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forest ecology

Direct and Indirect Assessment of Carbon Stock in Deadwood: Comparison in Calabrian Pine (*Pinus brutia* Ten. subsp. *brutia*) Forests in Italy

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Deadwood is a key element in forest ecosystems contributing to biodiversity conservation, carbon (C) stocking and cycling, and nutrient inputs to soil. Forest management has an important role to maintain deadwood temporary C stock by regulating the amount of deadwood in forests during harvesting operations. Deadwood C stocks can be estimated directly, by measuring C concentration in deadwood samples, or indirectly, by converting the biomass into the amount of C stored in the deadwood. The aim of the study was (1) to compare direct and indirect methods for deadwood C stocks estimation; (2) to determine differences between the two methods; and (3) to evaluate the most appropriate, easiest, and least expensive method depending on specific circumstances. The investigation was implemented in a Calabrian pine (*Pinus brutia* Ten. subsp. *brutia*) forest located in Central Italy. In 18 sample plots, deadwood biomass was measured separately by component (logs, snags, stumps) and decay class. During a field survey, 150 deadwood samples were collected and analyzed in the laboratory for moisture content, mass determination, and direct and indirect estimation of C content. The results showed small differences in the estimation of deadwood C stock using direct and indirect methods. We propose that indirect estimation of C stock, which is less demanding of time and monetary resources, can replace direct estimation, and using the same coefficient for different deadwood components and decay classes produces reliable estimates.

Keywords: carbon allocation, coarse woody debris, decomposition, forest management practices, sustainable forest management planning

Deadwood is an important component of forest ecosystems that includes nonliving components such as stems of dead trees lying on forest floor (logs), standing dead trees (snags), stumps, branches, and wood boles in all stages of decomposition (Harmon et al. 1986). In traditional forest management, deadwood was removed during thinning and final cutting because it was considered an obstacle to forest-management practices (Travaglini et al. 2007) and a potential source of biotic and abiotic stresses (Marage and Lemperiere 2005, Pastorella et al. 2016). Since the 1990s, with the implementation of sustainable forest-management principles, deadwood volume is considered as one of the most important indicators of forest biodiversity (Lassauce et al. 2011). Deadwood is considered a fundamental habitat for numerous rare and endangered species (Nordén et al. 2004, Persiani et al. 2015); an important seed bed for regenerating trees, ferns, and mosses (Marage and Lemperiere 2005); a key factor in nutrient cycling (Krankina and Harmon 1995); an important element in geomorphological and soil hydrological processes (Bragg and Kershner 1999); and for temporary C storage contributing to climate change mitigation (Kueppers et al. 2004).

According to the Intergovernmental Panel on Climate Change (IPCC 2003), deadwood represents an important forest carbon pool. The C stored in forests and its dynamics are information required by the United Nations Framework Convention on Climate Change-UNFCCC (1992), the Kyoto Protocol (1997), and the Marrakesh Accords (2001). The "Good Practice Guidance for Land Use, Land Use Change and Forestry" by IPCC (2003) recommends the measurement of the input and output of the five forest C pools (aboveground biomass, belowground biomass, deadwood, litter, and soil). Within these C pools, deadwood often accounts for 10–20% of the aboveground biomass in mature forests (Brown 2002, Guldin and Kaiser 2004).

In accordance with the above-mentioned documents, changes in the amount of stored C must be inventoried and monitored over time (Rock et al. 2008, Teissier du Cros and Lopez 2009). Changes in deadwood C stocks depend on many variables such as forest type,

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micro-climatic conditions, weather conditions (temperature and moisture), and forest-management practices (Green and Peterken 1997). Deadwood C stocks are influenced by forest practices adopted to maintain biodiversity and temporary C stocking to achieve management goals (Edwards et al. 2012). In practice, a percentage of snags and logs must be maintained in the forest during harvesting operations. This percentage depends on site and stand characteristics, and strategic objectives of forest management (Edwards et al. 2012).

At the national level, data on deadwood volume are available from National Forest Inventories (NFIs) (Tomppo et al. 2010), whereas C storage is obtained by converting the volume mass into the amount of C stored in the deadwood pool (Di Cosmo et al. 2013). Basic wood density must be known for this conversion. Normally, C content in deadwood is estimated to be about 50.0% of mass (Coomes et al. 2002), with estimates for conifers ranging between 52.1% (Birdsey 1992) and 48.0% (Tobin et al. 2007). However, a lack of information on C conversion constants has been highlighted (Woodall et al. 2008). Di Matteo et al. (2015) found C concentrations lower than the conventional 50.0% in most cases, leading to possible systematic errors.

Alternatively, deadwood C stock can be assessed through direct estimation, measuring C concentration in deadwood samples. The dry combustion method through an elemental analyzer is commonly used to directly determine C pools, which has been demonstrated to be more reliable than other methods based on C oxidation in forest ecosystems (Lettens et al. 2007). Moreover, the dry combustion method gives a direct measurement of nitrogen (N) content, also providing information about deadwood N stocking and organic-matter quality (C/N ratio). Although precise, the direct method is labor-intensive and cost-prohibitive. Thus, we tested if indirect methods, which are less labor-intensive and expensive, are reliable to measure C stocks in this forest type.

Starting from these considerations, the aim of this paper was to compare the deadwood C stock estimation using basic density by decay class and the C stock estimation with the direct method. The study was implemented in a Calabrian pine (*Pinus brutia* Ten. subsp. *brutia*) forest in Central Italy (Monte Morello forest in the Tuscany region). The Calabrian pine forest was chosen because few studies on deadwood in this type of forest are available in the international literature (La Fauci et al. 2006, Karahalil et al. 2017). In addition, degraded Calabrian pine forests—such as the Monte Morello forest—have high log and snag volumes, and are important terrestrial carbon reservoirs (De Meo et al. 2017).

