Coarse woody debris carbon stocks in natural spruce forests of Babia hora

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ABSTRACT: Although coarse woody debris (CWD) represents one of the major carbon pools in natural forest ecosystems, little information is available about its CWD carbon stocks. This study demonstrates the importance of proper estimation of carbon stocks in CWD, which accounts for the decay process of CWD, on an example of a natural mountainous spruce forest located in Central Europe. The study accounts for aboveground coarse woody debris including standing dead trees, lying deadwood, and naturally formed stumps. Basic mensurational information (diameter, height, decay class) about dead wood was collected in the field during the inventory of the forests of the nature reserve Babia hora. The data were used for the calculation of CWD timber volume. In the next step, CWD timber volume was converted to carbon stock using the carbon proportion of 50.1% and density values of decay classes derived from the information published elsewhere. The analysis revealed that when CWD timber volume was converted to carbon stocks using the basic wood density of fresh wood, C stocks were overestimated by 40% or more depending on the developmental stage and elevation. The results also revealed that as the elevation increases, CWD carbon stocks decrease and the differences between the developmental stages diminish.

Keywords: Babia hora nature reserve; deadwood; decay; elevation; natural forest; wood density

Recently, dead wood has become a widely discussed issue in forestry studies. The importance of its occurrence in forest stands has been emphasised in conjunction with the functioning and productivity of forest ecosystems (Humphrey et al. 2004); biodiversity (Ferris, Humphrey 1999; Humphrey et al. 2004; Saniga, Saniga 2004; Schuck et al. 2004); storage of nutrients and water (Harmon et al. 1986; Krankina et al. 1999); soil development and protection against soil erosion (Stevens 1997); rock fall and avalanches (Kupferschmidt et al. 2003); natural regeneration (Harmon, Franklin 1989; Mai 1999; Vorčák et al. 2005, 2006; Ulbrichová et al. 2006); climate change and accumulation of greenhouse gases in the atmosphere (Lombardi et al. 2008; Zell et al. 2009). In carbon sequestration studies, deadwood is recognised as an important component for conserving carbon stock. For example, in the USA 14% of the total forest carbon pool is stored in deadwood (Woodall et al. 2008).

Deadwood is usually divided into coarse and fine woody debris, although the minimum threshold diameter value varies a lot (0–35 cm, Cienciala et al. 2008). According to IPCC (2003), the border diameter is 10 cm. Harmon and Sexton (1996) found that below this diameter the decay rate increases exponentially, while above this diameter the decay rate decreases only slowly. From the two catego-

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ries, coarse woody debris (CWD) is regarded as a more significant component due to its dimensions and substantial time during which it persists in the ecosystem. Hence, CWD acts as a long-term carbon sink until the decomposition process is completed, which can sometimes take up to 1,000 years (Feller 2003) depending on wood characteristics (tree species, dimensions), climate characteristics (temperature and moisture, Woodall, Liknes 2008) and the position on the ground (contact with the ground, Radtke et al. 2004).

In spite of the recognition of the importance of CWD for carbon sequestration, the studies dealing with carbon stock in deadwood in Europe are still scarce. Research of the forestry community usually deals with the volume of coarse woody debris (e.g. Saniga, Schütz 2002; Jankovský et al. 2004; Rahman et al. 2008; Sefidi, Mohadjer 2010; etc.). However, from the works realised elsewhere in the world it is known that during the decomposition process coarse woody debris looses not only its volume, but also mass and density (Krankina, Harmon 1995; Harmon et al. 2000; Coomes et al. 2002). Therefore, for the correct estimation of CWD carbon stock, additional parameters to those usually measured biometrical characteristics (diameter, length) are needed, namely the density of a particular decay class and carbon amount in CWD.

The goal of the presented paper is to examine the importance of taking into account the decomposition process in carbon stock estimation even though no nutrient analyses and measurements of wood density are available from the studied region. This is a usual case in forestry studies, since detailed analyses are both time-consuming (Zell et al. 2009) and cost demanding. On the basis of the published works on CWD decay, we hypothesised that using a single value of wood density for all decay classes can produce incorrect and misleading results. Therefore, for the estimation of CWD carbon stock in the presented paper we approximated wood densities of particular decay classes of CWD on the basis of published values from other regions. In the next step, we compared this approach with simple estimation of carbon stock using only one value of wood density for all decay classes.

