



Distribution of dead wood volume and mass in mediterranean *Fagus sylvatica* L. forests in Northern Iberian Peninsula. Implications for field sampling inventory

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Abstract

Aim of the study: The aim of this study was to 1) estimate the amount of dead wood in managed beech (*Fagus sylvatica* L.) stands in northern Iberian Peninsula and 2) evaluate the most appropriate volume equation and the optimal transect length for sampling downed wood.

Area of study: The study area is the Aralar Forest in Navarra (Northern Iberian Peninsula).

Material and methods: The amount of dead wood by component (downed logs, snags, stumps and fine woody debris) was inventoried in 51 plots across a chronosequence of stand ages (0-120 years old).

Main results: The average volume and biomass of dead wood was 24.43 m³ ha⁻¹ and 7.65 Mg ha⁻¹, respectively. This amount changed with stand development stage [17.14 m³ ha⁻¹ in *seedling stage*; 34.09 m³ ha⁻¹ in *pole stage*; 22.54 m³ ha⁻¹ in *mature stage* and 24.27 m³ ha⁻¹ in *regular stand in regeneration stage*], although the differences were not statistically significant for coarse woody debris. However, forest management influenced the amount of dead wood, because the proportion of mass in the different components and the decay stage depended on time since last thinning. The formula based on intersection diameter resulted on the smallest coefficient of variation out of seven log-volume formulae. Thus, the intersection diameter is the preferred method because it gives unbiased estimates, has the greatest precision and is the easiest to implement in the field.

Research highlights: The amount of dead wood, and in particular snags, was significantly lower than that in reserved forests. Results of this study showed that sampling effort should be directed towards increasing the number of transects, instead of increasing transect length or collecting additional piece diameters that do not increase the accuracy or precision of DWM volume estimation.

Keywords: snags; downed logs; stumps; fine woody debris; beech; line intersect sampling.

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Introduction

Dead wood is one of the most important components of forest ecosystems. It provides important habitat elements for a wide array of biota and plays an important role in nutrient cycling (Kuehne *et al.*, 2008), carbon storage (Harmon, 2009), hydrology and the maintenance of several ecological functions in forest ecosystems (Harmon *et al.*, 1986; McComb & Lindermyer, 1999).

The amount of dead wood in a stand depends on a variety of factors such as climate, site productivity, tree species composition, disturbance regime (natural and/or anthropogenic), time since last disturbance, characteristics of the previous cohort of trees, current forest management strategy and successional stage (Harmon *et al.*, 1986; Siitonen *et al.*, 2000; Spies *et al.*, 1988; Herrero *et al.*, 2014). In natural forests, it has been hypothesized that the amount of dead wood follows a

“U-shaped” curve: it is highest immediately after a catastrophic disturbance, when many of the trees die; declines to a minimum in mid-succession as dead trees decompose; and then increases again during the old-growth stage as tree mortality increases (Spies *et al.*, 1988; Sturtevant *et al.*, 1997). However, in managed forests, silviculture could play a significant role in the dynamics of dead wood, so that it may not necessarily follow this “U-shaped” accumulation pattern.

In recent decades, forestry practice has gradually shifted towards a closer-to-nature approach, aiming to develop managed stands that are similar to natural stands in attributes such as structure, composition and regeneration processes (Bauhus *et al.*, 2009). As a result, silvicultural restrictions that limit the removal of dead wood have been introduced in many regions (Keeton & Franklin, 2005). The objective of those prescriptions is to create or maintain an adequate stock of dead wood and to promote structures associated with coarse woody debris (CWD) that may increase biodiversity (Franklin *et al.*, 1997; Siitonen *et al.*, 2000). On the other hand, there is a growing interest in harvesting logging residues for energy production, which might reduce both the amount and the diversity of woody debris (Verkerk *et al.*, 2011).

European beech (*Fagus sylvatica* L.) forests are one of the most common natural forest types in Central Europe. Several studies report the amount and distribution of CWD in stands with the highest degree of naturalness, namely, virgin and reserved beech forests (Christensen *et al.*, 2005; Mountford, 2002; von Oheimb *et al.*, 2007). However, few studies have examined forests within the Mediterranean region (Lombardi *et al.*, 2008; Marage & Lemperiere, 2005; Piovesan *et al.*, 2002). In managed forests, suppressed, unhealthy and senescent trees, representing potential sources of CWD, were generally removed. Therefore, there is a lack of basic information on the quantity, decay stage, and size of dead wood for managed beech stands in Southern Europe, as very few studies have been published in the scientific literature.

