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Enhancing deadwood reporting for forest ecosystems: Bridge equations to convert deadwood measured at any diameter threshold to reference diameters

Daniel Moreno-Fernández *, Isabel Cañellas, Laura Hernández, Patricia Adame, Iciar Alberdi

Institute of Forest Sciences (ICIFOR, INIA, CSIC), Crta. de la Coruña km 7.5, E-28040 Madrid, Spain

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ABSTRACT

National as well as international requirements have led to an increased need to quantify deadwood stocks in forest ecosystems given their important role not only in terms of carbon storage and regulation of the carbon cycle but also as biodiversity refugia. However, differences in definitions and field monitoring as well as gaps in existing data on deadwood mean that comparisons among countries and retrospective analyses are difficult. In this research, we propose two potential approaches to solve the most common gaps in forest deadwood monitoring. First, we develop bridging functions capable of converting deadwood measurements with a specific reference diameter to 7.5 cm (minimum diameter value in Spain) and 10.0 cm (the most common minimum value for international statistics) diameters for the main forest types while also addressing the effect of raising the minimum measurable size on the quantification of deadwood. Furthermore, we aim to calculate the ratios between the amount of standing deadwood, the most common indicator monitored in National Forest Inventories, and the entire deadwood pool as a proxy for estimating complete deadwood stocks when data are not available. For this objective, we use information obtained from the Spanish National Forest Inventory, linear models and 10-fold cross-validation. We estimate the percentage of deadwood omitted when the minimum deadwood size is increased for the main eight forest types in Spain as well as for the entire country, using two different approaches. The ratio between the amount of standing deadwood and the entire deadwood pool ranged between 0.14 and 0.45 depending on the forest type. The lowest values of this ratio were found in Open woodlands and the largest in Mediterranean conifers. The validation statistics (R^2 ranging from 0.82 in Evergreen broadleaves to 0.97 in Macaronesian broadleaves) indicate that the bridging functions we propose are robust and accurate. However, the ratios between the amount of standing deadwood and the entire deadwood pool performed poorer (R^2 ranging from 0.26 in Macaronesian conifers to 0.65 in Macaronesian broadleaves) and led to an overestimation of the total stocks. Our results are of value not only for the purposes of comparison and harmonization but also for the implementation of new forest monitoring systems.

1. Introduction

Quantifying forest deadwood has gained importance in recent times given its key role in different ecosystem functions, such as carbon storage, regulation of the carbon cycle (Moreno-Fernández et al., 2015; Shannon et al., 2022) or biodiversity refugia (Sandström et al., 2019; Uhl et al., 2022).

Therefore, increasing importance is being awarded by countries and international bodies to quantifying deadwood stocks in forest ecosystems (Woodall et al., 2009). Under the United Nations Framework Convention on Climate Change, industrialized countries must submit an annual inventory of their greenhouse gas sources and sinks. These inventories include “Land Use, Land-Use Change and Forestry” in which deadwood is one of the five carbon pools. There are also non-binding agreements, such as reporting to the Global Forest Assessment (FRA, 2023) of the FAO or the State of Europés Forests (SoEF, 2020), as requested by FOREST EUROPE every five years. The European Habitats Directive (OJEC, 1992) requires reports every six years under Article 17 on the species and habitat types in order to determine whether the conservation status is favourable, with deadwood also being a key

Abbreviations: NFI, National Forest Inventory.

* Corresponding author.
E-mail address: daniel.moreno@inia.csic.es (D. Moreno-Fernández).

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variable. New legislative proposals have also been put forward, such as the European Commission's proposal for a Nature Restoration Law (COM, 202/304), considering deadwood as a key parameter to be reported for forest ecosystems. Additionally, deadwood has become an important requisite for various certification programs (PEFC, 2010; Vítková et al., 2018). Furthermore, several carbon flux models or soil carbon models such as Yasso require deadwood data as a model input (Hernández et al., 2017; Liski et al., 2005). Therefore, the performance of these models will be enhanced with accurate measurements of deadwood stocks.

As a consequence, deadwood protocols are being integrated into the field tasks undertaken as part of the National Forest Inventories (NFIs) of countries (Rondeux et al., 2012) along with the establishment of international monitoring networks, such as the ICP Forests Programme (Michel et al., 2023; Moreno-Fernández et al., 2020; Puletti et al., 2019; Travaglini et al., 2007). This has allowed to undertake not only national-scale forest deadwood reports for international requirements (as the Global Forest Assessment) but also scientific studies in the United States (Woodall et al., 2008, 2021), Europe (Augustynczik et al., 2024; Puletti et al., 2017), Spain (Alberdi et al., 2020; Moreno-Fernández et al., 2020), Switzerland (Hararuk et al., 2020), Poland (Bujoczek et al., 2021, 2024) or Austria (Oettel et al., 2023) among others.

However, differences in definitions and sampling protocols among the different countries, such as survey design (e.g., fixed-area sample plot, line intersect method), decay-level classification (Herrmann et al., 2023), minimum measurable size or evaluable deadwood component, may hamper comparison among countries (we refer to Rondeux and Sanchez (2010) and Siitonen et al. (2023) for in-depth reviews of different methods to characterize forest deadwood). The most common minimum diameter (diameter threshold) considered for harmonization purposes is 10 cm (FRA, 2023; Rondeux and Sanchez, 2010; SoEF, 2020). In this regard, the FAO definition states that deadwood is "All non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Deadwood includes wood lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter or any other diameter used by the country".

