracy assessment was conducted to analyze the similarity between observed deadwood volumes and volumes estimated by bridges. A formal assessment requires deadwood volume data based on both local and reference definitions for the same field plots. Because such data were not available in the common DB, we used a simulation procedure. First, all deadwood elements were selected from the common DB for each country whose minimum diameter thresholds for their national definitions were less than the corresponding minimum diameter thresholds for the reference definitions. Selections were made for standing and lying components separately and for each reference (Ref_{10}, Ref_{12}, and Ref_{20}); in aggregate for both standing and lying deadwood and for all three references, elements were available for 1,359 plots. Second, for this reduced data set, deadwood volume, V_{ref*}, was calculated for each plot without application of bridges. For example, for a country whose national definition included a minimum diameter threshold of ≤10 cm, $V_{ref*} = V_{10*}$ was calculated using only elements from the country whose diameters were at least 10 cm. Third, for the same reduced dataset, an NFI minimum diameter threshold of 12 cm was simulated by deleting from

Table 6. Characteristics of the parameters for expansive per plot bridges.

Country	Lying/standing	Reference value	Local value	*a*	*b*	R^2	*n*
Ref_{10}: expansive Bf for diameter (*D*) thresholds							
CH	LS	10	12	1.0114	0.4618	0.9384	687
DE	S	10	20	1.0099	2.3551	0.8018	687
DE	L	10	12	1.1224	1.4376	0.907	569
USA	S	10	12	1.0124	0.58	0.9317	687
Ref_{10}: expansive Bf for length/height (*L*) thresholds							
DK	L	1.0	1.3	1.0276	0.303	0.9826	730
FI	L	1.0	1.3	0.9976	0.0989	0.9997	160
SE	L	1.0	1.3	1.0276	0.303	0.9826	730
Ref_{12}: expansive Bf for Diameter (*D*) thresholds							
DE	S	12	20	1.0189	1.83	0.8917	608
DE	L	12	20	1.1028	1.0127	0.9432	461
USA	S	12	12.7	1.001	0.1776	0.9951	573
Ref_{12}: expansive Bf for length/height (*L*) thresholds							
DK	L	1.0	1.3	1.0217	0.2493	0.9866	627
FI	L	1.0	1.3	0.9977	0.0994	0.9998	159
SE	L	1.0	1.3	1.0217	0.2493	0.9866	627
Ref_{20}: expansive Bf for length/height (*L*) thresholds							
DK	L	1.0	1.3	1.0116	0.139	0.9923	319
FI	L	1.0	1.3	0.9995	0.2595	0.9991	123
SE	L	1.0	1.3	1.0116	0.139	0.9923	319

The following information is reported: the country for which the bridge was developed, the deadwood component for which the function was developed (lying or standing), the local threshold used, the parameters *a* and *b* of the equation, the accuracy of the models in terms of R^2 and the number of plots (*n*) used to create the models.

the dataset all elements whose diameters were <12 cm. An expansive bridge in the form of equation 8 was then used to calculate $V_{ref} = V_{10}$. This procedure was implemented for $V_{ref*} = V_{10*}$ with NFI diameters of 12 and 20 cm and for $V_{ref*} = V_{12*}$ with NFI diameter of 20 cm. For lying and standing components separately, comparisons of V_{ref*} and V_{ref} included analyses of distributions of their differences, simple linear regressions of V_{ref*} against V_{ref} (Figure 8) and calculation of RMSE as

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_{ref*i} - V_{ref_i})^2}$$

where *i* denotes specific deadwood elements.