The results of the present study may improve the accuracy and precision of C estimates reported in the national inventories and provide quantitative and qualitative indications on different deadwood components (logs, snags, stumps) and decay classes, which are lacking. In addition, the results increase the information available to forest managers on deadwood management for climate change mitigation objectives. In particular, the coefficients provided for the Calabrian pine by this study can be used to define the correct amount of deadwood volume to mitigate climate change taking into account tradeoffs and synergies with other forest-ecosystem services.

Materials and Methods

Study Area

The study site was located in the peri-urban forest of Monte Morello (43°51′20″N; 11°14′23″E), near the urban area of Florence in Central Italy (Tuscany region). The peri-urban forest of Monte Morello covers a surface of about 1,035 hectares, derived from a reforestation carried out for soil protection objectives in the early 1900s. The main tree species used were: Calabrian pine (*Pinus brutia* Ten. subsp. *brutia*), Austrian black pine (*Pinus nigra* J.F. Arnold), cypress (*Cupressus* spp.), flowering ash (*Fraxinus ornus* L.), Turkey oak (*Quercus cerris* L.), and downy oak (*Quercus pubescens* L.). Currently, Monte Morello forest is a Calabrian pine and Austrian black pine-dominant forest, collectively representing more than 80.0% of the basal area (Cenni et al. 1998). Forest-management practices (i.e., thinning) have not been applied during stand development, and forest stands have been largely abandoned, with important consequences with regard to tree stability, mortality, and forest fire risk.

The altitude is between 55 m and 934 m a.s.l. The climate is typically Mediterranean with precipitation concentrated in the period from autumn to early spring. July is the driest month, whereas October and November are the wettest months. During the last decades (from the early 1980s), the total annual rainfall was 1,003 mm, and the average annual temperature was 13.9°C.

Field Measurements

The data were collected in 18 sample plots (circular fixed-area plot of 531 m^2) randomly located in the Monte Morello peri-urban forest. In each sample plot, all coarse woody debris pieces with a diameter greater than 5 cm were measured distinguishing by component (Di Cosmo et al. 2013): (1) logs (sound and rotting pieces of wood located on the ground); (2) snag (standing dead trees with a height greater than 1.3 m); and (3) stumps (standing dead trees truncated or cut to a height of less than 1.3 m). The 5-cm threshold was adopted because large deadwood is considered the most important component for biodiversity conservation (Nordén and Paltto 2001, Nordén et al. 2004) and C storage (Stevens 1997).

For each log in the sample plot, two diameters in the minimum section, two diameters in the end section, and the distance between the minimum section and the end section were measured (length of log). The minimum section was determined by measuring the diameter along the stem up to 5 cm. For snags and stumps, two diameters—at the cutting plane or broken height for the stump and

Management and Policy Implications

The results of the present study show that indirect estimation of deadwood C stock can replace direct estimation when necessary, allowing a faster and cheaper procedure for C stock determination in forests. These results can be useful for decisionmakers (forest managers and planners) to estimate the potential contribution of the deadwood to the carbon cycle in forest ecosystems. In addition, these results allow us to understand the role of forest deadwood in relation to climate change mitigation which helps decisionmakers in the choice of the most suitable forest management practices to enhance this forest component. Finally, the present study provided fresh density and basic density of Calabria pine (*Pinus brutia* Ten. subsp. *brutia*) distinguished by decay class (five decay-class classification system) and component (standing dead trees, lying deadwood, and stumps). These data will be useful for the scientific community and decisionmakers to develop future studies on C storage and C sequestration in the Calabrian pine forests.

at 1.4 m height for snags—and the height of standing dead tree (or height of stump) were measured. In addition, for each log, snag, or stump, two qualitative features were identified and recorded: species and decay class.

Decay class is a key variable to consider for deadwood C stock estimation, and it depends on the time since death and influence by the local environment (temperature and rainfall), species-specific decay rates, and substrate quality (Laiho and Prescott 2004). Decay class was assigned using the five decay-class classification system based on visual, geometric, and tactile features (Hunter 1990). The visual assessment of decay class has been executed considering the following key visible features (Næsset 1999, Paletto and Tosi 2010): (1) structure of bark; (2) presence of small branches with a diameter of less than 3 cm; (3) softness of wood; and (4) other visible characteristics (rot extension and development of fungus mycelium).

The volume of logs (V_l) was estimated using Huber's formula:

$$V_l = \frac{\pi}{4} \cdot L_l \cdot \left(\frac{D_l + d_l}{2}\right)^2 \tag{1}$$

where L_l is the length of a log (m), D_l is the maximum diameter as the average of two diameters in the end section (m), and d_l is the minimum diameter as the average of two diameters in the minimum section (m).

The volume of snags (V_s) was calculated using the following equation (Cannell 1984):

$$V_s = f \cdot \mathrm{BA} \cdot h \tag{2}$$

where BA is the basal area (m^2), f is the stem form factor of 0.5, and h is the height obtained from the hypsometric curve (m).

The volume of stumps (V_{st}) was calculated using the following equation:

$$V_{st} = \frac{\pi}{4} \cdot \left(\frac{H_{st} + h_{st}}{2}\right) \cdot \left(\frac{D_{st} + d_{st}}{2}\right)^2 \tag{3}$$

where H_{st} is the maximum height of stump (m), h_{st} is the minimum height of stump (m), D_{st} is the maximum diameter (m), and d_{st} is the minimum diameter (m).

In accordance with the procedure proposed by Paletto and Tosi (2010), 150 deadwood samples (cylindrical core) for logs, snags, and stumps in the plots were collected using a battery drill (20.4 V) with a modified bit. The modified bit was used to remove standard cylinders of wood with a volume between 15.3 cm^3 and 56.5 cm^3. The diameter of the cylinder was fixed (3 cm), whereas the length was variable and was measured by a caliper with an accuracy of 1/10 mm. In particular, 50 deadwood samples of Calabrian pine per component (logs, snags, and stumps) were collected. For each component, 10 samples per decay class were collected.