Therefore, it is necessary to develop harmonization tools to provide robust statistics which are comparable among countries. At the beginning of the harmonization process, a reference definition for the focal indicator should be agreed (Tomppo et al., 2010). Then, countries could try to assess the indicator under the reference definition in different ways/tools. Bridge functions can be used for this purpose, i.e. models capable of converting data based on national or local definitions to data based on reference definitions (Ståhl et al., 2012). There are several examples of bridge functions in the case of deadwood. Ligot et al. (2012) and Christensen et al. (2005) proposed curves for converting deadwood volume with a minimum diameter to standardized estimates with other diameter threshold values by fitting curves of the percentage of the measured volume against the change in diameter threshold values. Rondeux et al. (2012) proposed bridge functions to harmonize national deadwood data from different NFIs to provide a common definition through linear models. Similarly, Söderberg et al. (2014) proposed ratios to convert deadwood volume between different threshold diameters in Sweden.

In addition to the harmonization, robust and accurate bridge functions may allow the minimum size values to be increased in future NFIs. This would mean that despite a much-reduced sampling effort, comparisons with previous data could still be made without sacrificing valuable information.

Another gap in NFI deadwood monitoring is the temporal comparison. The temporal series of this variable may be lacking in some countries since, as previously mentioned, deadwood protocols are relatively novel. In Spain, data on deadwood with a minimum diameter of 7.5 cm was first recorded when the field tasks of the Third NFI cycle (1997 – 2007) were already underway. Moreover, in the Second Spanish NFI cycle (1986–1996) information was only recorded for standing dead trees (Alberdi et al., 2020). Hence, for long-term retrospective deadwood analyses, predicting deadwood for the Second NFI requires modelling approaches or the use of ratios between living wood and deadwood, fitted with data from more recent inventories (Alberdi et al., 2020). Other approaches, such as the proportion/ratio of standing deadwood to total deadwood, however, have not been explored in the case of Spain. In this regard, remote sensing applications, such as airborne and terrestrial LiDAR, can provide accurate information on standing dead trees with high spatiotemporal resolution, although their performance in the case of lying deadwood is poorer, often requiring more complex algorithms (Marchi et al., 2018). By combining the ratios of standing deadwood to the overall deadwood and incorporating the data acquired from LiDAR scans of standing dead trees, we can obtain a comprehensive picture of deadwood stocks with notable spatiotemporal precision.

Hence, the aim is to fill gaps in existing deadwood data and contribute to more robust and harmonized assessments of deadwood in forest ecosystems. In this context, we aim to achieve the following specific objectives: i) address the effect of increasing the minimum measurable size on the quantification of deadwood, ii) develop bridging functions capable of converting deadwood measurements with a specific diameter to 7.5 cm (minimum diameter for the Spanish NFI) and 10 cm (the most common threshold diameter for international statistics), and iii) calculate the ratios between the amount of the standing deadwood and the entire deadwood pool and compare the performance of these ratios with the bridging functions. These objectives will be pursued at forest-type level, because this can be a determining factor for forest stocks (e.g., Alberdi et al. (2020) and Oettel et al. (2023) although see Travaglini et al. (2007)).

2. Material and methods

2.1. Deadwood data in the National forest Inventory

The Spanish NFI records information on deadwood in a subplot of a 15 m radius. However, this data is not gathered in every Spanish NFI plot but rather in a sample of plots that accounts for almost 75 % of the total Spanish NFI sample (Alberdi et al., 2017). Thus, 3 out of 4 plots are systematically selected. In Spain, the sampling unit is the province, so it may happen that there are forest types in which the number of plots is low and therefore present an unacceptable error. In these cases, the sample is reinforced when possible. In these plots, the deadwood pieces are classified into the following categories: i) dead standing trees (including, dbh $\geq$ 7.5 cm, height $\geq$ 1.3 m), ii) dead lying trees (dbh $\geq$ 7.5 cm), dead standing and lying saplings (2.5 $\leq$ dbh $<$ 7.5 cm), iii) lying coarse wood pieces/downed branches (diameter at the thinnest end $\geq$ 7.5 cm, length $\geq$ 30 cm), iv) stumps (diameter at midheight $\geq$ 7.5 cm, total height $<$ 1.3 m), v) coppice stumps (representative diameter at mid height $\geq$ 7.5 cm, total height $<$ 1.3 m) and vi) accumulations (diameter $\geq$ 7.5 cm of a representative branch at half length) (Alberdi et al., 2020). Additionally, the species is identified when possible and the degree of decomposition is assigned to each piece according to Hunter (1990) and Guby and Dobbertin (1996). Lying dead trees are measured when the greater diameter of the piece is within the plot, while the other deadwood categories (standing dead trees, branches and stumps) are measured when more than 50 % of the piece is inside the plot (Alberdi et al., 2017).