The main components of CWD are standing dead trees, stumps and downed logs (DWM). While sampling standing dead trees is no different than sampling live trees, sampling the other components presents some methodological issues. Volume is perhaps the most common metric used to characterize DWM and is the basis for estimating DWM mass and carbon. However, many estimators require calculating the volume of each piece of wood in the sample, and results may change depending on the formulae used to compute individual piece volume. Line intersect sampling (LIS) has been considered as an efficient and reliable method to estimate the volume of downed logs (Warren

& Olsen, 1964). Traditionally, volume estimates using line intersect sampling are based on the intersect diameter, which gives an unbiased estimator of the total volume per unit area, without the need to estimate individual piece volume (van Wagner, 1968). However, other LIS estimators that require calculating individual log volume, assuming specific geometric shapes, have also been used. Equations include Huber and Smalian’s formulae (which assume that the log shape is a frustum of a paraboloid), the formula for the volume of a conical frustum, Newton’s formula (which assumes that the log shape is a solid of revolution) and relatively ad hoc formulae such as the average-of-ends or conic-paraboloid (Fraver *et al.*, 2007). Previous studies have showed that different formulae may result in differences in precision and accuracy (Monleon, 2008). Fraver *et al.* (2007) obtained the greatest accuracy with a conic-paraboloid formula, high precision with Newton’s and poor performance with Smalian’s and the conical frustum formulae. Different formulae not only result in different performance, but also require different measurements of diameters or lengths, which may also influence the amount of field time and, therefore, the cost. In addition, there are a number of design options associated with the LIS method, such as transect length or the number of replicates that require careful examination (Woldendorp *et al.*, 2004). Previous studies have shown that total transect length is the main variable affecting the precision of the estimate (Bell *et al.*, 1996; van Wagner, 1968).

The aim of this study was to examine the quantity, distribution and temporal dynamics of dead wood in a natural beech forest (*Fagus sylvatica* L.) in the Northern Iberian Peninsula, and to assess some of the LIS sampling and measurement design options in this environment. Our specific objectives were: (1) to assess the amount, quality and distribution of dead wood [CWD (including downed logs, snags and stumps) and fine woody debris (FWD)] along a chronosequence of four different stand development stages (stand ages from 0 to 120 years old), and (2) to evaluate two different sampling features for downed logs: a) the impact of estimating downed log volume through different formulae, to determine which is the most appropriated for use in field protocols and b) the optimal transect length of LIS method to obtain the minimum sampling variance.

Material and methods

The study area is situated in the Aralar Forest in Navarre (42° N, 2° W; Northern Iberian Peninsula; Figure 1). Altitude ranges from 930 to 1,370 m asl. The

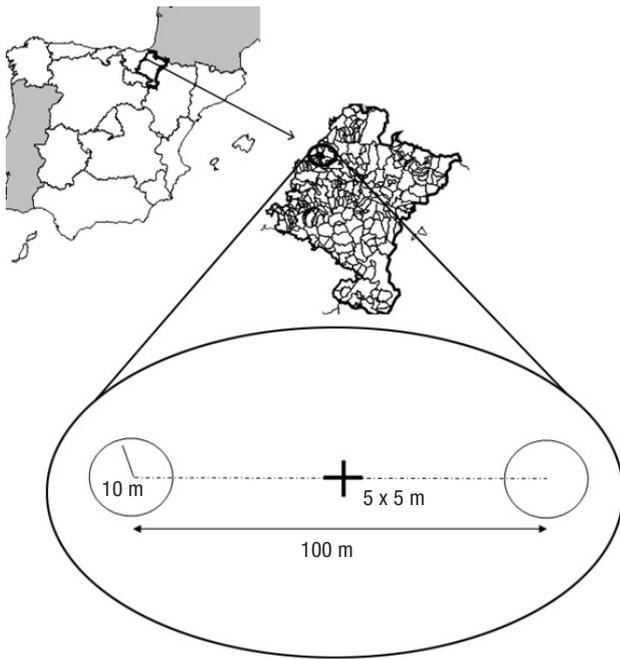


Figure 1. Location of the study area and diagram of the sampling plot. The discontinuous line and bold type line represent the transects where downed logs and FWD were tallied, respectively. Circles represent the plots where snags were tallied.

climate is Atlantic, warm and moist. Mean annual temperature and rainfall are 11.4 °C and 130 cm, respectively. The Aralar Forest covers 2,193 ha, of which 55% is forestland and the remaining grassland. The forestland is dominated by pure stands of beech (*Fagus sylvatica* L.) (94% of the forested area).

The study area was divided into four stand development stages: *SS*, seedling stage (<20 year old), where a new cohort is regenerating following harvest; *PS*, pole stage (20-40 year old), young forest stands following the first thinning (thinning intensity equal to 25% of the basal area); *MS*, mature stage (40-120 year old), older forest stands undergoing commercial thinning; and *RSRS*, regular stand in regeneration stage (>120 year old), stands in a natural regeneration process under a shelter wood system.

Fifty one plots were installed in the study area following a stratified random sampling design, with stand development stage as strata. The number of plots in each development stage was selected proportional to its area, with an approximate density of 1 plot every 22 ha. However, RSRS only covered 14 ha, so three plots were installed in this developmental stage (Table 1). Plots consisted of a 100 m long transect to sample large downed logs, and two 10 m-radius circular subplots (628.32 m² total area) at the beginning and at the end of the transect, to sample dead standing trees. A diagram of this sampling plot is shown in Figure 1.

All standing dead trees with diameter at breast height (dbh) ≥ 7.0 cm were tallied, and species, height, dbh, decay state, presence of excavated cavities, azimuth and distance to the plot centre were recorded. Five decay classes were considered, from nearly sound wood to the most advanced stages of decomposition, following Goodburn & Lorimer (1998). To ensure objectivity and consistency, the decay stage was always assessed by the same person, a forester with extensive experience and knowledge about the subject.