MATERIAL AND METHODS

Babia hora is an isolated mountain massif belonging to the outer Western Carpathian mountain range situated in the northern part of Slovakia at the border with Poland. The massif of Babia hora is built of tertiary flysch rocks, mainly sandstones, marl, claystones, slate and conglomerates. The soil types that occur in the area are raw soil, Andosol and most frequently Podzol. The mean annual precipitation is 1,600 mm, and the mean annual temperature 2°C. The forest stands are almost entirely composed of Norway spruce (*Picea abies* [L.] Karst.) with a small admixture of rowan (*Sorbus aucuparia* L.) and Silver fir (*Abies alba* Mill.).

In 1926, a nature reserve was established to preserve natural mountainous spruce forest ecosystems in this region. Originally the nature reserve encompassed 117.6 ha, but in 1974 the reserve was enlarged and currently its area is 503.94 ha (Korpeľ 1989). In the region of the nature reserve, 57 permanent circular sample plots were established in 2002 (Merganič et al. 2003), each with an area of 0.05 ha (i.e. radius = 12.62 m). The plots are located at an elevation ranging from 1,173 m to 1,503 m a.s.l., the latter representing the timber line in this region. The plots are equally divided between the three main developmental stages of virgin forests: stage of growth, maturity and breakdown as defined by Korpeľ (1989), i.e. each group

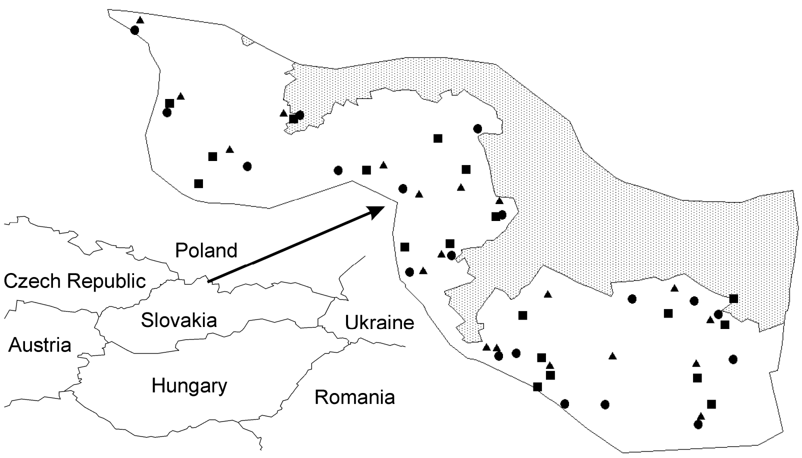

Fig. 1. Location of sample plots in the Nature Reserve Babia hora. Legend: ▦ – alpine meadows and stands of mountain dwarf pine, Sample plots in the developmental stage of: ● – Growth, ■ – Maturity, ▲– Breakdown

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consists of 19 plots (Fig. 1). The plots were further equally divided between four elevation categories (below 1,260 m; 1,261–1,360 m; 1,361–1,460 m; above 1,460 m a.s.l.) in order to detect an elevation gradient in data.

In each plot, dead standing trees or snags and lying dead wood (lying stems and stumps) above 7 cm in diameter were recorded. The category of stumps encompassed all naturally formed stumps and snags of the height smaller that 1.3 m, since the examined area is excluded from management practices. For dead standing trees and snags taller than 1.3 m in height, their tree height and diameter at breast height were assigned. In the case of lying dead wood, its total length and diameter at ½ of its length was measured, whereas for stumps only the diameter at 0.3 m height was determined.