We selected SNFI plots in which deadwood data was recorded (including plots with deadwood equal to zero) from the most recently sampled set of plots from the 3rd (1997–2007) and 4th NFI (2008 to date), resulting in a data set encompassing 55,463 plots (Fig. 1). We calculated the volume of each piece according to the methodology proposed by Alberdi et al. (2020). Therefore, the volume of the dead trees (stem and branches) was estimated using species-specific equations included in the Spanish NFI. Besides the tree species, these equations also take into account tree shape (Alberdi et al., 2014; MMA, 1990). The

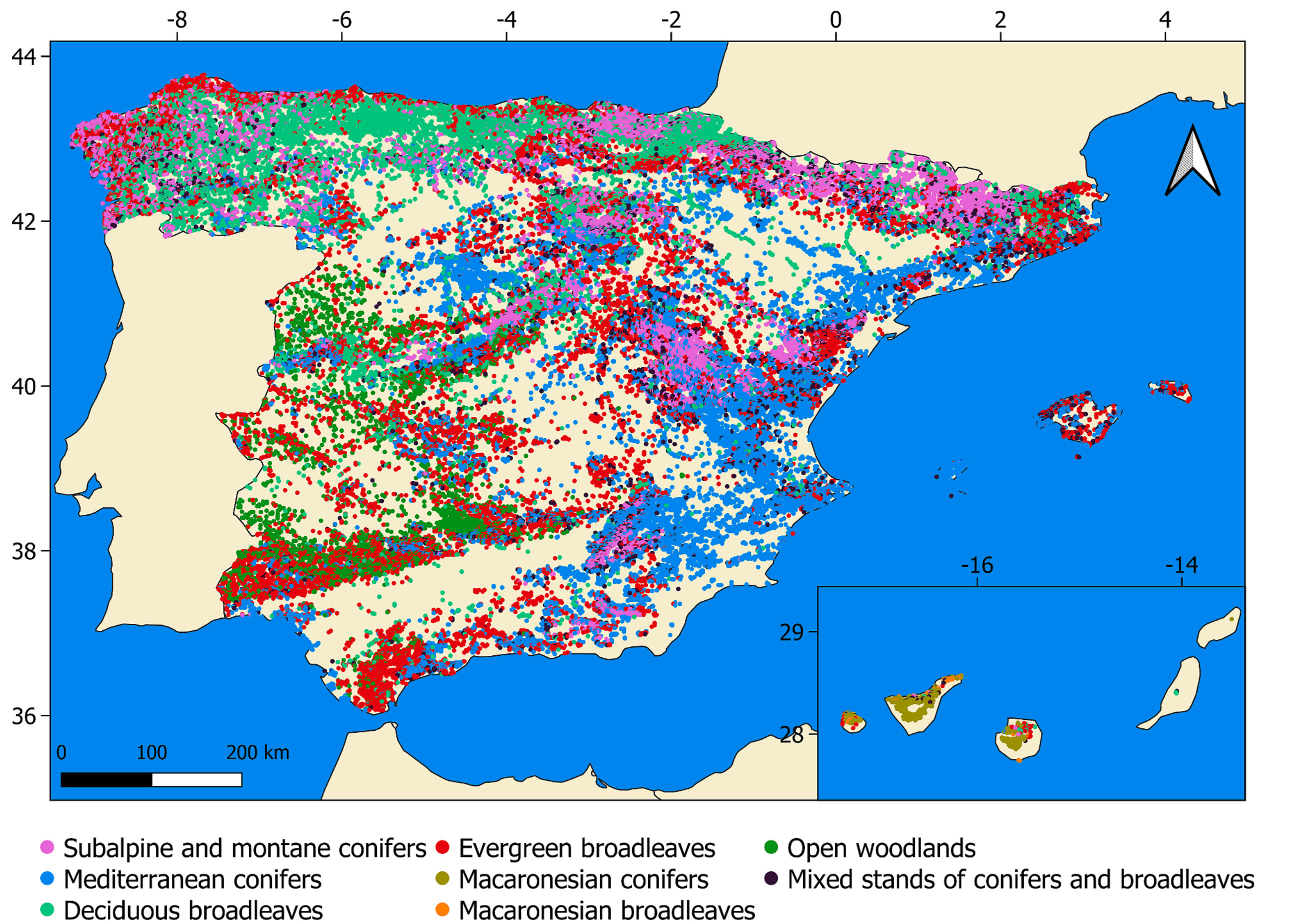

Fig. 1. Location of the plots in the Spanish National Forest Inventory where deadwood samples were collected. The system of coordinates is WG84.

volume of lying coarse wood pieces/downed branches was calculated using Smalian's formula while the Huber's formula was used to calculate the volumes of stumps and accumulations (Crecente-Campo et al., 2016).

We used the Spanish Forest Map to assign a forest type to each plot. In order to facilitate the interpretation of the results, we aggregated these forest types into eight broader spectrum types: i) Subalpine and montane conifers (n = 9,064 plots), ii) Mediterranean conifers (n = 15,058 plots), iii) Deciduous broadleaves (n = 10,102 plots), iv) Evergreen broadleaves (n = 12,988 plots), v) Macaronesian conifers (n = 1,091 plots), vi) Macaronesian broadleaves (n = 171 plots), vii) Open woodlands (n = 2,637 plots) and viii) Mixed stands of conifers and broadleaves (n = 4,352 plots) (Fig. 1). The SNFI also records information on the silvicultural activity (eg., regeneration fellings or thinnings) in the plot. We used this information to assign a binary value of no management/management to each plot.

2.2. Statistical analyses

To achieve the first two specific goals. i.e., address the effect of increasing the size threshold value on the quantification of deadwood and develop bridging functions, we first split the dataset according to eight minimum diameter values or diameter thresholds: 7.5 cm, 10.0 cm, 12.5 cm, 17.5 cm, 22.5 cm, 27.5 cm, 32.5 cm and 37.5 cm. Thus, the first class included pieces with a minimum diameter of 7.5 cm and no restriction for the maximum, the second class included pieces with a minimum diameter of 10.0 cm and no restriction for the maximum and the same for the other classes. We refer to the previous section for a comprehensive description of the deadwood category's diameter measurement location. We then upscaled the volumes to values per hectare (m^3/ha) multiplying the piece volume (in m^3) by 10.000 (m^2/ha) and dividing by the area of the deadwood subplot (m^2). These values per ha were aggregated per plot and threshold value. Hence, there were eight values for deadwood, one for each diameter threshold values. It is important to highlight the fact that the adjustment of the diameter threshold value led to a decrease in the number of plots with deadwood data. In order to mitigate potential bias, we assigned a value of 0 m^3/ha to these plots. This means that the total number of plots (n = 55,463 plots) remained constant, regardless of the minimum diameter size.