Estimating the volume of individual snags is challenging. Typically, volume is estimated from equations for live tree volume of the same species, but the shape of a decayed snag may be very different from that of a live tree, the bark may be lost, and the stem is often broken. Fraver *et al.* (2007) found that the volume of downed logs could be estimated accurately as the average volume of the frustum of a cone and the frustum of a paraboloid, an approach that has been adapted for snags (Eskelson *et al.*, 2016). First, to estimate the top diameter for broken snags, a height-diameter equation was fitted to 116 live trees measured in the forest inventory, using a Chapman-Richards model (Richards, 1959). The height of each snag was predicted. If the measured height was greater than or equal to the predicted height, it was assumed that the top was not broken. The snag volume was calculated using the volume formulae for a paraboloid and a cone, and the results averaged. However, if the measured height was less than the predicted height, it was assumed that the top was broken. The top diameter was calculated assuming a conic and a paraboloid shape, the snag volume calculated using the formulae for a frustum of a paraboloid and of a cone, and the results averaged. Once the individual volume of each snag was determined, snag volume per plot (m³ ha⁻¹) was estimated as [Eq. 1]:

$$V_i = 10000 \left(\sum_{j=1}^{n_i} \frac{v_{ij}}{628.32} \right) \quad [\text{Eq. 1}]$$

where V_i (m³ ha⁻¹) is the estimated snag volume of plot i ; n_i is the number of snags tallied in plot i ; and v_{ij} (m³) is the volume of snag j in plot i , calculated as explained above.

Downed logs were sampled in the 100 m transects. Large downed logs, which we considered to be dead and fallen trees with diameter ≥ 7.0 cm, downed on the ground or suspended by one of its extremes, but with an inclination greater than 45° from vertical, were sampled in the full, 100 m transect (Figure 1). A threshold diameter of 7 or 7.6 cm to separate between coarse and fine woody debris is the most common choice among National Forest Inventories (Woodall *et al.*,

Table 1. Total number of plots and number of plots containing dead wood components by stand development stage

Stand development stage	Symbol	Area (ha)	Sample size	Plots containing CWD			FWD
				Snags	DWM	Stumps	
Seedling	SS	75	3	0	3	2	1
Pole	PS	205	9	3	9	7	9
Mature	MS	760	36	3	35	23	33
Regular stand in regeneration	RSRS	14	3	1	3	3	2
Total		1,054	51	7	50	35	45

Note: CWD is coarse woody debris (snags+DWM+stumps); DWM is downed logs; FWD is fine woody debris.

2009) and was adopted here. This threshold was consistent with that used for the snag diameter. For each downed log, the species, diameter at the intersection point between the transect and the centreline of the log, small-end, large-end diameter, midpoint diameter, length, decay state and signs of wildlife use were recorded. In addition, the distance from the beginning of the transect to the point of intersection between the log centreline and the transect was also recorded.

DWM volume per plot ($\text{m}^3 \text{ha}^{-1}$) was estimated [Eq. 2] as Warren & Olsen (1964), van Wagner (1968), Woodall & Monleon (2008):

$$V_i = 10000 \left(\frac{\pi}{2L} \sum_{j=1}^{n_i} \frac{v_{ij}}{l_{ij}} \right) \quad [\text{Eq. 2}]$$

where V_i ($\text{m}^3 \text{ha}^{-1}$) is the estimated DMW volume of plot i ; L (m) is the length of transect; n_i is the number of intersected pieces in transect i ; and l_{ij} (m) and v_{ij} (m^3) are the length and volume of piece j in transect i , respectively.

Individual DMW volume was calculated according to Huber, Smalian, conical frustum, Newton, and relative ad hoc formulae such as average-of-ends or conic-paraboloid (Fraver *et al.*, 2007).

Fine woody debris, which were considered to be pieces of wood with diameter greater than 1 cm and smaller than 7 cm, were sampled in the central 10 m of the transect (Figure 1). Only transect diameter was measured. Total volume of FWD per plot was estimated using Eq. 2, with the volume of individual pieces computed using the intersection diameter formula.

Stumps were also sampled in the transect. For each intersected stump, two diameters and two heights were measured and averaged. Assuming that the cross section of a stump can be approximated by a circle, the inclusion probability of a stump (π_{ij}) was estimated following Kaiser (1983) [Eq. 3]:

$$\pi_{ij} = \left[d_{ij}L + \pi d_{ij}^2 / 4 \right] / A \quad [\text{Eq. 3}]$$

where d_{ij} (m) is the diameter of the stump, L (m) the length of the transect, and A (m^2) the area of the forest unit.

Then, if the volume of the stump is approximated by a cylinder, the estimator of estimated stump volume was [Eq. 4]:

$$V_i = \frac{10000}{A} \left(\sum_{j=1}^{n_i} \frac{v_{ij}}{\pi_{ij}} \right) = 10000 \left(\sum_{j=1}^{n_i} \frac{\pi d_{ij} h_{ij}}{4L + \pi d_{ij}^2} \right) \quad [\text{Eq. 4}]$$

where V_i ($\text{m}^3 \text{ha}^{-1}$) is the stump volume of plot i ; A (m^2) the area of the forest unit; v_{ij} (m^3), d_{ij} (m) and h_{ij} (m) are the volume, diameter and height of stump j in plot i , respectively; L (m) is the length of transect.