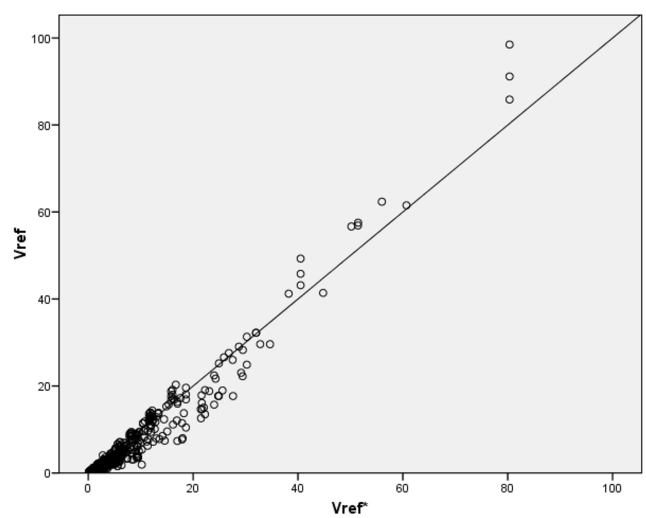

Figure 8. Result of the accuracy assessment: relationship between V_{ref} and V_{ref*} (in $m^3\ ha^{-1}$) for the 1,359 plots considered. The trend line corresponds to $Y = X$.

Results

Deadwood volume per ha was estimated for each plot for which data were recorded in the DB using four definitions: the original deadwood volume estimated by the countries using their national definitions (V_{NFI}) and harmonized estimates, $V_{Ref_{10}}$, $V_{Ref_{12}}$, and $V_{Ref_{20}}$, corresponding to the three reference definitions with minimum diameter thresholds of 10, 12, and 20 cm. Per plot deadwood volume was also estimated for the reference categories of spatial position (lying or standing), decay classes (four classes), and woody species (three classes). For each European plot, the forest category based on the European system of nomenclature implemented by the EEA (2007) was also available, whereas for American plots three forest types based on the main three species composition classes were used. These estimates are based only on data in the DB contributed by 10 countries, and do not necessarily represent a probability sample for the countries. Therefore, the estimates are not construed to be representative of actual large area conditions in any of the 10 countries.

The accuracy results are reported first, because they provide the foundation for many of the other results. Accuracy assessments were conducted separately for the three references and for the lying and standing spatial components. For the lying component, data could be used for 1,208

Table 7. Effects on harmonization based on estimates of the sum of average deadwood volumes per ha and mean harmonized deadwood volumes per ha using plots with V_{NFI} >0 (4,985 plots) and total available plots (9,208 plots).

	NFI	Ref_{10}	Ref_{12}	Ref_{20}
	m^3 ha^{-1}			
Sum of average volumes	79,303.83	76,654.55	73,244.27	55,776.31
Mean volume estimates				
4,985 plots	15.91	15.38	14.69	11.19
9,208 plots	8.61	8.32	7.95	6.06

NFI for values based on original national definitions; Ref_{10}, Ref_{12} and Ref_{20}, for values after harmonization based on reference definitions.

plots. A simple linear regression of plot-level volumes obtained from field observations versus volume predictions obtained from bridges produced estimates of the intercept-slope pair as (0.84, 0.95), which are close to the ideal values of (0, 1) and $R^2 = 0.95$. In addition, more than 82% of deviations between observations and predictions, expressed as proportions of observations, were <0.50. In addition, RMSE as a proportion of the observation mean was approximately 0.47. For the standing component, data could be used for 151 plots. Estimates of the intercept-slope pair were (0.18, 0.96), $R^2 = 0.97$; more than 85% of deviations expressed as a proportion of observations were <0.25, and RMSE as a proportion of the observation mean was approximately 0.26.

The effects of harmonization are illustrated by comparing estimates based on the national definitions and the three reference definitions (Table 7). For plots represented in the DB, in terms of the sum of the per ha average deadwood volume estimates, the differences between the original NFI values (V_{NFI}) and the three adopted reference definitions ($V_{Ref_{10}}$, $V_{Ref_{12}}$, and $V_{Ref_{20}}$) ranged between 3 and 30%. Of the 4,985 DB plots with $V_{NFI} > 0$, the mean harmonized deadwood volume estimates decrease as the minimum diameter threshold increases: mean per plot deadwood volume decreases from $V_{NFI} = 15.91$ m^3 ha^{-1} to $V_{Ref_{20}} = 11.19$ m^3 ha^{-1}. On the total of 9,208 plots, including the 4,223 plots for which deadwood volume is 0, independently of the definitions adopted, $V_{Ref_{10}}$, $V_{Ref_{12}}$, and $V_{Ref_{20}}$ decreased from 8.61 m^3 ha^{-1} of V_{NFI} to 8.32, 7.95, and 6.06 m^3 ha^{-1}, respectively (Table 7).