Other forethoughts adopted during the field measurements were: working only in days with dry weather (that is, two days without rain) and conservation of deadwood samples in hermetic plastic bags. These forethoughts were adopted in accordance with the protocol for the collection of deadwood samples of the 2nd Italian National Forest Inventory (Di Cosmo et al. 2013). These indications are based on empirical data collected and analyzed in prior studies in Italy (Morelli et al. 2007, Paletto and Tosi 2010).

Laboratory Analysis

The deadwood samples collected in the field were analyzed in laboratory for moisture content and mass determination. In order not to alter the quality of deadwood samples and moisture level, the analysis was carried out within 24 h of sample collection. The tests were carried out over three days: during the first day, the fresh weight of the deadwood sample was determined using an analytical balance. Subsequently, the sample was dried in the oven for 48 h at the temperature of 50°C. During the third day, the sample was reweighed for the determination of the dry weight after cooling in a dryer with silica gel. The data obtained from the laboratory analyses were used to calculate the moisture content (MC_d) using Equation 4:

$$\mathrm{MC_d} = \frac{W_w - W_d}{W_d} \times 100 \tag{4}$$

where MC_d is moisture content as a percentage of oven-dry weight (%), W_w is green weight of wood (g), and W_d is oven-dry weight of wood (g). In addition, fresh (or green) density (D_w) and basic (or dry) density (D_d) were calculated, starting from laboratory data. The results of the laboratory analysis allowed us to determine moisture content, fresh density, and basic density of Calabria pine deadwood by component and decay class.

Carbon Content Estimation

Indirect Estimation

The C stock in deadwood was indirectly estimated by converting the deadwood volume into the mass of C stored. Volumes in plots were converted to mass using the appropriate basic density value distinguished by component and decay class. Subsequently, deadwood mass was converted to the corresponding C storage using a C content coefficient. In accordance with the IPCC (2003), C content of deadwood is approximately 50.0%. Direct chemical analysis for C shows that there are differences linked to the species and to the method. The C content of pine wood obtained both by direct analysis and by extractive analysis is 49.9% (Matthews 1993). Several studies carried out in North America and Europe have estimated the C content in the pine species to be between 45.8% and 50.9% (direct analysis). The equation used to estimate the C stock was as follows:

$$C_i = \sum_{i=1}^{i-5} \sum_{j-1}^{j-3} V_{ij} \cdot D_{d_{ij}} \cdot 0.4991 \tag{5}$$

where C_i is the total carbon stock (C stock) (g) estimated indirectly, V_{ij} is the volume of component j and decay class i (m^3), $D_{d_{ij}}$ is the basic wood density of component j and decay class i (g cm^{-3}), and 0.4991 is the carbon factor of pine wood from literature.

Direct Estimation

After oven drying, deadwood samples were homogenized with a cutting mill (Retsch SM100) and a rotor speed of 1500 min^{-1} until a final fineness of 0.25 mm was obtained. The C content of the homogenized samples was measured by dry combustion on a Thermo Flash 2000 CN soil analyzer (Thermo Fisher Scientific). To this aim, 10–20-mg samples were weighed into Ag-foil capsules and loaded into an automatic sampler. The samples in the capsules were then dropped into a combustion tube at a temperature above 900°C, in a constant stream of helium as the carrier gas. In "flash combustion," the sample is converted rapidly and quantitatively into its gaseous components (pure N_2 and CO_2). The gaseous combustion products are carried by the helium through another tube filled with reduced copper. Water is removed by a magnesium perchlorate trap. Finally, the detection is carried out using a thermal conductivity detector that produces an electrical signal proportional to the concentration of N and C. The final result is the percentage content of N and C contained in the original sample.

The carbon content calculation was performed using the following formula:

$$C_{\mathrm{d}} = C_{\%} \cdot D_{\mathrm{mass}} \tag{6}$$

where: C_{d} = C analyzed by direct estimation (MgC ha^{-1}), $C_{\%}$ = percentage C content, and D_{mass} = mass of deadwood (Mg ha^{-1}).

Overall, 150 deadwood samples were analyzed, with a number of replicates for each deadwood component and decomposition class ranging from 7 to 25. Statistical analysis was performed on C percentage of deadwood, by factorial ANOVA using deadwood components and decay classes as independent variables, followed by Fisher's LSD post hoc test, to assess differences among deadwood components in the same decay class and differences among decay classes for the same deadwood component (Statistica 7, StatSoft Inc.).

Results

Moisture Content, Fresh Density, and Basic Density

The results of our laboratory analysis (Table 1) showed that the first decay class was characterized by the lowest moisture content (*U*%) (74.8% for logs, 78.3% snags, and 49.9% for stumps). Conversely, the highest moisture content occurred in the samples of the 2nd decay class for logs (154.7%), and of the fourth decay class for snags (187.0%) and stumps (151.2%). The fresh density values were between 0.302 g cm^{-3} and 0.764 g cm^{-3} for the logs, between 0.243 g cm^{-3} and 0.753 g cm^{-3} for the snags, and between 0.399 g cm^{-3} and 0.914 g cm^{-3} for the stumps. In all cases, the downward trend from the first to fifth decay class was confirmed. Concerning the values of basic density estimated for five decay classes and three components, the results confirmed the descending trend from the first decay class to the fifth decay class (Figure 1). The average losses of initial mass because of the transaction from a decay class to the next were 20.5% for logs (range between 27.8% from third to fourth decay class and 12.6% from first to second decay class), 21.9% for snags (range between 36.5% from fourth and fifth decay class and 9.8% from first to second decay class), and 25.9% (range between 47.6% from first and second decay class and 15.6% from third and fourth decay class).

Table 1. Moisture content (*U*%), fresh density (D_w), and basic density (D_d) of Calabrian pine deadwood by component and decay class.

