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SHORT COMMUNICATION

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Variation of deadwood density by decay class in Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco) stands in Italy

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Abstract

Aim of study: To estimate fresh and basic density values of Douglas fir deadwood for the five decay classes used in the National Forest Inventories (NFIs).

Area of study: Rincine forest in Tuscany region (Italy).

Materials and methods: 140 samples of Douglas fir deadwood (28 for each decay class; 14 of which were collected in summer and 14 in winter) were collected and analysed in the laboratory. The samples were weighed fresh, then placed in the oven for 3 days at 60°C. Afterwards the samples were weighed dried. The laboratory data were used to estimate moisture content (%), fresh and basic density by decay class.

Main results: The results showed that the trend of basal density decreased from 1st to 5th decay class (0.43 g cm^{-3}, 0.39 g cm^{-3}, 0.37 g cm^{-3}, 0.29 g cm^{-3} and 0.20 g cm^{-3}). An average basic density of 0.34 g cm^{-3} could be used in future studies concerning the estimation of C-stock in Douglas fir deadwood.

Research highlights: The moisture content of all decay classes of lying deadwood is influenced by the season (winter *vs.* summer) and consistent with the local climate regime.

Additional key words: lying deadwood; decomposition rate; decay classes; basic density; carbon pool

Abbreviations used: dbh (diameter at breast height); GHGs (greenhouse gases); LIS (Line Intersect Sampling); NFIs (National Forest Inventories).

Authors' contributions: AC contributed with field data collection and data processing. AA and AO contributed with field data collection. CB performed laboratory analysis and data processing. AP contributed with manuscript writing and statistical analyses. IDM contributed with manuscript writing and research supervision.

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Introduction

Deadwood plays a key role in forests, as it provides microhabitat and food for several species, influences soil fertility and productivity, protects against rockfalls and landslides, and facilitates the regeneration of forests (Herrero *et al.,* 2016). The scientific community and policy makers have recognized that deadwood is also essential in the global carbon (C) cycle and climate change mitigation through the temporary storage of carbon dioxide (CO_2) from the atmosphere (Takahashi *et al.,* 2015). As emphasized by the United Nations Framework Convention on Climate Change (UNFCCC), the C stored in forests and its changes in the five C pools – aboveground biomass, belowground biomass, deadwood, litter, and soil – must be continuously quantified and monitored. Deadwood is defined as all the non-living woody biomass that is standing or lying on the forest floor and is affected by the dynamics of carbon release and sequestration. According to Pan *et al.* (2011), deadwood is responsible for the storage of 73.0±6.0 PgC, corresponding to 8% of the carbon stored in forest ecosystems worldwide, while Brown (2002) estimated that the contribution of deadwood in forests is between 10% and 20% of total carbon storage. Hence, a robust quantification of deadwood C stock and fluxes is required to report removals and sinks of greenhouse gases (GHGs) (Weggler *et al.,* 2012).

The indirect estimation of deadwood contribution to C-storage requires the conversion of deadwood volume to biomass using values of basic density by species and decay class (Di Cosmo *et al.,* 2013). Generally, data of deadwood volume are available from National Forest Inventories (NFIs), local forest inventories or management unit plans, but usually NFIs databases do not provide information about basic densities. Furthermore, in the international literature, values of basic density by decay class are available only for a few tree species, and are considered only to provide approximate values, because of the possible risk of errors (Harmon & Sexton, 1996). Therefore, country specific studies that provide basic density values for the most important tree species and by decay classes are needed. The aim of this study is to contribute to fill this research gap by providing fresh and basic density values for the five decay classes of Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco) deadwood.

The choice of Douglas fir depends on the fact that, like in many Central European forests, also in Italy Douglas fir is one of the most abundant non-native tree species cultivated. In Italy, Douglas fir was introduced in 1882 and widely used in the afforestation programmes developed after the World Wars, in reason of its characteristics of productivity and timber quality. Currently, most Italian regions are characterized by the presence of Douglas fir plantations, mainly located in Central Italy (Castaldi *et al.,* 2017). In Tuscany, Douglas fir covers 3,360 ha in pure stands and 2,112 ha in mixed stands (Regional Forest Inventory of Tuscany 1998). Initially, the main claim of productive Douglas fir plantations realized in Tuscany was the wood production and particularly to obtain cellulose for paper industry. Currently the importance of these planted stands is rising, not in reason of the interest in the timber production, but mainly for their role of ecosystem services providers (Brockerhoff *et al.,* 2013).