Following this, we addressed the impact of raising the deadwood diameter threshold on deadwood quantification using the following formula:

$$Diff_{7.5ji} = 100\frac{(DW_{7.5i} - DW_{ji})}{DW_{7.5i}} \tag{1}$$

where *Diff* is the percentage of deadwood amount omitted when the deadwood values is increased from 7.5 cm to the *j*-th diameter threshold (*j* ranges from 10.0 cm to 37.5 cm) in the *i*-th plot. $DW_{7.5i}$ is the deadwood (m^3/ha) using the 7.5 cm threshold diameter value and DW_{ji} is the deadwood volume of the *i*-th plot calculated using the *j*-th diameter value. These values calculated at plot level were then averaged at country and forest-type level. Since *Diff* did not follow a normal distribution, we also provide median values. We also calculated the percentage of plots without deadwood data when increasing the diameter threshold relative to the total number of plots by forest type and for the entire country.

In order to link the deadwood volume measured of any size to the data for 7.5 cm, we propose the following linear model formulation:

$$DW_{7.5i} = \mu + \alpha DW_{ji} + \beta TH_j + \gamma DW \times TH_{ji} + \varepsilon_{ij} \tag{2}$$

where TH_j (in cm) is the threshold diameter value for each observation, included in the model to take into account the effect of the different diameter value of the observations. $DW \times TH_{ij}$ is the interaction of both variables. μ is the intercept of the model while α, β and γ are the unknown but estimable model parameters. Finally, ε is the model error assumed to follow a normal distribution with mean 0 and standard deviation σ. These linear models were developed for the forest types mentioned above. We assessed the performance of this approach using a 10-fold cross-validation including 70 % of the data in order to train the models and the remainder for validation purposes. For each of the 10 validation splits by forest type, we calculated the R^2 as the square of the correlation between the observed and predicted outcomes (Kvålseth, 1985), bias as the average of the difference between observed and predicted values, root mean squared error (RMSE) as the square root of the average of the square of the error and RMSE in percentage. These statistics were averaged at forest-type level and country level. We used this linear model formulation for the case of the minimum diameter value of 10.0 cm ($DW_{10.0}$). Additionally, we fitted these models again including the binary factor no management/management to be applied in plots where this information is available.

In order to quantify the total amount of deadwood in a given plot when the only data available is that for standing dead trees, we calculated the ratio of the volume of standing dead trees in relation to the total volume of deadwood for each plot (RatioSDT). Subsequently, we created training and validation data as above and calculated the RatioSDTs per forest type. In this case, we also performed a 10-fold cross-validation to evaluate the performance of RatioSDT in the quantification of the total volume of deadwood and calculated the statistics defined above. For the calculation of RatioSDT, we considered only plots with presence of deadwood to skip the ratio 0/0, which is undefined.

3. Results

As expected, we found that the deadwood volume decreased as the diameter value increased, both at national level (whole data set) and for the eight forest types considered (Fig. 2). No notable differences were observed for *Diff* when distinguishing between forest types, which is primarily due to the high variations observed within each forest type (Table 1). Increasing the diameter threshold of the deadwood also involved an increase of the plots without deadwood, which is more remarkable for Macaronesian conifers, Evergreen broadleaves and Open woodlands while the forest type Subalpine conifers was less affected (Fig. 3).

The statistics derived from the 10-fold cross-validation for the bridging functions indicated high predictive capacity. The mean values for R^2 ranged from 0.82 to 0.97 and the mean values of the bias were close to zero, ranging between −0.1198 and 0.0840 (Table 2). The RMSE in percentage for the bridge functions took values between 36 % and 150 %. Despite the binary variable no management/management had a significant contribution to the models, the performance of the models did not vary when including this factor (Supplementary Material 1).

The average values for the RatioSDT ranged between 0.14 (Open-woodlands) and 0.45 (Macaronesian broadleaves). The standard deviation for RatioSDT, however, was higher than the average value for all the forest types, indicating high variability among plots (Table 3). In regard to the 10-fold cross-validation statistics, the R^2 of the forest types reached the largest value for Macaronesian broadleaves (0.69) and the lowest for Macaronesian conifers (0. 26). The negative values of the bias for all the forest types revealed that this approach overestimated the total stocks of deadwood. Finally, the RMSE in percentage reached the lowest values for Macaronesian broadleaves (122 %) and the largest for Open woodlands (887 %).