Decay state of downed logs and stumps was determined according to a 5 decay class system, where class 1 downed logs were solid, with intact bark and little sign of decomposition, and class 5 downed logs were structurally weak, with no bark and elliptical cross sections, following Sollins (1982).

The estimated downed log, snag and stump volume were converted into dead wood mass ($\text{Mg} \text{ha}^{-1}$) by multiplying the individual snag, downed log or stump volume (in Eqs. 1, 2 and 4) by the average bulk density of each decay class (Martirena, 2007) estimated for beech forests in Spain [0.541, 0.348, 0.251, 0.176 and 0.147 $\text{g} \text{cm}^{-3}$ for decay classes 1 through 5, respectively].

A simultaneous inventory was carried out to estimate live tree biomass. Trees were tallied in 15-m radius circular plots installed in the centre of each transect, and the species, dbh and total height (ht) recorded. Stand-level variables such as mean diameter at breast height (dbh, cm), dominant height (H_0 , m), mean total height (ht, m), number of trees (N , trees ha^{-1}), stand basal area (BA, $\text{m}^2 \text{ha}^{-1}$) and age (yr) were calculated. Live tree biomass was calculated from biomass equations developed by Montero *et al.* (2005). Plots were classified in three groups depending on the time since the last thinning (Thinning 1: less than 5 years, Thinning 2: between 5 and 10 years and Thinning 3: more than 10 years).

Statistical methods

Total and mean (per ha) volume and mass of dead wood in the forest and in each developmental stage were estimated using standard stratified random sample formulae (Cochran, 1977). Differences in the volume and mass of dead wood components among stand development stages were tested using one-way ANOVA. For pairwise comparisons, the family-wise error rate was controlled using Tukey's procedure with $p \leq 0.05$. The influence of the number of years since the last thinning in the amount of dead wood was examined in mature stands, because only in this stage the sample size is large enough to carry out this analysis. Again, means were compared with the Tukey pairwise comparison with $p < 0.05$.

To examine the effect of transect length on the variance of the CWD estimator, subsets of the sample, based on the distance of each piece to the beginning of the transect, starting at 20 m and then in 5 m steps, were selected. The variance with each subset was calculated. The distance was not measured in 6 plots, so the sample size for this analysis was 45 plots.

SAS 9.4 (SAS Institute Inc., 2014) and R (R Core Team, 2013) statistical programmes were used for the statistical analyses.

Results

Dead wood volume and mass by component and stand development stage.

The estimated total volume and mass of dead wood, including both CWD (DWM, snags and stumps) and FWD, were 25,744 m³ (SE: 3,050 m³) and 8,060 Mg (SE: 936 Mg), respectively. This yielded an average of 24.43 m³ ha⁻¹ (SE: 2.89 m³ ha⁻¹) and 7.65 Mg ha⁻¹ (SE: 0.89 Mg ha⁻¹), respectively, across the four stand developmental stages (Table 2). The estimated mean amount of dead wood ranged between 17.14 m³ ha⁻¹ (SE: 3.94 Mg ha⁻¹) in SS stands and 34.09 m³ ha⁻¹ (SE: 11.90 Mg ha⁻¹) in PS stands (Table 2), although neither the volume nor the mass of dead wood was significantly different among successional stages ($p=0.13$ and 0.40 ; F-test on 3 and 47 d.f., respectively). The differences in the volume and mass of the separate CWD components (DWM, snags and stumps) were not statistically significant among stand development classes, either. In contrast, a significantly higher value of FWD was found in the PS stage ($p=0.0022$, F-test on 3 and 47 d.f.). Although the mass of CWD was similar among development stages, the CWD ratio (CWD mass/live biomass) was greater in SS than in PS and MS, because the live biomass in PS and MS was almost identical. The mean ratio of

RSRP stands was greater than 100% because of the small amount of live biomass after harvest.

By component, the greatest proportion of dead wood mass was in downed logs (45.5 %), followed by stumps (34.0 %) and FWD (19.5 %) (Table 2). The mass in snags was negligible (1%). However, the proportion of CWD mass by component differed among stand development stages. In SS, following harvest, the most important dead wood component was stumps (58.6%) followed by downed logs (31.5%). As stands developed, CWD was dominated by downed logs and later, when harvesting started in the RSRS stage, by stumps (Figure 2).

There were significant differences in total mass of CWD and downed logs as a function of the number of years since the last thinning, with the mass of dead wood decreasing as the time since thinning increased (Table 3).

CWD volume by decay class

Most of the CWD volume in the study area (>65%) was in the least decayed classes (classes 1 and 2) (Figure 3). The greatest proportion of CWD volume was in decay class 2, followed by decay class 3 and then 1. The distribution of CWD volume by decay classes changed with developmental stage, although the least decayed classes tended to dominate throughout. In SS most of the CWD volume was in decay class 3 (Figure 3a), but there was some volume in decay classes 2, 4 and 5. In PS, most of the volume was in decay classes 1 and 2. A more homogeneous pattern was found in MS, where CWD was evenly distributed across decay classes. Finally, in RSRS most of the CWD volume was in decay class 2. The highest value of volume in decay class 5 was found in this older stage. By components, the distribution of downed logs (Figure 3b) and stumps (Figure 3c) by decay class was similar across developmental stages, albeit with some differences. In SS, decay class 3 dominated downed log and stump volumes, but those volumes were also relatively high for the more advanced stages ($dc > 3$). In PS, downed log volumes was concentrated in the first two classes, but stump volume was distributed across all decay classes. In MS stands, downed logs and stumps were distributed across all the decay classes. In contrast, in RSRS, downed log volume was distributed evenly across decay classes and most of the stump volume was concentrated in decay class 2.