Material and methods

The data to estimate fresh and basic density values were collected in a study area in Central Italy (Rincine forest, Tuscany region) characterized by a Douglas fir reforested area with an average age of 50 years. The Rincine forest is a public forest complex located in the north-east part of Florence province (N 43°52′, E 11°34′; 400 m a.s.l.) that is managed by the Union of Municipalities of Valdarno and Valdisieve. It extends over an area of 1,450 ha, where Douglas fir stands cover 106.5 ha and are the result of reforestation activities that started in the end of 1970’s and finished early in the 1980’s. Despite the small reforested area, the Rincine forest can be considered a standard situation and representative of the reforestation carried out throughout the Tuscany region in the XXth century. For this reason, it was selected as a study area. The reforestation was performed on degraded sweet chestnut (*Castanea sativa* Mill.) stands and on abandoned agricultural lands. Douglas fir was originally planted to produce wood pulp for cellulose, but it is currently managed to produce wood chips or sawn products. Silvicultural treatments, in particular thinning from below are applied every 10-15 years removing about 20% of basal area. The main objective of thinning interventions is to protect the stands from the north-east wind and from other extreme weather events (*e.g.* storms).

The climate is characterized by precipitations concentrated in autumn (November is the rainiest month) with a dry summer in which July is the driest month. The average annual temperature is 9.2°C (maximum 17.8°C in July and August and minimum of 1.5°C in January), while the average rainfall is 1,273 mm with a maximum peak in autumn in November and a minimum in July (58 mm).

Field measurements were taken in the Douglas fir stand, where data were collected in 25 circular sampling plots (fixed-area of 531 m^2) randomly located in the study site. In the study, 25 sampling plots were used to investigate more than 1% of the total area of Douglas fir stand by adopting the size and shape of the sampling plots used in the Italian NFI. The center of each sampling plot was randomly generated using the Random points inside polygons routine of QGIS 2.18.7 (QGIS DT, 2017), establishing a number of points – one every 4.0-ha of forest area – with a minimum distance of 100 m between points to avoid overlap. Within each sampling plot, dendrometric data of standing living trees – *i.e.* species, height, and diameter for all trees with a diameter at breast height (dbh) larger than 10 cm – and deadwood (standing dead trees, lying deadwood, and stumps) were recorded. For deadwood, a 10-cm diameter limit was considered because large deadwood (coarse woody debris) is considered the most important component for biodiversity conservation (Brin *et al.,* 2011), and for C storage (De Meo *et al.,* 2018). In the case of standing dead trees and stumps, two perpendicular diameters (dbh for standing trees and on the maximum height of stump from ground level) and total height were measured. Lying deadwood was measured using the line intersect sampling (LIS) method (Warren & Olsen, 1964). All lying woody debris that intersects a transect was measured with a caliper at the point of intersection of the transect and the log central axis. We delimited two transects of 26 m in length within each sampling plot, from North to South and East to West to form a cross in accordance with the methodological options proposed by Bell *et al.* (1996). Besides, the decay class for all deadwood components was recorded using a visual assessment based on some key variables and visible characteristics (Næsset *et al.,* 1999) and considering the 5-decay class classification system used in the NFIs (Bayraktar *et al.,* 2020).

The volume of standing living trees was calculated using the following equation (eq. 1), provided by the Italian NFI specific for Douglas fir (Tabacchi *et al.,* 2011):

$$V_{living\_trees} = b_0 + b_1 d^2 h + b_2 d \tag{1}$$

where: V_{living_trees} = volume of standing living trees including stem and branches (m^3 ha^{-1}); h = height (m); d = diameter at breast height (cm); b_0 = -7.9946; b_1 = 3.3343·10^{-2}; and b_2 = 1.2186.

Standing dead trees volume was calculated from stand basal area and tree height obtained using the hypsometric curve, while stumps volume was estimated using the Smalian's formula (De Meo *et al.,* 2017). Lying deadwood volume was estimated using the equation proposed by Van Wagner (1968) for the LIS method:

$$V_{lying\_deadwood} = \left(\pi^2 \sum \frac{d_i^{\,2}}{8L} \right) \tag{2}$$

where: $V_{lying\_deadwood}$ = volume of lying deadwood (m^3 ha^{-1}); L = transect length (m); and d_i = average diameter (mean of the two diameters) of the intersection point along the transects (cm).