Component/decay class	*U*%	D_w (g cm^{-3})	D_d (g cm^{-3})
Logs			
Decay class 1	74.8	0.7640	0.4470
Decay class 2	154.7	0.6680	0.2726
Decay class 3	143.3	0.5570	0.2357
Decay class 4	103.1	0.4023	0.2048
Decay class 5	126.8	0.3019	0.1330
Snags			
Decay class 1	78.3	0.7534	0.4176
Decay class 2	86.4	0.7160	0.3767
Decay class 3	102.0	0.6181	0.3113
Decay class 4	187.0	0.6580	0.2366
Decay class 5	74.9	0.2418	0.1503
Stumps			
Decay class 1	49.9	0.9137	0.6349
Decay class 2	92.7	0.6111	0.3327
Decay class 3	100.4	0.5268	0.2562
Decay class 4	151.2	0.5063	0.2163
Decay class 5	111.8	0.3985	0.1782

C Stock Estimation

The results showed that Monte Morello peri-urban forest was characterized by a high quantity of deadwood (75.1 m^3 ha^{-1}) compared with the average of Italian forests (8.8 m^3 ha^{-1}). The deadwood volume was concentrated in the logs with an average volume of 59.9 m^3 ha^{-1} followed by snags (13.9 m^3 ha^{-1}) and stumps (1.25 m^3 ha^{-1}). Considering the distribution of deadwood volume by decay class, the results showed that in Monte Morello, the volume of logs was concentrated in the third decay class (54.0% of total volume) followed by the second and fourth decay class (respectively with 25.0% and 14.0% of total volume). The volume of snags was equally distributed among the first three decay classes (with 32.0%, 35.0%, and 32.0%, respectively, of total volume of this component). The volume of stumps was concentrated in the third and fourth decay classes (respectively 56.0% and 32.0%).

Starting from these data, the total C stock in deadwood in Monte Morello peri-urban forest was 9.94 MgC ha^{-1} (7.29 MgC ha^{-1} in logs, 2.50 MgC ha^{-1} in snags, and 0.15 MgC ha^{-1} in stumps).

In addition, the results showed that C percentage in deadwood ranged from 47.0 to 54.0%, with a mean value of 49.1% (Figure 2, top). Among deadwood components, stumps showed on average a higher C percentage, significant in the first, third, and fifth decay classes. Among decay classes, stumps and logs showed the highest C percentage in the first and forth decay classes, respectively, whereas snags did not show any significant differences.

N percentage content (Figure 2, middle) showed a clear trend among decay classes, with the ranking decay class 5 > decay class 4 > decay class 1, 2, and 3 for logs and snags; for stumps, class 1 showed lower values than class 2 and 3, also. Within each decay class, no difference was observed among deadwood components. As a consequence, deadwood C/N ratio revealed an opposite trend showing the ranking decay class 1 > decay class 2 and 3 > decay class 4 and 5 for logs and stumps, decay class 1 and 2 > decay class 3 > decay class 4 and 5 for snags. In the first decay class, the C/N ratio (Figure 2, bottom) was highest value in stumps and lowest in snags, whereas no differences among deadwood components were observed in other decay classes.

Comparing direct and indirect estimation, C content (MgC ha^{-1}) showed the same trend, with the highest stock in the logs, in the second and third decay classes (Table 2). A highly significant linear regression (Figure 3) between the two methods, independent of deadwood component or decomposition class, was found

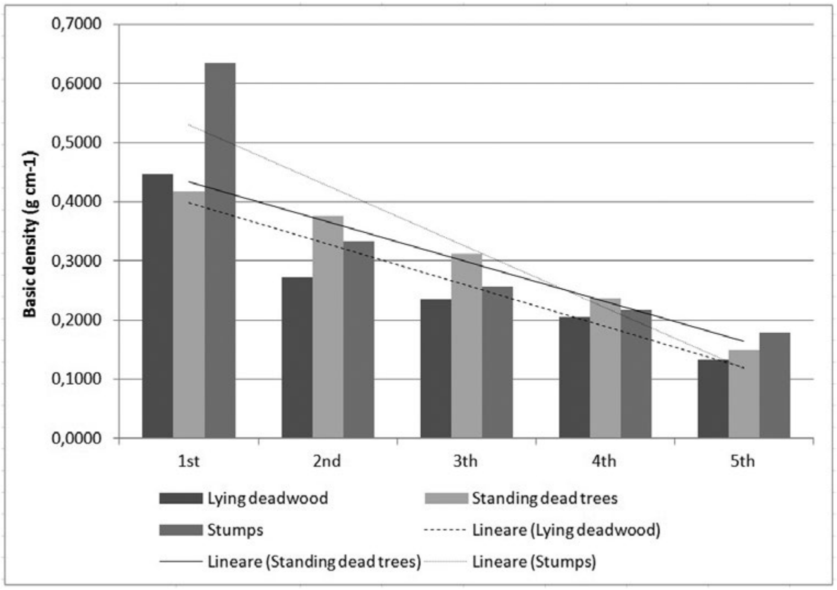

Figure 1. Basic density values (g cm^{-3}) of Calabrian pine deadwood by component (logs, standing dead tree, stumps) and decay class (five-class classification system).