Because the reference definitions relate only to minimum diameter thresholds, their use does not alter the distribution of deadwood volume estimates by categories of spatial position, decay class, or woody species (Table 8). The ratio of estimates of lying deadwood volumes to estimates of standing deadwood volumes and, similarly, the percentages of deadwood volumes by species classes (conifer-broadleaved-unclassified) are quite stable over the different definitions.

The distributions of deadwood volume estimates by the four harmonized decay classes (Table 1, Reference 3) were also quite stable relative to the definitions. Percentages of estimates of deadwood volume by the five classes (A, B, C, D, and not available) range from 16 to 8%.

For all 14 European forest categories (Barbati et al. 2006), deadwood volume estimates decreased when changing from the NFI definitions to the three reference definitions (Table 9; Figure 9). The percentage reductions in deadwood volume estimates when changing from V_{NFI} to $V_{Ref_{10}}$, $V_{Ref_{12}}$, and $V_{Ref_{20}}$, respectively, were smallest for alpine coniferous forests and greatest for broadleaved evergreen forests. For the three American forest types, changing from V_{NFI} to $V_{Ref_{10}}$ produced an increase in mean deadwood volume estimates of 3.2% for aspen forest, 3.8% for paper birch, and 4.5% for balsam poplar and changing from V_{NFI} to $V_{Ref_{12}}$ had a minimal effect (−1.6, −0.1, and −0.4%).

The effects on mean deadwood volume estimates when changing from V_{NFI} to $V_{Ref_{10}}$ vary by country and range from a 3.3% increase to a 30.3% decrease. Changing from V_{NFI} to $V_{Ref_{12}}$ produced decreases in mean deadwood estimates by country ranging from 1.1 to 40.5% and changing from V_{NFI} to $V_{Ref_{20}}$ produced decreases ranging from 9.8 to 63.5%.

Discussion

Although the majority of NFIs collects data to facilitate nationwide forest monitoring, deadwood is a relatively new variable for most NFIs (Rondeux 1999a, Rondeux and Sanchez 2010). In most cases the methodologies adopted for its assessment have not been specifically studied or tested, so it is difficult to determine whether any particular approach is better than another. However, the increasing emphasis on multifunctional forest uses, and sustainable forest management has led to expansion of the scopes of NFIs, particularly in areas related to biodiversity and carbon pools. Thus, the emergence of methodological problems related to selection of variables, data collection and processing protocols, and cross-country harmonization of estimates should not be surprising. The study herein reported is the first attempt to

Table 8. Comparison between deadwood volume estimates based on original national definitions (V_{NFI}) and the three reference definitions tested ($V_{Ref_{12}}$, $V_{Ref_{12}}$, and $V_{Ref_{20}}$).

	NFI	Ref_{10}	Ref_{12}	Ref_{20}
Spatial components: standing/lying	71/29	73/27	73/27	74/26
Species: coniferous/broadleaved/unclassified	55/40/5	57/39/4	57/40/3	56/41/3
Decay classes (A/B/C/D/not available)[1]	16/21/44/11/8	15/21/46/10/8	15/21/46/10/8	15/21/46/10/8

Values are expressed as a percentage considering standing/lying components, species, and decay classes.
[1] See Table 1 for definitions of decay classes.

Table 9. Results of the harmonization test carried out on 9,208 plots.

Identification	Name	NFI	Ref_{10}	Ref_{12}	Ref_{20}	Plots
Europe						
1	Boreal forest	4.25	2.83	2.77	2.21	365
2	Hemiboreal and nemoral Scots pine forest	8.3	7.24	6.84	5.73	359
3	Alpine coniferous forest	20.88	20.29	19.88	18.8	311
4	Atlantic and nemoral oakwoods, Atlantic ashwoods, and dune forest	8.86	7.19	6.7	4.11	101
5	Oak-hornbeam forest	7.17	6.66	6.37	5.12	549
6	Beech forest	11.39	11.11	10.82	9.41	435
7	Mountainous beech forest	9.33	8.8	8.6	7.55	274
8	Thermophilous deciduous forest	2.97	2.49	2.35	1.58	366
9	Broadleaved evergreen forest	0.16	0.08	0.07	0.03	133
10	Coniferous forests of the Mediterranean, Anatolian and Macronesian regions	2.95	2.7	2.64	2.09	121
11	Swamp forest	4.23	3.85	3.78	3.44	146
12	Floodplain forest	9.53	6.77	6.36	5.21	31
13	Non-riverine alder, birch, or aspen forest plantations	4.37	3.62	3.52	3.43	82
14	Plantations and self-sown exotic forest	5.75	4.52	4.12	2.81	1,569
USA						
901	Aspen forest	9.34	9.64	9.19	6.55	3,465
902	Paper birch forest	14.58	15.13	14.6	10.73	636
904	Balsam poplar forest	9.57	10	9.61	7.42	265