In each plot, four to eight lying deadwood samples were collected for a total of 140 samples (28 samples for each decay class). Half of the samples was collected in summer (July-August 2021), while the other half in winter (November-December 2021). Deadwood samples were collected in two different periods to test whether or not the season affects their moisture content. Samples were taken after Paletto & Tosi (2010) protocol, that is, a cylindrical core of deadwood using a battery drill (20.4 V) with a modified bit was collected from each deadwood sample. The diameter of the cylinder was fixed (3 cm), while the length was variable, and it was measured with a calliper with an accuracy of 1/10 mm (the extracted volume ranged between 15.30 cm^3 and 56.52 cm^3).

Each deadwood sample was analysed in the laboratory for moisture content and mass determination. The procedure was as follows (adapted from De Meo *et al.,* 2018): (1) the fresh weight of deadwood sample was determined using an analytical balance the first day after the field measurement; (2) the sample was dried in a stove for 72 hours at a temperature of 60°C; and (3) the sample was re-weighed after this time to determine the dry weight after cooling in a dryer with silica gel. The results obtained from laboratory analyses were used to calculate moisture content (%), fresh density (or green density), basic density (or dry) for each deadwood sample, and the average for each decay class. The formulas used to calculate the parameters (Eqs. 3 and 4) for each deadwood sample are as follows (Paletto & Tosi, 2010):

$$MC_d = \frac{W_w - W_d}{W_d}(100) \tag{3}$$

$$D_w = \frac{W_w}{V_w} \tag{4}$$

$$D_d = \frac{W_d}{V_w} \tag{5}$$

where: MC_d = moisture content as a percentage of oven-dry weight (%); D_w = fresh density (g/cm^3); D_d = dry density (g/cm^3); W_w = green weight of wood (g); W_d = oven-dry weight of wood (g); and V_w = fresh volume of wood (cm^3).

The main descriptive statistics provided using XLStat 2020 were obtained (mean, standard deviation, min, max) for field and laboratory results for each decay class. The non-parametric Kruskal-Wallis test was applied to determine if there were statistically significant differences among decay classes for moisture content, fresh density, and basic density, while the non-parametric Mann-Whitney test was used to determine the existence or not of statistically significant differences between winter and summer samples. Non-parametric tests were applied since the sample size is not large enough and the assumption

Table 1. Deadwood volume (m^3 ha^{-1}) distribution by component and decay class (mean and standard deviation) for Douglas-fir stands in Rincine forest (Italy)

Decay class/Component	Standing dead trees	Lying deadwood	Stumps
1st decay class	4.46 ± 19.44	5.05 ± 15.35	0.69 ± 1.82
2nd decay class	6.94 ± 14.31	6.30 ± 8.33	4.45 ± 3.34
3rd decay class	1.90 ± 5.07	10.10 ± 11.15	3.51 ± 3.86
4th decay class	0.00	4.45 ± 5.26	6.55 ± 22.31
5th decay class	0.00	2.24 ± 4.83	5.40 ± 15.82
Total	13.31 ± 23.39	28.15 ± 23.89	20.61 ± 29.03

of normality is violated (Norman, 2010): Shapiro-Wilk test: p=0.006, a=0.01; Anderson-Darling test: p=0.007, a=0.01.

Results and discussion

The results showed an average height of 32.4 m, mean diameter of 37.0 cm, average basal area of 60.7 m^2 ha^{-1}, and average volume of standing living trees of 864.12 m^3 ha^{-1} for the sampling sites. In addition, a total deadwood volume of 62.01 m^3 ha^{-1} was estimated, divided by component as follows: 21.4% standing dead trees, 45.4% lying deadwood, and 33.2% stumps. Hence, deadwood volume represents roughly 6.7% of the total volume (living and non-living), and the ratio between deadwood and growing stock volume is equal to 0.072.

The results by decay class are presented in Table 1, with the following volume distribution: 10.20 m^3 ha^{-1} in the 1st class, 17.69 m^3 ha^{-1} in the 2nd class, 15.51 m^3 ha^{-1} in the 3rd class, 11.0 m^3 ha^{-1} in the 4th class and 7.64 m^3 ha in the last class. Values presented in Table 1 show a balanced distribution of deadwood volume by decay class mainly due to natural mortality. It is interesting to emphasize the larger values of stumps volume in comparison to results reported in other studies conducted in Italy which show a stumps volume of 1.58 m^3 ha^{-1} (20.7% of total deadwood volume) in a mixed oaks forest (Paletto *et al.,* 2014), and of 1.25 m^3 ha^{-1} (1.7% of total deadwood volume) in a Calabrian pine forest (De Meo *et al.,* 2017). Values in this study are likely due to the presence of sweet chestnut stumps with diameters over 60 cm in our study.