Assessment of LIS design options

Total downed log volume was estimated using seven different formulae to compute the volume of individual

Table 2. Amount of dead wood by component and stand development stage

	Dead wood		DWM		Snag		Stump		FWD	
	m ³ ha ⁻¹	Mg ha ⁻¹	m ³ ha ⁻¹	Mg ha ⁻¹	m ³ ha ⁻¹	Mg ha ⁻¹	m ³ ha ⁻¹	Mg ha ⁻¹	m ³ ha ⁻¹	Mg ha ⁻¹
ALL										
Mean	24.43	7.65	10.89	3.48	0.24	0.07	8.61	2.60	4.68	1.49
SE	2.89	0.89	1.52	0.47	0.14	0.04	1.56	0.46	0.99	0.32
Minimum	1.36	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	90.62	28.14	52.82	14.41	12.35	4.30	45.96	13.34	37.54	12.66
SS (A=75 ha)										
Mean	17.14	3.94	5.35	1.24	0.00	0.00	9.17	2.31	2.63	0.39
SE	9.43	2.07	2.25	0.55	0.00	0.00	6.03	1.53	2.63	0.39
Minimum	1.36	0.34	1.36	0.34	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	33.98	7.51	9.14	2.23	0.00	0.00	20.55	5.20	7.90	1.16
PS (A=205 ha)										
Mean	34.09	11.90	14.34	5.33	0.20	0.09	7.34	2.42	12.21	4.06
SE	8.15	2.53	2.93	1.16	0.13	0.07	3.65	1.01	4.49	1.50
Minimum	4.05	1.52	1.23	0.43	0.00	0.00	0.00	0.00	0.49	0.16
Maximum	81.04	24.96	26.42	9.70	1.15	0.62	35.20	9.85	37.54	12.66
MS (A=760 ha)										
Mean	22.54	6.87	10.63	3.25	0.20	0.05	8.82	2.65	2.90	0.92
SE	3.22	1.00	1.94	0.58	0.17	0.04	1.82	0.56	0.60	0.19
Minimum	2.05	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	90.62	28.14	52.82	14.41	6.03	1.51	45.96	13.34	14.37	5.00
RSRP (A=14 ha)										
Mean	24.27	7.68	4.50	1.07	4.12	1.43	13.01	4.38	2.64	0.80
SE	7.08	1.95	3.23	0.63	4.12	1.43	1.76	0.57	1.34	0.44
Minimum	13.69	0.34	0.60	0.34	0.00	0.00	9.51	0.00	0.00	0.00
Maximum	37.70	11.18	10.91	2.29	12.35	4.3	15.07	5.24	4.35	1.51

Note: Dead wood is CWD+FWD; CWD is snags+DWM+stumps; DWM is downed logs; FWD is fine woody debris; SE is the standard error; A is the area; SS is seedling stands; PS is pole stands; MS is mature stands; RSRP is regular stand in regeneration stands.

pieces (Table 4). The highest volume was estimated when using the intersection diameter, followed by Smalian's, while Huber's resulted on the lowest volume. The greatest standard error was obtained using Smalian's, followed by the intersection diameter, conic-paraboloid and Newton's formulae. However, the smallest coefficient of variation (CV %) was obtained using the intersection diameter.

Figure 4 shows the standard error of the mass of CWD (Mg) as a function of transect length. The standard error decreased rapidly as transect length increased, stabilizing at about 60-70 m.

Discussion

The estimated amount of CWD was small compared to reported values for CWD pools in European beech

forest reserves. Christensen *et al.* (2005) estimated a mean CWD volume of 130 m³ ha⁻¹, ranging from almost 0 to 550 m³ ha⁻¹. Lombardi *et al.* (2010), in Italian montane beech forests, reported a mean volume of 60 m³ ha⁻¹, ranging from 2 to 143 m³ ha⁻¹, and Vandekerckhove *et al.* (2009), in lowland forests of North-Western and Central Europe, reported a mean volume of 53 m³ ha⁻¹, ranging from 6 to 500 m³ ha⁻¹. Large amounts of CWD (>100 m³ ha⁻¹) were found in French beech forest reserves (Mountford, 2002), Hungarian submontane forests (Odor & Standovar, 2003), the Krkonoše National Park of the Czech Republic (Vacek *et al.*, 2015) or in old-growth, beech-dominated forest reserves of the northwestern Carpathians (Kucbel *et al.*, 2012).