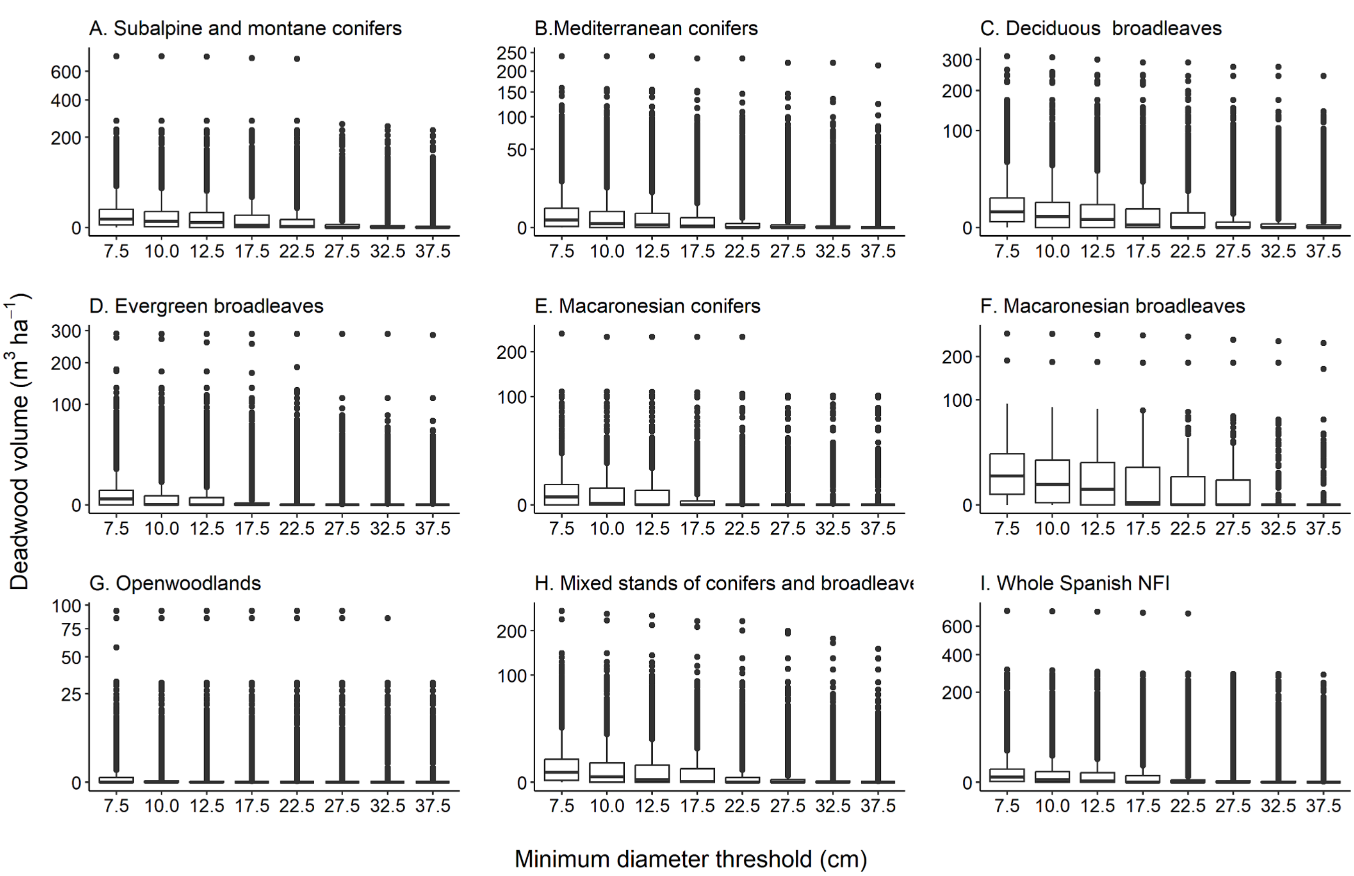

Fig. 2. Boxplots for deadwood volume (m^3/ha) by diameter threshold and forest type.

Table 1
Averaged values ± standard deviation for the percentage of deadwood ($Diff_{7.5j}$) omitted when the minimum diameter threshold is increased from 7.5 cm to 10.0, 12.5, 17.5, 22.5, 27.5, 32.5, 37.5 cm (see equation (1)). Median values are between brackets.

Forest type	$Diff_{7.5-10.0}$	$Diff_{7.5-12.5}$	$Diff_{7.5-17.5}$	$Diff_{7.5-22.5}$	$Diff_{7.5-27.5}$	$Diff_{7.5-32.5}$	$Diff_{7.5-37.5}$
Subalpine and montane conifers	23.7 ± 30.8 (9.4)	36.4 ± 35.9 (23.2)	55.8 ± 38.3 (57.7)	69.3 ± 35.9 (89.9)	78.8 ± 31.9 (98.5)	85.8 ± 27.2 (100)	90.6 ± 22.7 (100)
Mediterranean conifers	27.5 ± 33.9 (11.4)	40.5 ± 38.1 (28.5)	58.7 ± 38.9 (66.1)	71.5 ± 36.1 (94.8)	81.3 ± 31.3 (100)	87.9 ± 26 (100)	92.7 ± 20.6 (100)
Deciduous broadleaves	28.9 ± 33.4 (14.3)	42.9 ± 37.6 (32.2)	60 ± 38.2 (67.4)	70.7 ± 36 (94.3)	77.8 ± 33.1 (99.5)	82.9 ± 30.1 (100)	86.9 ± 27 (100)
Evergreen broadleaves	35.9 ± 38.7 (18.8)	51.5 ± 41 (47.3)	69.6 ± 38.4 (97.3)	79.2 ± 34.3 (100)	85.3 ± 30.1 (100)	89.8 ± 25.8 (100)	92.8 ± 22 (100)
Macaronesian conifers	27 ± 37.6 (5.9)	43.5 ± 42.1 (27.4)	64.5 ± 41.9 (100)	76.8 ± 37.5 (100)	84.8 ± 31.6 (100)	89.7 ± 26.8 (100)	92.7 ± 23.5 (100)
Macaronesian broadleaves	20.1 ± 29.8 (6.9)	37.1 ± 36.4 (23.2)	58.5 ± 38.9 (61.5)	69.1 ± 36.8 (93.5)	76.5 ± 33.9 (100)	83.8 ± 28.9 (100)	88.5 ± 24.4 (100)
Open woodlands	32.7 ± 41.7 (3.3)	43.1 ± 44.3 (21.7)	57 ± 45.2 (82.5)	65.3 ± 43.8 (100)	72.7 ± 41.4 (100)	78.2 ± 38.7 (100)	82.4 ± 35.7 (100)
Mixed stands of conifers and broadleaves	28.1 ± 34.3 (12.1)	41.9 ± 38.8 (29.2)	59.7 ± 39.4 (68.4)	72 ± 36.1 (96.9)	80.7 ± 31.6 (100)	87.4 ± 26.6 (100)	91.8 ± 22.1 (100)
Whole NFI	33 ± 38.7 (13)	41 ± 41.3 (25.7)	52 ± 43.4 (54.7)	59.3 ± 43.9 (84.8)	64.6 ± 43.8 (97.9)	68.3 ± 43.5 (100)	71 ± 43.1 (100)