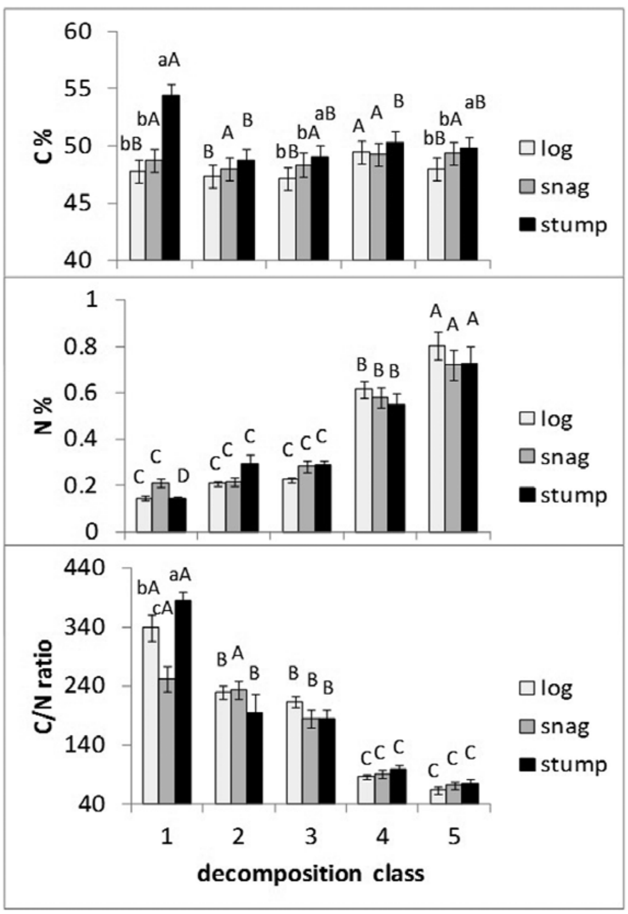

Figure 2. C (top) and N (middle) percentage and C/N ratio (bottom) of Calabrian pine deadwood by component and decay class. Different lower-case letters (when reported) indicate significant differences among deadwood components (log, snag, stump) in the same decay class; different upper-case letters indicate significant differences among decay classes in the same deadwood component (Fisher LSD post hoc test).

($y = 0.9661x + 0.007$, $R^2 = 0.9999$). Finally, the results showed small differences in the estimation of deadwood C stock using direct and indirect methods (Table 2). For the five decay classes of logs, the average difference was 0.0417 MgC ha^{-1} (range between –0.007 MgC ha^{-1} of fourth decay class and 0.135 MgC ha^{-1} of third decay class), whereas the average difference for the five decay classes of snags and stumps was 0.0068 MgC ha^{-1} (range between –0.0007 MgC ha^{-1} and 0.0186 MgC ha^{-1}) and –0.0001 MgC ha^{-1}, respectively (range between –0.0030 MgC ha^{-1} and 0.002 MgC ha^{-1}).

Discussion

The results of the present study are comparable with those reported by Paletto and Tosi (2010) for three alpine pine species (Table 3): Austrian black pine (*Pinus brutia* Ten. subsp. *brutia*), Scots pine (*Pinus sylvestris* L.), and Swiss pine (*Pinus cembra* L.). The comparison of the results among species shows higher values of moisture content for the Calabrian pine than the other three pine species. These differences are probably due to different climatic and micro-climatic conditions between alpine and Mediterranean forests.

Renvall (1995) estimated the basic density for four decay classes of Scots pine deadwood in Finland (0.2673 g cm^{-3} first decay class, 0.2444 g cm^{-3} second decay class, 0.2171 g cm^{-3} third decay class, 0.1939 g cm^{-3} fourth decay class), whereas Söderström et al. (2007) estimated the following wood density values for Scots pine in Sweden: 0.2170 g cm^{-3} first decay class, 0.2315 cm^{-3} second decay class, 0.2425 g cm^{-3} third decay class, 0.2569 g cm^{-3} fourth decay class.

The results of the present study on deadwood C stock are comparable with those of other similar studies. The values of C stock are influenced by multiple variables such as development stage and forest-management practices. In this sense, Paletto et al. (2014) highlighted that the C stock in deadwood is strongly influenced by forest management. These authors estimated a C content in oak (*Quercus* spp.) forests in the south of Italy between 2.28 MgC ha^{-1} (0.98

Table 2. Volume (m^3 ha^{-1}), mass (Mg ha^{-1}), and direct carbon content (MgC ha^{-1}) of Calabrian pine deadwood by component and decay class.

Component/decay class	Volume (m^3 ha^{-1})	Mass (Mg ha^{-1})	Indirect C-stock (MgC ha^{-1})	Direct C-stock (MgC ha^{-1})
Logs				
Decay class 1	2.9	1.3	0.6347	0.6216
Decay class 2	15.05	4.1	2.0082	1.9441
Decay class 3	32.37	7.63	3.7343	3.5992
Decay class 4	8.51	1.74	0.8529	0.8604
Decay class 5	1.09	0.14	0.0707	0.0672
Snags				
Decay class 1	4.48	1.87	0.9159	0.9105
Decay class 2	4.82	1.81	0.8883	0.8697
Decay class 3	4.48	1.39	0.6827	0.6723
Decay class 4	0.12	0.03	0.0141	0.0148
Decay class 5	0.02	0.003	0.0013	0.0010
Stumps				
Decay class 1	0.002	0.001	0.0005	0.0010
Decay class 2	0.07	0.02	0.0119	0.0097
Decay class 3	0.7	0.18	0.0876	0.0883
Decay class 4	0.4	0.09	0.0423	0.0453
Decay class 5	0.07	0.01	0.0065	0.0050

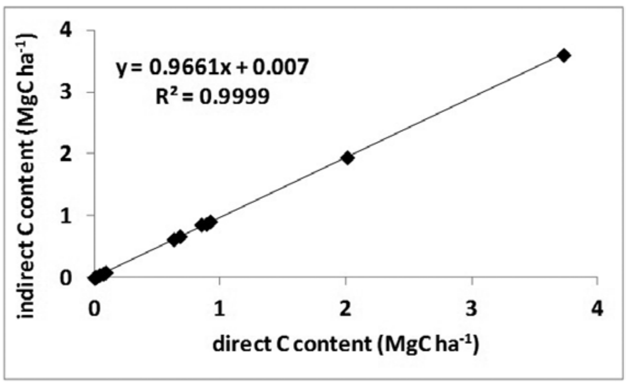

Figure 3. Linear regression between direct and indirect C estimation of Calabrian pine deadwood.