Average deadwood volume (in m^3 ha^{-1}) by European forest categories (EEA, 2006) and American forest types before the harmonization (column NFI) and after the harmonization on the basis of the three reference definitions adopted (columns Ref_{10}, Ref_{12}, and Ref_{20}). The number of plots is also reported.

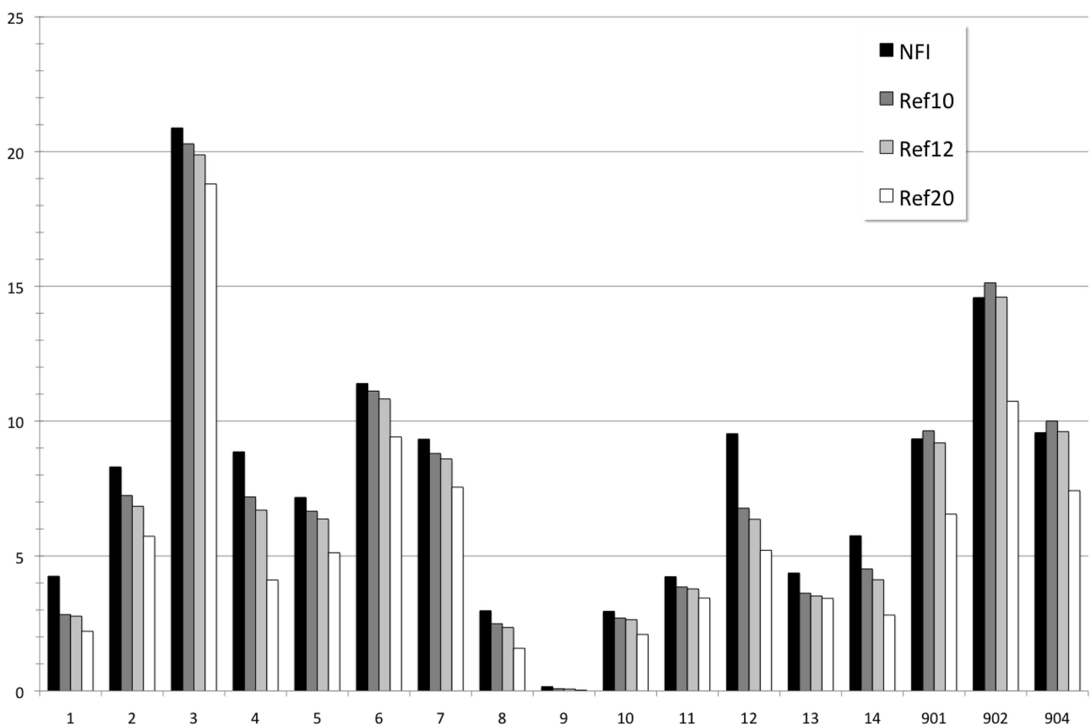

Figure 9. Mean volumes (in m^3 ha^{-1}) per European forest categories and American forest types before (NFI) and after harmonization (Ref10, Ref12, and Ref20). Data represent the mean of 9,208 plots. Descriptions of European forest categories (1–14) and American forest types (901, 902, and 904) are in Table 9.

harmonize deadwood volume estimates using NFI data, the primary source of information for national and international reporting purposes. The investigations were based on a sample of NFI data from 4,842 plots from nine European countries and 4,366 plots from the United States.