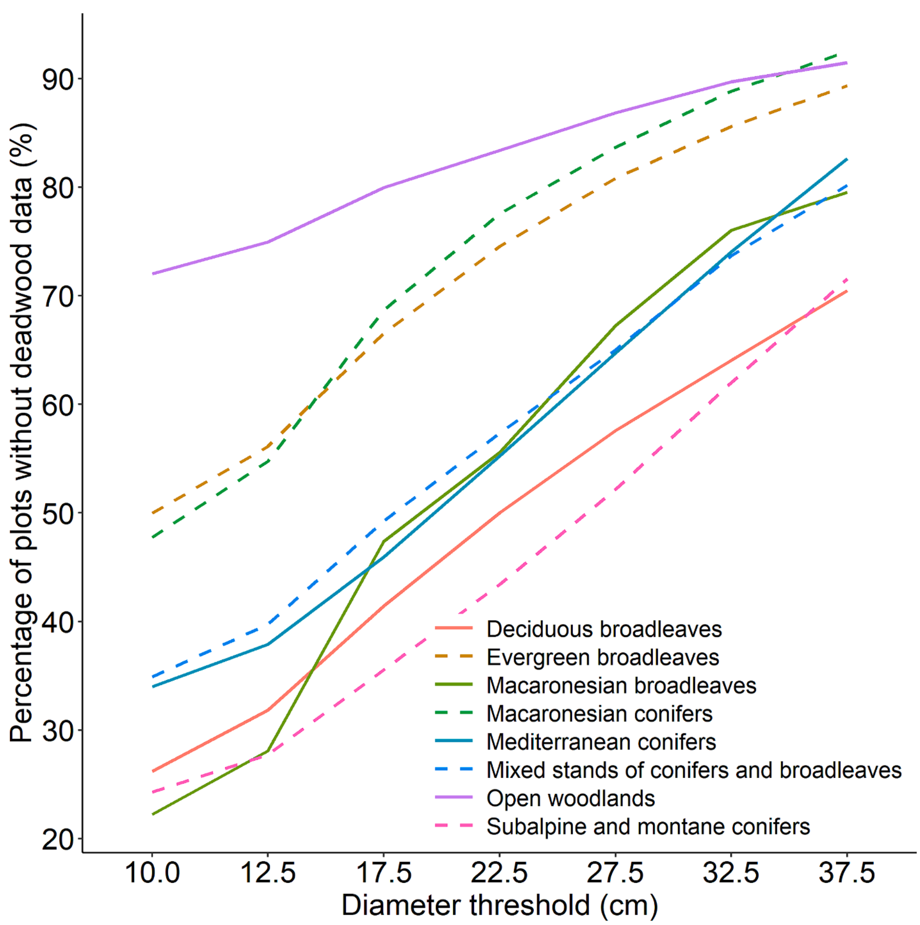

Fig. 3. Percentage of plots without deadwood data relative to the total number of plots by diameter threshold and forest type.

4. Discussion

The bridge functions proposed in this research exhibited adequate validation statistics and were in line with previous bridge functions for deadwood (Rondeux et al., 2012), ensuring their applicability to external data. This external data may embrace areas from other countries with analogous forest types for harmonization purposes, or it could consist of future Spanish NFI data, obtained using a larger size value, thus reducing the required sampling effort.

Our bridge equations can be applied to convert deadwood from any reference diameter to the most common diameter (10 cm) threshold, which can be useful when larger diameter threshold are selected. Our functions are applicable in plots with or without signs of silvicultural operations (Supplementary Material 1), whereas the generic functions are suitable for scenarios where the management status of the plots is unknown (Table 2). According to 'The State of Europés Forest', around 7

Table 2
Bridging function to convert deadwood data (*DW*) measured at any deadwood diameter (*TH*) to a diameter threshold of 7.5 cm and 10.0 cm ($DW_{7.5}$ and $DW_{10.0}$, respectively). R^2, bias and root mean squared error (RMSE, absolute terms and in percentage between brackets) are mean values obtained from a 10-fold cross-validation. $DW_{7.5}$ and DW are deadwood stocks in $m^3\ ha^{-1}$ and *TH* is in cm.