Quantities are normally much lower in managed forests than in unmanaged old-growth forests (Green & Peterken, 1997; Paletto *et al.*, 2014), as most of the

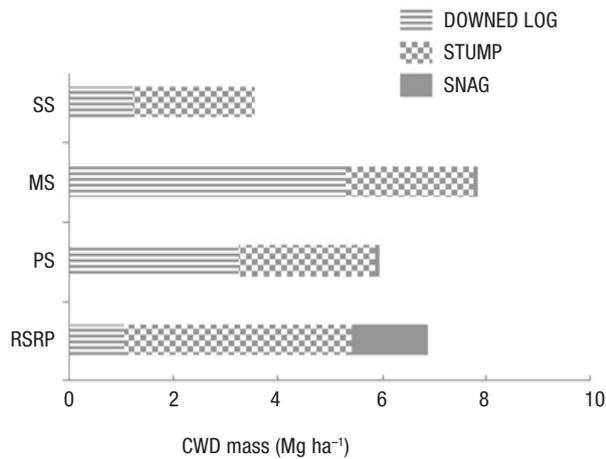


Figure 2. Mass (Mg ha⁻¹) of CWD components by stand development stage. Note: SS is seedling; PS is pole; MS is mature; RSRP is regular stand in regeneration.

large-sized, harvestable timber is extracted. Previous research showed that, on average, the quantity of dead wood in managed forest stands could be a third lower than that in unmanaged forest (Commarmot *et al.*, 2005). So, studies in managed beech forest showed a CWD volume lower than 5 m³ ha⁻¹ in Eastern Spain (Hernando *et al.*, 2013); lower than 10 m³ ha⁻¹ in Central Bohemia (Bilek *et al.*, 2011) or between 8.8 and 47.1 m³ ha⁻¹ in different districts in Italy (Paletto *et al.*, 2012). The relatively large variability among those volume estimates suggest that the amount of CWD may be influenced by factors such as site conditions and management practices. The estimate of CWD volume from this study, an average of 19.75 m³ ha⁻¹ for the entire forest, is within the range of reported values for managed forests and much less than that for reserved forests.

Our results increase the knowledge about the ecology of beech managed forests and can be used as reference values for similar Mediterranean forests. Since the type of management greatly influences the presence and distribution of deadwood in forests and its ecological role, silvicultural strategies can maintain or increase the volume of dead wood. Natural reserves with a long history of protection may serve as a guideline for natural levels of CWD. Based on data from those sites, a variety of target values for CWD volume have been proposed [Ammer (1991); Angelstam *et al.* (2003); BMLFW (2007); Müller *et al.* (2005); Siitonen (2001)]. Our results show that there were very few snags compared with the recommended target found in other studies (Bretz Guby & Dobbertin, 1996; Green & Peterken, 1997). In Switzerland, Bretz Guby & Dobbertin (1996) reported an average of 9.3 m³ ha⁻¹ in unmanaged sites and 1.1 m³ ha⁻¹ in managed sites, a

Table 3. Mass of dead wood by component as a function of time since thinning in mature stands

	p-value	Mass (Mg ha ⁻¹)		
		Time since last thinning		
		<5 years	5-10 years	>10 years
CWD	0.0251	5.52a	6.17a	2.93b
DWM	0.0051	4.9a	2.6b	1.3b
Stump	0.0784	2.02ab	4.38a	1.53b
FWD	0.6101			

Note: CWD is coarse woody debris (snags+DWM+stumps); DWM is downed logs; FWD is fine woody debris. The same letter indicates that the difference of mass among the years since the last thinning classes is not significant at P < 0.1.

volume similar to our estimates. Downed dead wood was much more abundant than standing wood, comprising 50% of the total CWD volume approximately. This proportion was higher than 65% in PS stands because downed logs were left on site due to the low value of small timber. In contrast, in MS stands, downed dead trees were the result of natural mortality and were generally larger. The volume of the stumps reflects the intensity of the harvest, but they tend to have rather homogeneous characteristics (similar heights, regular surfaces, artificial aspects, and similar decay states). Paletto *et al.* (2012) found a stump volume greater than 60 m³ ha⁻¹ in Italy, in a Matese district beech forest, a very large amount compared with that of logs and snags, due to silvicultural activities.

The distribution of CWD mass by state of decay is important for sustainable woody debris management. The distribution of dead wood into decay class gives an indication of the temporal variation in tree felling and mortality and can be used as an indicator of the history of the stand (Rouvinen *et al.*, 2005). The large fraction of CWD in intermediate stages of decay in stands up to PS was probably related to silvicultural activities. The large proportion of dead wood in decay state 3 in SS stands showed its long persistence, if the pieces are large and consists mainly of woody debris that had naturally fallen and have not been removed.

The distribution of the stand development stages in the study area is a spatiotemporal mosaic of stand ages. Dead wood mass ranged from 0.34 to 28.14 Mg ha⁻¹, with the youngest stands (less than 20 years) having a lower amount of CWD on average (3.94 Mg ha⁻¹) than the old (7.68 Mg ha⁻¹) and mature (6.87 Mg ha⁻¹) stands. Thus, our results showed that forest management and silviculture can not only lower the overall amount of CWD, but also modify the temporal distribution and affect the generalized “U-shaped” pattern postulated for natural forests (Figure 5). The influence of management was apparent in the decrease