MgC ha^{-1} logs, 0.82 MgC ha^{-1} snags and 0.48 MgC ha^{-1} stumps) for multifunctional managed forests and 0.70 MgC ha-1 (0.24 MgC ha^{-1} logs, 0.27 MgC ha^{-1} snags and 0.19 MgC ha^{-1} stumps) for intensively managed forests. In the present study, the high values of deadwood C stock (9.94 MgC ha^{-1}) compared with other studies are due to the absence of forest-management practices in the Monte Morello forest in the last 50 years. Many authors have pointed out that deadwood C stock is closely related to forest-management practices (Green and Peterken 1997, Kirby et al. 1998, Duvall and Grigal 1999, Paletto et al. 2014): generally, stored carbon has a growing trend from forests managed for timber and bioenergy production to unmanaged forests and forests in protected areas (i.e., national and regional parks, natural reserves, Natura 2000 sites). The results of these studies on the deadwood C stock estimation and the influence of forest management practices on C stock provide information to forest managers to adopt strategies to increase or decrease the amount of deadwood volume in forests.

As far as the method of estimation is concerned, conventionally C stock in deadwood is estimated indirectly, using a fixed percentage of 49.9 (Matthews 1993). However, during the decomposition process, changes in C percentage and C/N ratio are expected, following changes in size (Harmon et al. 1986) and chemical composition including lignin content (Harmon et al. 2013). Lombardi et al. (2012) found a lower concentration in deadwood than in

Table 3. Moisture content (%) and basic density values (g cm^{-3}) by component, species, and decay class of four pine species.

Component/decay class/species	Austrian black pine	Scots pine	Swiss pine	Calabrian pine
Moisture content (%)				
Logs				
Decay class 1	68.9	112.2	93.2	74.8
Decay class 2	47.1	36.3	114.9	154.7
Decay class 3	33.6	23.7	23.7	143.3
Decay class 4	51.8	38.2	38.2	103.1
Decay class 5	69.3	32.2	32.2	126.8
Snags				
Decay class 1	43.1	57.7	14.6	78.3
Decay class 2	29.9	31.4	18.9	86.4
Decay class 3	27.3	20.6	20.6	102.0
Decay class 4	32.0	28.5	28.5	187.0
Decay class 5	57.6	45.2	45.2	74.9
Basic density values: snag + logs (g cm^{-3})				
Decay class 1	0.42	0.42	0.38	0.43
Decay class 2	0.47	0.41	0.38	0.33
Decay class 3	0.43	0.41	0.40	0.27
Decay class 4	0.37	0.20	0.31	0.22
Decay class 5	0.24	0.21	0.20	0.14

Note: Source: present study and Paletto and Tosi (2010).

living silver fir (*Abies alba* Mill.) and European beech (*Fagus sylvatica* L.), as well as variability among decay classes. Other studies on temperate forests (Weiss et al. 2000, Bütler et al. 2007) reported values of around 50% for individual tree species of Central Europe that remained stable during the whole decomposition process of deadwood.

As pointed out recently, chemical characterization of deadwood decay classes is often lacking for specific tree species (Petrillo et al. 2016), and to our knowledge, no direct measurements of C content of different deadwood component and decay class have been performed on pine species growing in a Mediterranean climate. The different climate conditions influence the decomposition process of deadwood and, consequently, the C stock. In particular, in a Mediterranean climate, the decomposition process is faster, whereas in the boreal climate, this process is slower with long transition times from one decay class to the next. A decrease in deadwood density during the decomposition process was found to be the most important factor determining C stocks, with either direct or indirect estimation.

Conversely, a significant increase in N was found in more decomposed classes with respect to living trees or the first two decomposition classes, with a consequent decrease in C/N ratio (Bütler et al. 2007, Lombardi et al. 2012). Our results confirmed and added new evidence of a significant increase in N during the decomposition process, from 0.14 in decay class 1 to 0.80 N% in decay class 5, with an almost fivefold increase. The increase in nutrients (mainly N and phosphorus) is commonly reported with increasing decay stage (Bütler et al. 2007, Palviainen et al. 2010, Lombardi et al. 2012), but not for Austrian black pine. N enrichment is the result of (1) relative enrichment caused by C and mass loss and (2) active transfer by fungi (Harmon et al. 1986), which was demonstrated by Petrillo et al. (2016) to be the main mechanism. The decrease in C/N ratio was therefore a simple consequence of N concentration increasing with the decay stage. A longer residence time of deadwood in the last decay classes has been commonly observed (Harmon et al. 2013), together with a relative increase in lignin and a decrease in cellulose content. The decrease in C/N ratio, being a rough indicator of organic matter decomposability, supports the evidence of different decomposition rates among decomposition classes, which are constrained by the availability of macronutrients (Weedon et al. 2009). The pattern of N percentage among deadwood decomposition classes hampers the extrapolation of a conversion coefficient to be used for indirect estimation of N stock from deadwood biomass. These results highlighted that direct estimation is useful for forest managers when assessing deadwood N pool and/or deadwood quality, but is not needed for broad-scale deadwood C stock estimations.

Conclusions

In conclusion, our results highlighted that the applied method (direct or indirect) has a negligible influence on C stock assessment. However, in order to improve the C stock assessment, it would be important to use specific basic density values for species, decay class, and component. Indeed, a decrease in the basic density values during the decomposition process was found to be the most important factor determining C stock.

These findings indicate that indirect estimation allows a faster and cheaper procedure for C stock determination in pine forests. From a practical point of view, the negligible differences between direct and indirect assessment suggest the opportunity to use the basic density per species in order to estimate C stock in deadwood. This method of estimating the deadwood C stock is particularly useful in NFIs and in forest planning and management. Robust data on deadwood in forests can target forest managers' choices more effectively in order to better manage this important forest carbon pool.

Direct estimation may be more appropriate in specific studies, when additional information, such as N and C/N ratio, is collected to understand qualitative changes during the decomposition process.

During the study, a major concern was the assignment of a decay class to deadwood samples. The five-class system used, based on a visual assessment, is affected by the subjectivity of the operator. In order to minimize any bias in the visual assessment, the forest technicians involved in the field measurements received training over two days. An important challenge for future studies is to define a system of classification of deadwood decomposition stages based on objective and measurable variables, such as wood resistance, finalized at establishing clearly defined boundaries among decay classes.