Forest type	Model formulation	R^2	Bias	RMSE
Threshold value of 7.5 cm				
Subalpine and montane conifers	$DW_{7.5}$ = 0.080 + 0.908·DW + 0.094·TH − 0.011·TH·DW	0.92	−0.0100	3.81 (59.69)
Mediterranean conifers	$DW_{7.5}$ = -0.078 + 0.934·DW + 0.061·TH + 0.011·TH·DW	0.84	−0.0043	2.83 (93.22)
Deciduous broadleaves	$DW_{7.5}$ = 0.707 + 0.951·DW + 0.087·TH + 0.009·TH·DW	0.90	−0.0167	4.15 (59.4)
Evergreen broadleaves	$DW_{7.5}$ = 0.386 + 0.968·DW + 0.035·TH + 0.009·TH·DW	0.82	0.0005	2.58 (110.35)
Macaronesian conifers	$DW_{7.5}$ = 0.132 + 0.947·DW + 0.062·TH + 0.007·TH·DW	0.89	0.0144	3.17 (84.79)
Macaronesian broadleaves	$DW_{7.5}$ = 0.790 + 0.869·DW + 0.131·TH + 0.013·TH·DW	0.95	0.0840	4.84 (35.49)
Open woodlands	$DW_{7.5}$ = 0.041 + 1.004·DW + 0.002·TH	0.90	0.0001	1.02 (144.8)
Mixed stands of conifers and broadleaves	$DW_{7.5}$ = 0.069 + 0.938·DW + 0.147·TH + 0.011·TH·DW	0.90	−0.0003	3.23 (73.72)
Whole NFI	$DW_{7.5}$ = 0.224 + 0.932·DW + 0.062·TH + 0.011·TH·DW	0.89	0.0005	3.30 (79.41)
Threshold value of 10.0 cm				
Subalpine and montane conifers	$DW_{10.0}$ = -0.449 + 0.875·DW + 0.087·TH + 0.011·TH·DW	0.93	−0.013	3.43 (63.44)
Mediterranean conifers	$DW_{10.0}$ = -0.369 + 0.877·DW + 0.055·TH + 0.012·TH·DW	0.85	0.0049	2.55 (102.05)
Deciduous broadleaves	$DW_{10.0}$ = -0.217 + 0.917·DW + 0.079·TH + 0.008·TH·DW	0.91	0.0145	3.45 (62.73)
Evergreen broadleaves	$DW_{10.0}$ = -0.118 + 0.927·DW + 0.031·TH + 0.009·TH·DW	0.87	−0.0035	2.01 (121.92)
Macaronesian conifers	$DW_{10.0}$ = -0.233 + 0.911·DW + 0.053·TH + 0.007·TH·DW	0.91	−0.0569	2.51 (85.6)
Macaronesian broadleaves	$DW_{10.0}$ = -0.217 + 0.846·DW + 0.130·TH + 0.012·TH·DW	0.97	−0.1198	4.34 (36.05)
Open woodlands	$DW_{10.0}$ = -0.060 + 0.989·DW + 0.002·TH + 0.002·TH·DW	0.90	0.004	0.81 (149.78)
Mixed stands of conifers and broadleaves	$DW_{10.0}$ = -0.460 + 0.897·DW + 0.064·TH + 0.011·TH·DW	0.91	−0.0046	2.71 (77.32)
Whole NFI	$DW_{10.0}$ = -0.278 + 0.893·DW + 0.056·TH + 0.011·TH·DW	0.91	0.0004	2.79 (0.91)

% of the forest carbon corresponds to deadwood (SoEF, 2020), although a substantial fraction is underestimated when the minimum value is increased from 7.5 cm to 10.0 cm, which, according to our results, leads to around 6–19 % of the deadwood volume (in median terms) being omitted. All of this makes that bridge equations presented here are not only important for harmonization of the carbon budget but also to improve the input in other modelling approaches, eg. Yasso model.

The amount of deadwood omitted highlights the need to consider reference definitions as well as the impossibility of aggregating (without further calculations for comparability) national estimates when the minimum size value considered or the methodologies used for their estimation differ.

Table 3
Ratio of the volume of standing dead trees relative to the total volume of deadwood (RatioSDT; standard deviation in brackets). R^2, bias, root mean squared error in absolute terms (RMSE) and in percentage (RMSE%) are mean values obtained from a 10-fold cross-validation.

Forest type	RatioSDT	R^2	Bias	RMSE	RMSE %
Subalpine and montane conifers	0.25 (0.33)	0.52	−4.86	29.15	309.77
Mediterranean conifers	0.16 (0.29)	0.47	−3.31	22.66	520.54
Deciduous broadleaves	0.29 (0.33)	0.41	−1.48	19.84	210.47
Evergreen broadleaves	0.21 (0.32)	0.38	−1.89	15.98	441.28
Macaronesian conifers	0.27 (0.36)	0.26	−1.03	18.65	279.49
Macaronesian broadleaves	0.45 (0.32)	0.69	−3.16	22.23	121.87
Open woodlands	0.14 (0.32)	0.37	−2.85	15.66	886.84
Mixed stands of conifers and broadleaves	0.23 (0.32)	0.44	−2.26	17.26	292.90
Whole NFI	0.22 (0.32)	0.41	−3.07	23.39	371.11

The validation statistics (modest R^2 and overestimation) for the RatioSDT suggest that this approach should be used with caution. Similarly, in Alberdi et al. (2020), it was also found that deadwood stocks were overestimated when employing the ratio of deadwood to living biomass (in biomass weight units) but R^2 was not provided, which complicates the comparison between methodologies. Moreover, the only alternative to estimating deadwood data when a given inventory does not include deadwood measurements is to use these ratios or other modelling approaches (Alberdi et al., 2020; Doerfler et al., 2017; Moreno-Fernández et al., 2020).