Harmonization efforts focused on constructing bridges to produce estimates based on reference definitions using data collected according to national definitions. The effects on overall estimates and estimates by categories of spatial position, decay class, and species composition using three different minimum diameters thresholds (10, 12, and 20 cm) were evaluated. Harmonization of categories of spatial position, decay class, and woody species was relatively easy because national and reference definitions were nearly equivalent. Thus, most bridges were either reductive or neutral. For reductive and neutral bridges, plot estimates were assumed not to be influenced by plot shape or size and not by sampling procedures for selecting deadwood elements. Harmonization to accommodate differences in piece- and plot-level estimation protocols were more difficult and in some cases required expansive bridges.

Inevitably, the application of bridges, especially expansive bridges, alters the original values acquired in the field; thus, quantification of effects of the bridges is important. A formal accuracy assessment is possible only on the basis of data acquired in the field for this purpose; however, such data were not available for this study. Therefore, a procedure was used for a subsample of the dataset: 1,208 plots for lying deadwood components and 151 plots for standing deadwood components. In general, deviations between plot-level observations and plot-level predictions obtained using the bridges were comparable and small. However, there was a slight tendency for the bridges to overestimate volume for plots with small observed volumes and to underestimate volumes for plots with large observed volumes. In addition, deviations tended to increase when the minimum diameter threshold increased, probably because of the combination of two effects: the average volume of deadwood elements also increases with increasing minimum diameter and a large minimum diameter required a greater alteration of the original data during the harmonization process. Deviations for the harmonization of lying deadwood were greater than those for standing deadwood. Because the average volumes for the two element types were similar, the differences in deviations were probably due to the fact that for standing deadwood, harmonization tended to entail only minor alterations of observed volumes.

On the basis of lessons learned from this experiment carried out in COST Action E43, multiple recommendations may be proposed for facilitating harmonization of deadwood variable estimates. First, information on the geographic location of deadwood pieces should be collected in the field. Such information would facilitate harmonization with respect to plot size and configuration. Second, classification of deadwood elements on the basis of their lying or standing spatial position in a manner that permits easy conversion to reference classes would be useful. Third, classification of lying deadwood and dead stems with respect to piecewise volume calculation methods (e.g., Huber and Smalian) would contribute to greater ease in harmonization. Fourth, acquisition of minimum and maximum diameters and the length between them for all CWD elements, regardless of the national approaches to volume calculation, would greatly contribute to development of taper models and development of bridges. Fifth, acquisition of data for a top minimum diameter of 0 in addition to the data for the national minimum top height would permit estimation that would be harmonized with respect to any reference threshold.

This study does not address all aspects of the harmonization of deadwood estimates, so considerable work still remains. Stump volume was not included in estimates because sufficient data were not available. Differences in overall deadwood volume and volume by decay class for different silvicultural techniques, stand types, age classes, dominant species composition classes, and forest structure classes were not been studied because relevant information was not available (Gore and Patterson 1986). Nevertheless, further studies in these areas are necessary because, for example, intensely managed forests probably contain less deadwood than accumulates naturally because dead trees are generally removed (Siitonen et al. 2000, Hill et al. 2005, Lombardi et al. 2010). Finally, the relationships between deadwood and threats to biodiversity that may result from predicted climatic changes should also be investigated (Thomas et al. 2004).

Conclusions

Five primary conclusions may be drawn from this study. First, and most importantly, the results clearly indicate that bridges that produce harmonized deadwood estimates based on reference definitions may be constructed, regardless of the national definitions used to collect the data. Further, the accuracy of the harmonization process we used is estimated to be 23.17%. Second, harmonization of categories of spatial position, decay class, and woody species class was relatively easy, although harmonization with respect to piece- and plot-level estimation was more difficult because expansive bridges were more frequently required. Third, as should be expected, harmonized estimates based on reference definitions may deviate considerably from estimates based on national definitions. However, rather large ranges of minimum diameter thresholds (10–20 cm) had little effect on the proportions of deadwood volume estimates by spatial position, decay class, woody species, and forest category. In addition, consistency in this regard for European and American deadwood data separately suggests the possibility of global harmonization. Fourth, as noted in the Discussion, considerable harmonization work yet remains. Fifth, the recommendations of WG3 of COST Action E43 provided in the Discussion should be given serious consideration, regardless of whether individual countries are inclined to modify features of their NFIs.

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