A high moisture content was obtained for the 1st decay class compared to the following three classes, as it is showed by results from laboratory by decay classes (Fig. 1a): 59.3% for 1st class, 32.4% for 2nd class, 42.8% for 3rd class, 52.2% for 4th class, and 108.3% for 5th class. Paletto & Tosi (2010) also reported a similar trend – higher moisture content in the 1st class compared to the following ones – for black pine (*Pinus nigra* subsp. *nigra*) and Scot pine (*Pinus sylvestris* L.). Furthermore, the high moisture content of the 5th class is likely due to the consistency of the residual wood fragments that absorb atmospheric humidity especially during autumn-winter season (Teodosiu & Bouriaud, 2012). The non-parametric Kruskal-Wallis test showed statistically significant differences among the five decay classes for moisture content (p=0.001, a=0.01).

The results for deadwood fresh density by decay class showed a decreasing trend from the 1st to the 5th class (Fig. 1b): 0.68 g cm^{-3} for the 1st class, 0.51 g cm^{-3} for the 2nd class, 0.50 g cm^{-3} for the 3rd class, 0.43 g cm^{-3} for the 4th class, and 0.41 for the 5th class. Therefore, value changes between one decay class and the next one are between -49.2% (from 1st to 2nd class) and -59.2% (from 4th to 5th class). The non-parametric Kruskal-Wallis test showed statistically significant differences among the five decay classes for fresh density (p<0.0001, a=0.01).

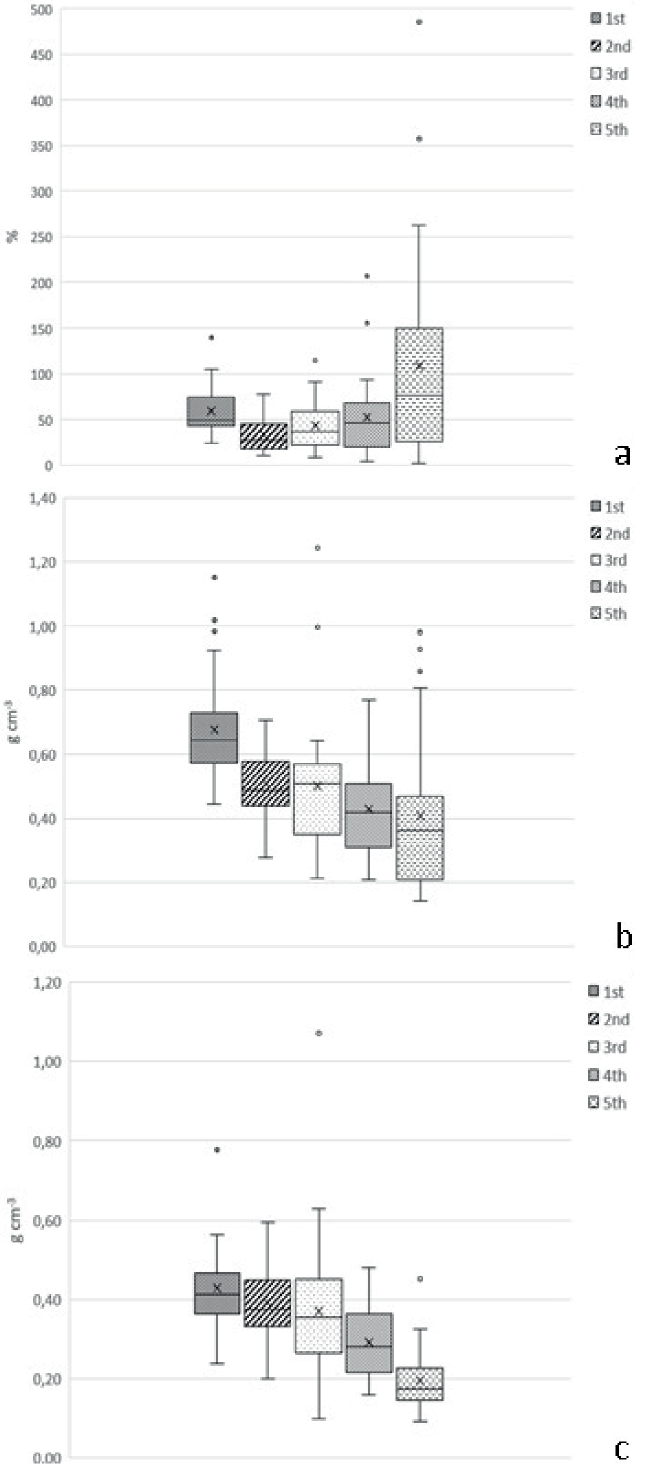

Figure 1. (a) Moisture content (%), (b) Fresh density values (g cm^{-3}) and (c) Basic density values (g cm^{-3}) of Douglas fir deadwood by decay class