The RatioSDT varied considerably depending on forest type, which can be explained by differences in forest management. In this regard, Christensen et al. (2005) found that the ratio of standing deadwood with respect ranged from 25 % to 45 % in *Fagus sylvatica* L. forests depending on the *F. sylvatica* forest type. These values closely align with ours in Deciduous Broadleaves (29 % ± 33 %), a forest type that encompasses *F. sylvatica*. Furthermore, previous works already highlighted the importance of stand variables such as age, stem density or average height together with thinning intensity to predict deadwood stocks (Richardson et al., 2009; Russell et al., 2012). Despite the mentioned variations in RatioSDT, the standing dead trees are an important category for the total stock of deadwood accounting, with values ranging from 0.14 to 0.45. In this regard, it is important to note that standing dead trees and downed dead trees are the categories that store the largest amount of deadwood (Alberdi et al., 2020; Christensen et al., 2005). However, forest management modifies both the amount of standing dead trees (Oettel et al., 2023) and the remaining deadwood categories (Paletto et al., 2014). This might influence potentially the established relationship between the standing dead wood and the total amount of deadwood (Christensen et al., 2005).

In this study, we considered all pieces with a diameter larger than 7.5 cm regardless of their category. Many NFIs, however, do not include stumps or accumulations (Woodall et al., 2009). These two categories are the least relevant for deadwood quantification, accounting just for 6 % of the total deadwood fraction (Alberdi et al., 2020). Given the ease of identification and measurement of standing and lying dead trees in the field, especially in scenarios where budget constraints and limited objectives prioritize the reporting of deadwood volume or biomass, focusing solely on these categories could be a pragmatic approach. This targeted recording may not significantly compromise the accuracy of the data, making it a practical and resource-efficient strategy.

Increasing the minimum diameter implies an increase of the plots without deadwood which is relevant for deadwood stocks estimation. From a modelling point of view, raising the amount of zero complicates the statistical analyses and restricts the statistical approaches available. In these cases, models with a Tweedie distribution of errors or hurdle-gamma models can be powerful alternatives (Alberdi et al., 2020; Rebollo et al., 2024). However, Tweedie is a three-parameter distribution while hurdle-gamma models require two equations (binomial and gamma) to be fitted (Brooks et al., 2017; Tweedie, 1984), which may complicate the analyses (but see glmmTMB R package).

In this study, however, concerns regarding deadwood estimates and data gap filling are not addressed. For instance, the relevance of deadwood with a diameter of less than 7.5 cm remains unclear in the case of Spanish forests as only standing and lying saplings between 2.5 cm and 7.5 cm are monitored (but not included in this study), lacking the rest of deadwood fractions. Moreover, the task of estimating the contribution of this smaller deadwood is complicated by the lack of data. This fact restricts the development of bridge functions for deadwood without restrictions in diameter, curves for deadwood versus diameter or curves relating the deadwood percentage loss and the deadwood threshold (Ligot et al., 2012), given that a model should not be used to extrapolate values for points outside the range of training data (Hahn, 1977; Menéndez-Miguélez et al., 2021).

Both the bridge equations and the percentages of standing dead trees were calculated using the fixed plot area method, i.e. sampling the deadwood with a given size value within a plot (with 15 m radius in the case of Spain). However, apart from this methodology, other approaches can be used for deadwood stocks quantification, such as point transect sampling or line intersect sampling, which are commonly used in NFIs (Rondeux et al., 2012) given their efficiency and reduced sampling effort (Ritter and Saborowski, 2012, 2014). The estimates of deadwood stocks, however, may vary among methodologies. Hence, we recommend that the approaches presented here must be applied with caution when other sampling methods are used.

Finally, awareness should also be given to the role of remote sensing applications for deadwood quantification, such as terrestrial and airborne laser scanning (see review in Marchi et al. (2018)). Combined with traditional field sampling, the use of these novel approaches based on remote sensing could help to fill the gaps in the data and provide more complete and robust statistics. Furthermore, these methods could provide deadwood data at annual scale, thus addressing the issue of time intervals between inventories, which is one of the limitations of the NFIs. Moreover, combining data for standing dead trees derived from remote sensing with RatioSDT opens a new avenue for deadwood monitoring.

5. Conclusions

The estimation of deadwood stocks is highly dependent on the minimum size considered and therefore, harmonization tools are required for comparison purposes. In this regard, the bridge functions proposed in this research have been shown to provide a powerful tool for this purpose and/or to reduce the sampling efforts in upcoming cycles of the NFIs. The ratio of standing dead trees relative to the total deadwood volume, however, tends to overestimate deadwood, as reported with previous approaches, which suggests that there is a room to improve approaches for retrospective analyses.

Currently, the most commonly used threshold for deadwood quantification is a minimum diameter of 10 cm. We have estimated that increasing the diameter threshold from 7.5 cm to 10.0 cm, which implies omitting around 6–19 % of the deadwood volume according to median values. These results should be taken into account in the establishment of new monitoring networks.

Finally, the fact that our analyses were performed at forest-type scale allows extrapolation to other countries with similar forest types.

CRediT authorship contribution statement

Daniel Moreno-Fernández: Writing – original draft, Formal analysis. **Isabel Cañellas:** Writing – review & editing, Resources, Conceptualization. **Laura Hernández:** Writing – review & editing. **Patricia Adame:** Writing – review & editing. **Iciar Alberdi:** Writing – review & editing, Resources, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Data availability statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request. NFI plot information is freely available at MITECO repository, https://www.miteco.gob.es/en/biodiversidad/servicios/ banco–datos naturaleza/informacion–disponible/.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.112112.

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