Since deadwood represents an important forest C pool, improving the informative potential by taking into account the species, the three deadwood components (logs, snags, and stumps) and the decay classes would help make C accounting easier. Based on our knowledge, no comparisons between direct and indirect estimation of C stock have been carried out before in this type of forest. The C stored in deadwood and its changes must be inventoried and monitored over time for successful implementation of climate-change-mitigation policies. For this reason, more empirical data are needed to develop a database to share data on different species, different management strategies, and different environmental situations.

Literature Cited

Birdsey, R.A. 1992. *Carbon storage and accumulation in United States forest ecosystems*. General Technical Report WO-59. USDA Forest Service, Washington, DC.

Bragg, D.C., and J.L. Kershner. 1999. Coarse woody debris in riparian zones. *J. For.* 4:30–35.

Brown, S. 2002. Measuring carbon in forests: Current status and future challenges. *Environ. Pollut.* 116:363–372.

Bütler, R., L. Patty, R.C. Le Bayon, C. Guenat, and R. Schlaepfer. 2007. Log decay of *Picea abies* in the Swiss Jura Mountains of Central Europe. *Forest Ecol. Manage.* 242:791–799.

Cannell, M.G.R. 1984. Woody biomass of forest stands. *Forest Ecol. Manage.* 8:299–312.

Cenni, E., F. Bussotti, and L. Galeotti. 1998. The decline of a *Pinus nigra* Arn. reforestation stand on a limestone substrate: The role of nutritional factors examined by means of foliar diagnosis. *Ann. Sci. Forest* 55:567–576.

Coomes, D.A., R.B. Allen, N.A. Sčoty, C. Goulding, and P. Beets. 2002. Designing systems to monitor carbon stocks in forests and shrublands. *Forest Ecol. Manag.* 164:89–108.

De Meo, I., E.A. Agnelli, A. Graziani, K. Kitikidou, A. Lagomarsino, E. Milios, K. Radoglou, and A. Paletto. 2017. Deadwood volume assessment in Calabrian pine (*Pinus brutia* Ten.) peri-urban forests: Comparison between two sampling methods. *J. Sustainable For.* 36(7):1–21.

Di Cosmo, L., P. Gasparini, A. Paletto, and M. Nocetti. 2013. Deadwood basic density values for national-level carbon stock estimates in Italy. *Forest Ecol. Manag*. 295:51–58.

Di Matteo, G., Tunno, I., Nardi, P., De Angelis, P., Bertini, G., Fabbio G. 2015. C and N concentrations in different compartments of outgrown oak coppice forests under different site conditions in Central Italy. *Ann. For. Sci*. 71(8):885–895.

Duvall, M.D., and D.F. Grigal. 1999. Effects of timber harvesting on coarse woody debris in red pine forests across the Great Lakes states, U.S.A. *Can. J. For. Res*. 29:1926–1934.

Edwards, D.M., M. Jay, F.S. Jensen, B. Lucas, M. Marzano, C. Montagné, A. Peace, and G. Weiss. 2012. Public preferences for structural attributes of forests: Towards a pan-European perspective. *Forest Policy Econ*. 19:12–19.

Green, P., and G.F. Peterken. 1997. Variation in the amount of dead wood in the woodlands of the Lower Wye Valley, UK in relation to the intensity of management. *Forest Ecol. Manag*. 98:229–238.

Guldin, R.W., and H.F. Kaiser. 2004. *National report on sustainable forests—2003*, FS-766. USDA Forest Service, Washington, DC.

Harmon, M.E., B. Fasth, C.W. Woodall, and J. Sexton. 2013. Carbon concentration of standing and downed woody detritus: Effects of tree taxa, decay class, position, and tissue type. *Forest Ecol. Manag*. 291:259–267

Harmon, M.E., J.F. Franklin, F.J. Swanson, P. Sollins, S.W. Gegory, J.D. Lattin, N.H. Anderson, S.P. Cline, N.G. Aumen, J.R. Sedell, G.W. Lienkaemper, K. Cromak, and K.W. Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. *Adv. Ecol. Res*. 15:133–302.

Hunter, M.L. 1990. *Wildlife, forests and forestry: Principles of managing forests for biological diversity*. Prentice-Hall, Englewood Cliffs, NJ. 360 p.

IPCC. 2003. *Good practice guidance for land use, land-use change and forestry*. Available at: http://www.ipcc-nggip. iges.or.jp/public/gpglulucf/gpglulucf_contents.htm; last accessed Mar. 3, 2018.

Karahalil, U., E.Z. Baskent, G. Sivrikaya, and B. Kiliç. 2017. Analyzing dead wood volume of Calabrian pine (*Pinus brutia* Ten.) in relation to stand and site parameters: A case study in Köprülü Canyon National Park. *Environ. Monit. Assess*. 189(3):112.

Kirby, K.J., C.M. Reid, R.C. Thomas, and F.B. Goldsmith. 1998. Preliminary estimates of fallen dead wood and standing dead trees in managed and unmanaged forests in Britain. *J. Appl. Ecol*. 35:148–155.

Krankina, O.N., and M.E. Harmon. 1995. Dynamics of the dead wood carbon pool in Northwestern Russian boreal forests. *Water Air Soil Poll*. 82:227–238.

Kueppers, L.M., J. Southon, P. Baer, and J. Harte. 2004. Dead wood biomass and turnover time, measured by radiocarbon, along a subalpine elevation gradient. *Oecologia* 141:641–651.

La Fauci, A., S. Bagnato, O.I. Gugliotta, and R. Mercurio. 2006. Osservazioni preliminari sulla necromassa in popolamenti di pino laricio nel Parco Nazionale dell'Aspromonte. *Forest@* 3:54–62.

Laiho, R., and C.E. Prescott. 2004. Decay and nutrient dynamics of coarse woody debris in northern coniferous forests: A synthesis. *Can. J. For. Res*. 34:763–777.