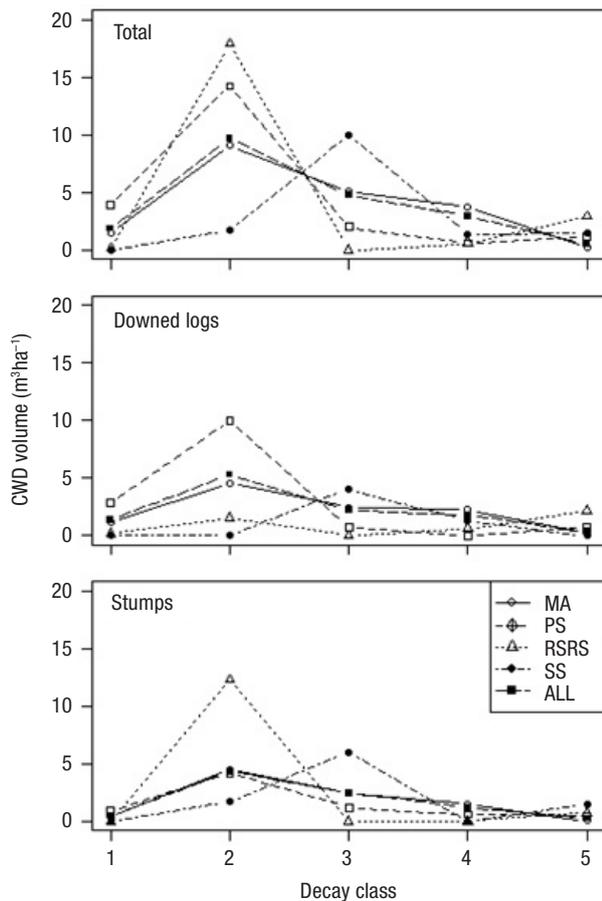


Figure 3. Volume of CWD, downed logs, and stumps by decay class and stand development stage.

of the mass of CWD and downed logs with time since thinning, which was significant lower 10 years after thinning. This period could be enough for decay to reduce the mass on the thinning residues, especially if size of the pieces left is relatively small. Thinning and harvest in managed stands can decrease CWD volumes because large pieces are removed for their commercial value and because large equipment involved in the operations breaks up the woody debris on the forest floor, increasing surface area and thus increases decay rates (Graves *et al.*, 2000). However, Duvall & Grigal (1999) or Herrero *et al.* (2010) have reported CWD accumulations in managed pine forests after thinning operations.

Several studies have shown that the amount of dead wood and live tree stocking are interconnected (Lombardi *et al.*, 2008). Forests with considerable live tree volume accumulate large quantities of dead wood as well. So, the ratio of dead to live wood (CWD ratio) is often used as a method to inform about the capacity of the stand to generate CWD. Previous researchers have calculated ratios dead to live volume from 13% to 37% (Christensen *et al.*, 2005), 40% (Lombardi *et al.*, 2010) or 75% (Vandekerckhove *et al.*, 2009). However, this

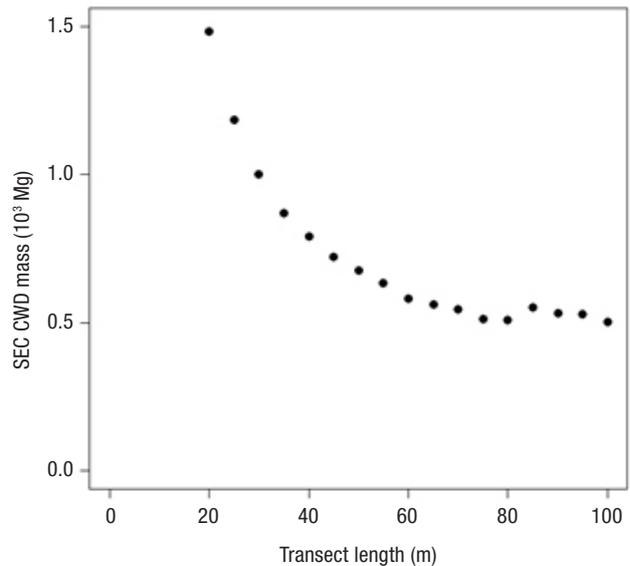


Figure 4. Standard error of CWD mass (Mg) as a function of transect length (m).

ratio may not be very informative in managed stands, because the amount of live biomass can change drastically due to management and stand development stage. After harvest in particular, when most of the live wood has been removed, the ratio of CWD to live biomass can become exceedingly high. For this reason, the ratio should be used under similar conditions of stand age or management (Herrero *et al.*, 2014).

FWD is an important component for biodiversity. Krus & Jonsson (1999) and Schiegg (2001) pointed out the importance of small woody debris for the diversity of saproxylic fungi and insects, indicating that this dead wood component should not be overlooked in ecological studies. In our study, the proportion of mass of FWD to total mass of dead wood (CWD+FWD) was 19.5%. Previous studies have shown both smaller than 10% (Krus & Jonsson, 1999) and higher values than our findings (Nordén *et al.*, 2004; Woodall & Liknes, 2007). The latter study examined the influence of latitude in CWD and FWD stocks, suggesting that the latitude at which CWD and FWD carbon stocks roughly equal each other (equilibrium point) might serve as an indicator of changes in C stock equilibrium under a global warming scenario.