The basic density values obtained varied from a minimum of 0.20 g cm^{-3} for the 5th decay class, to a maximum of 0.43 g cm^{-3} for the 1st class (Fig. 1c). The trend among decay classes is well-defined as showed by the percentage

Table 2. Mean values and standard deviation of moisture content, and fresh and basic density for summer (n=14) and winter (n=14) deadwood samples, by decay class, for Douglas-fir stands in Rincine forest (Italy)

Decay class	Moisture (%)		Fresh density (g cm^{-3})		Basic density (g cm^{-3})	
	Summer	Winter	Summer	Winter	Summer	Winter
1st decay class	58.8±19.1	59.9±33.4	0.74±0.17	0.61±0.15	0.47±0.11	0.39±0.06
2nd decay class	26.9±21.0	38.0±15.2	0.55±0.11	0.47±0.05	0.44±0.11	0.34±0.04
3rd decay class	38.3±30.2	47.4±21.4	0.50±0.30	0.50±0.10	0.39±0.25	0.35±0.09
4th decay class	31.7±24.0	72.7±51.9	0.38±0.10	0.48±0.14	0.30±0.11	0.29±0.07
5th decay class	48.5±64.3	168.1±126.5	0.29±0.18	0.52±0.25	0.19±0.10	0.20±0.05

decrease from class to class: -60.8% from 1st to 2nd class, -62.9% from 2nd to the 3rd class, -70.8% from the 3rd to the 4th class, and -80.4% from the 4th to the 5th class. The non-parametric Kruskal-Wallis test showed statistically significant differences among the five decay classes for the basic density (p<0.0001, a=0.01).

The moisture content (%) was higher for the winter samples than for the summer samples, for all decay classes (Table 2). These results are consistent with the climatic regime of the area which is characterized by rainy winters and dry summers. The average differences are included in a range between 1.07% for 1st class and 119.5% for 5th class. The Mann-Whitney test show statistically significant differences in the moisture content between winter and summer samples only for the last two decay classes (4th class: p=0.004, a=0.01; 5th class: p<0.0001, a=0.01). Higher average fresh density was obtained for summer than for winter samples for the first two classes (*i.e.* average difference of 0.13 g cm^{-3} for 1st class and 0.08 g cm^{-3} for 2nd class); whereas for the last two decay classes, the fresh density was higher for winter than for summer samples (*i.e.* average difference of 0.11 g cm^{-3} for 4th class and 0.23 g cm^{-3} for 5th class).

The Mann-Whitney test showed statistically significant differences in the fresh density values between winter and summer samples for the 2nd (p=0.007, a=0.01) and 5th decay class (p=0.004, a=0.01). The basic density was higher for summer than for the winter samples for all but the last one decay classes, with the following average differences: 0.08 g cm^{-3} for the 1st class, 0.10 g cm^{-3} for the 2nd class, and 0.04 g cm^{-3} for the 3rd class. However, there were statistically significant differences only for the 2nd decay class (p=0.001, a=0.01).

We estimated the C-stock in deadwood indirectly by converting the deadwood volume into biomass and C stored, based on deadwood volume and basic density. The deadwood carbon pool is about 10.87 Mg ha^{-1} for the Douglas fir stands analysed in this study, partitioned as follows: 2.18 Mg ha^{-1} in 1st class, 3.46 Mg ha^{-1} in 2nd class, 2.88 Mg ha^{-1} in 3rd class, 1.61 Mg ha^{-1} in 4th class and 0.75 Mg ha^{-1} in the last class.

The results presented in this study contribute to fill a research gap by providing basic density values for Douglas fir. Furthermore, findings from this research can be useful at the local level to better understand the role of deadwood as carbon pool and address the management of this component in Douglas fir stands. At global level, the basic density values given by decay class can be used for indirect carbon pools estimation based on NFIs data for Douglas-fir stands.

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