Lassauce, A., Y. Paillet, H. Jactel, and C. Bouget. 2011. Deadwood as a surrogate for forest biodiversity: Meta-analysis of correlations between deadwood volume and species richness of saproxylic organisms. *Ecol. Indic*. 11:1027–1039.

Lettens, S., B. De Vos, P. Quataert, B. Van Wesemael, B. Muys and J. Van Orshoven. 2007. Variable carbon recovery of Walkley-Black analysis and implications for national soil organic carbon accounting. *Eur. J. Soil Sci*. 58:1244–1253.

Lombardi, F., P. Cherubini, R. Tognetti, C. Cocozza, B. Lasserre, and M. Marchetti. 2012. Investigating biochemical processes to assess deadwood decay of beech and silver fir in Mediterranean mountain forests. *Ann. Forest Sci*. 70:101–111.

Marage, D., and G. Lemperiere. 2005. The management of snags: A comparison in managed and unmanaged ancient forests of the Southern French Alps. *Ann. Forest Sci*. 62:135–142.

Matthews, G. 1993. *The carbon content of trees*. Forestry Commission, Technical Paper 4. HMSO, London, 25 p.

Morelli, S., A. Paletto, and V. Tosi. 2007. Il legno morto dei boschi: Indagine sulla densità basale del legno di alcune specie del Trentino. *Forest@* 4:395–406.

Næsset, E. 1999. Relationship between relative wood density of *Picea abies* logs and simple classification systems of decayed coarse woody debris. *Scand. J. Forest Res*. 14:454–461.

Nordén, B., and H. Paltto. 2001. Wood-decay fungi in hazel wood: Species richness correlated to stand age and dead wood features. *Biol. Conserv*. 101:1–8.

Nordén, B., M. Ryberg, F. Götmark, and B. Olausson. 2004. Relative importance of coarse and fine woody debris for the diversity of wood-inhabiting fungi in temperate broadleaf forests. *Biol. Conserv*. 117:1–10

Paletto, A., and V. Tosi. 2010. Deadwood density variation with decay class in seven tree species of the Italian Alps. *Scand J. Forest Res*. 25:164–173.

Paletto, A., I. De Meo, P. Cantiani, and F. Ferretti. 2014. Effects of forest management on the amount of deadwood in Mediterranean oak ecosystems. *Ann. Forest Sci*. 71:791–800.

Palviainen, M., L. Finén, R. Laiho, E. Shorohova, E. Kapitsa, and I. Vanha-Majamaa. 2010. Phosphorus and base cation accumulation and release patterns in decomposing Scots pine, Norway spruce and silver birch stumps. *Forest Ecol. Manag*. 260:1478–1489.

Pastorella, F., A. Avdagić, A. Čabaravdić, A. Mraković, M. Osmanović, A. Paletto. 2016. Tourists' perception of deadwood in mountain forests. *Ann. Forest Res*. 59:311–326.

Peichl, M., and M.A. Arain. 2006. Above- and belowground ecosystem biomass and carbon pools in an age-sequence of temperate pine plantation forests. *Agr. Forest Meteorol*. 140:51–63.

Persiani, A.M., F. Lombardi, D. Lunghini, V.M. Granito, M. Tognetti, O. Maggi, S. Pioli, and M. Marchetti. 2015. Stand structure and deadwood amount influences saproxylic fungal biodiversity in Mediterranean mountain unmanaged forests. *iForest* 9: 115–124.

Petrillo, M., P. Cherubini, G. Fravolini, M. Marchetti, J. Ascher-Jenull, M. Schärer, H.A. Synal, D. Bertoldi, F. Camin, R. Larcher, and M. Egli. 2016. Time since death and decay rate constants of Norway spruce and European larch deadwood in subalpine forests determined using dendrochronology and radiocarbon dating. *Biogeosciences* 13:1537–1552.

Renvall, P. 1995. Community structure and dynamics of wood-rotting Basidiomycetes on decomposing conifer trunks in northern Finland. *Karstenia* 35:1–51.

Rock, J., F.W. Badeck, and M.E. Harmon. 2008. Estimating decomposition rate constants for European tree species from literature sources. *Eur. J. Forest Res*. 127:301–313.

Söderström, F., H. Petersson, N. Kruys, and G.Ståhl. 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 Ecol. Manag*. 243:19–27.

Stevens, V. 1997. *The ecological role of coarse woody debris: An overview of the ecological importance of CWD in B.C. forests*. Ministry of Forests Research Program, British Columbia, 26 p.

Teissier du Cros, R., and S. Lopez. 2009. Preliminary study on the assessment of deadwood volume by French national forest inventory. *Ann. For. Sci*. 66:302.

Tobin, B., Black, K., McGurdy, L., Nieuwenhuis, M. 2007. Estimates of decay rates of components of coarse woody debris in thinned Sitka spruce forests. *Forestry* 80(4):455–469.

Tomppo, E., Gschwantner, T., Lawrence, M., and R.E. McRoberts. 2010. *National Forest inventories. Pathways for common reporting*. P. 541–553. European Science Foundation, Strasbourg.

Travaglini, D., A. Barbati, G. Chirici, F. Lombardi, M. Marchetti, and P. Corona. 2007. ForestBIOTA data on deadwood monitoring in Europe. *Plant Biosyst*. 141:222–230.

Weedon, J.T., Cornwell, W.K., Cornelissen, J.H., Zanne, A.E., Wirth, C., Coomes, D.A. 2009. Global meta-analysis of wood decomposition rates: A role for trait variation among tree species?. *Ecol. Lett*. 12:45–56.

Weiss, P., K. Schieler, K. Schadauer, K. Radunsky, and M. Englisch. 2000. *Carbon budget of Austrian forests and considerations about Kyoto Protocol*. Monograph M-106. P. 94. Federal Environment Agency, Wien.

Woodall, C.W., Heath, L.S., Smith, J.E. 2008. National inventories of down and dead woody material forest carbon stocks in the United States: Challenges and opportunities. *Forest Ecol. Manag*. 256:221–228.