Measures of dead wood are often incorporated in studies and protocols that monitor the health and biodiversity of forests, including national forest inventories, such as those of Canada (CFIC, 2008) or USA (Woodall & Monleon, 2008). The sampling design and estimation procedures have important consequences for the precision and accuracy of the estimators and for the effort required (Monleon, 2008). Typically, the primary interest is on the CWD volume and mass, to

Table 4. Estimated downed log volume computed by different formulae. The equations give the piece volume (v_{ij})

	Total (m ³ ha ⁻¹)	SE	CV (%)
Intersection diameter $v_{ij} = \pi(DI)_{ij}^2 l_{ij} / 40000$	10.89	1.52	13.92
Newton $v_{ij} = \pi l_{ij} \left[(DS)_{ij}^2 + 4(DM)_{ij}^2 + (DL)_{ij}^2 \right] / 240000$	9.84	1.47	14.90
Smalian $v_{ij} = \pi l_{ij} \left[(DS)_{ij}^2 + (DL)_{ij}^2 \right] / 80000$	10.45	1.54	14.71
Huber $v_{ij} = \pi l_{ij} (DM)_{ij}^2 / 40000$	9.54	1.44	15.08
Conical frustum $v_{ij} = \pi l_{ij} \left[(DS)_{ij}^2 + (DL)_{ij}^2 + (DS)_{ij} (DL)_{ij} \right] / 120000$	9.92	1.44	14.55
Average-of-ends $v_{ij} = \pi l_{ij} \left[(DS)_{ij} + (DL)_{ij} / 2 \right]^2 / 40000$	9.66	1.40	14.47
Conic-paraboloid $v_{ij} = \pi l_{ij} \left[5(DS)_{ij}^2 + 5(DL)_{ij}^2 + 2(DS)_{ij} (DL)_{ij} \right] / 480000$	10.18	1.49	14.63

Note: v_{ij} is the volume of the individual piece (m³); l_{ij} is the length of the piece (m); DI, DS, DM and DL are the diameter at the intersection between the piece and the transect, and the small end, midpoint, and large end diameters, respectively (cm); SE is the standard error; CV(%) is the coefficient of variation.

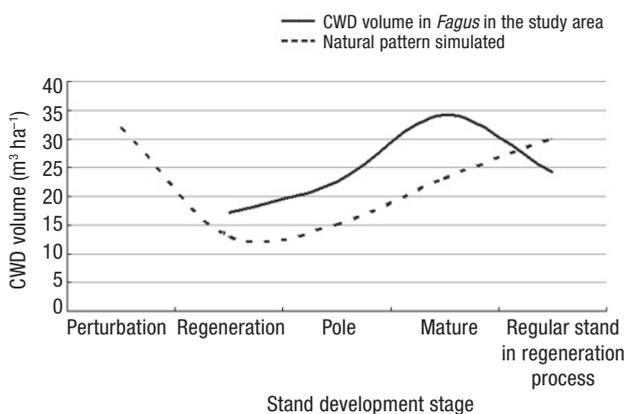


Figure 5. CWD volume by stand development stage in the study area compared to simulated “U-shaped” accumulation pattern.

assess the amount of dead wood in forest ecosystems and to link with C budgets and biodiversity levels (Woldendorp *et al.*, 2004). For our site, the downed log volume estimated by the intersection diameter, which does not rely in assuming a specific log shape, gave the highest estimate of total volume and mass. In general, we would expect that the intersection volume would be smaller than Smalian’s volume, because the later tends to over-estimate the volume (Husch *et al.*, 1972; Ozcelik *et al.*, 2006; Monleon, 2008). In this study, however, the volume estimated with Smalian’s formulae was the second highest. In deciduous species such as beech, log shape is frequently very irregular, so that both end diameters could be smaller than the intersect diameter, partly because of the presence of hollow sections (Williams & Gove, 2003). Because all

the volume formulae assume that pieces follow some specific geometric form, an approach that is free of such assumption, such as the intersect diameter, may be even more accurate with irregularly shaped pieces.

Choosing the best estimation formulae can involve changes in measurement protocols, which in some cases may result in higher costs (Monleon, 2008). Newton’s, Smalian’s, Huber’s, Conical frustum, Average-of-ends and Conic-paraboloid formulae require measurement of one or more of the large-end, small-end, and midpoint diameters. However, measuring those diameters did not result in an increase of precision compared with measuring only the intersect diameter. In fact, the formula that require mid-point diameter showed the highest values of the CV and, therefore, recording this diameter does not improve the performance of the estimator. In contrast, measuring the intersect diameter avoids having to leave the transect path to measure the diameters at both ends or at the midpoint of the piece (Monleon, 2008). Note that none of these methods actually requires a measurement of piece length, because individual piece volume is proportional to piece length for all formulae (l_{ij} in eq. 2, Table 4). Therefore, the length of the piece cancels out in eq. 2, and thus only the appropriate diameters have to be measured in the field. The intersection diameter could be considered the most simple and effective method. It only requires measuring the diameter at intersection point and gives an unbiased estimate of volume without any assumptions about the shape of the downed logs.

Conclusions

In this study, we estimated the amount, quality and distribution of dead wood along a chronosequence of four different stand development stages in beech stands. The total amount of dead wood was much lower than that found in unmanaged, old-growth forests. The average volume and mass of CWD was not statistically different among stand development stages. However, the silvicultural treatments changed the size and the distribution of snags, downed logs and stumps by decay class. The LIS method with the intersect diameter was superior to other methods in terms of precision and ease of implementation. Finally, in the study site, transect length greater than 60 m did not result in a noticeable decrease in the variance of the estimators, suggesting that increasing the number of transects may be more efficient than increasing transect length beyond that distance. This value, however, may be different in different sites, so a pilot study to determine optimal length and the number of transects is always recommended.

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