The decay class was assessed using the 8-degree scale as proposed by Holeksa (2001). The decay classes are characterized on the basis of the presence or absence of bark, twigs and branches, log shape, texture, and position with respect to the ground. Decay class 1 represents the least decayed dead wood with intact bark, present twigs and branches, round shape, smooth surface, intact texture, and the position elevated on support points. As the decay process proceeds, the twigs, parts of branches and bark become traces to absent. For example, in decay class 4, only stubs of branches of diameter greater than 4–5 cm are present, a knife can slide up to 3 cm into a log, and crevices up to 0.5 cm deep are present. In the next decay classes, bark and branches are absent, wood becomes softer and fragmented, and the round shape becomes elliptical. Decay class 8 represents the most decomposed dead wood, when the log is on the ground overgrown by mosses and vascular plants. Due to a high frequency of crown and stem breakage, tree volume of dead standing trees was calculated using an integral equation, which was based on the models of stem shape derived by Petráš (1986, 1989, 1990). The simplified form for calculating the volume of stem inside bark is as follows:

$$v = \frac{\pi}{40{,}000} \times \int_0^{hR} d\left(h_i, hM, d_{1.3}, \vec{a}, sp\right)^2 dh \qquad (1)$$

Where:

v – tree volume in m^3,

hR – real (measured) tree height in m,

hM – simulated tree height in m (estimated from the diameter-height curves derived from undamaged trees, Merganič *et al.* 2003),

$d_{1.3}$ – tree diameter at 1.3m height in cm,

d – tree diameter at the i^{th} tree height (h_i) in cm,

a – vector of tree-species specific parameters in the model of stem shape,

sp – tree species.

The volume of stumps was estimated as the volume of a cylinder of the height equal to 0.3 m. The volume of lying dead wood (logs) was calculated as the volume of a second degree paraboloid using Huber's formula:

$$v = h \times g_{1/2} \qquad (2)$$

Where:

v – volume of the log in m^3,

h – length of the log in m,

$g_{1/2}$ – cross-sectional area at ½ length of the log in m^2.

Total volume of coarse woody debris was given as a sum of the volumes of standing dead trees, stumps and lying logs.

Carbon storage in wood is obtained by converting the volume mass into the amount of carbon stored in this pool. For this conversion, carbon content in wood and wood density need to be known. Usually, carbon content in wood is estimated to be 50% (Coomes et al. 2002). Weiss et al. (2000) published more precise data for individual tree species of Central Europe. According to these authors, carbon content in Norway spruce wood is 50.1% of the dry mass and remains stable during the whole decomposition process of deadwood (Bütler et al. 2007). Basic wood density of Norway spruce living trees fluctuates between 0.41 g·cm^{-3} (Bütler et al. 2007; Morelli et al. 2007) and 0.45 g·cm^{-3} (Weiss et al. 2000). As wood decays, basic wood density decreases steadily (Harmon et al. 2000) depending on many factors as it is described e.g. in Radtke et al. (2004).

Since in our research object Babia hora no measurements of CWD wood density were performed, for the calculation of carbon amount in CWD we used the values published from other locations. Our literature review revealed that most of the studies dealing with the decay of CWD of Norway spruce (*Picea abies* [L.] Karst.) came from northern Europe (Krankina, Harmon 1995; Næsset 1999; Harmon et al. 2000; Yatskov 2001). From the two lately performed European studies, one comes from Italy (Morelli et al. 2007), while the other one comes from Switzerland (Bütler et al. 2007). For the purpose of our work we used the information about wood density of Norway spruce CWD in different decay stages provided by Næsset (1999), Harmon et al. (2000), Yatskov (2001), Bütler et al. (2007) and Morelli et al. (2007).

Table 1. Basic wood density of Norway spruce coarse woody debris per decay class calculated from the derived linear model Equation (3)

	Decay class according to the scale of Holeksa (2001)									
	0 (living trees)	1	2	3	4	5	6	7	8	Avg
Density (g·cm^{-3})	0.430	0.394	0.357	0.321	0.284	0.248	0.211	0.175	0.138	0.266

Since each of the mentioned studies uses another scale of wood deterioration with a different number of decay stages (3 to 8), the scales were first converted to the scale of Holeksa (2001) applied in Babia hora considering the verbal description of the decay degrees. Holeksa (2001) distinguishes 8 decay classes, while 0 stands for living trees, class 1 represents the least decomposed deadwood, and class 8 the most decomposed deadwood.

After the harmonisation of the different scales, the values of wood density were plotted against the harmonised degree of decay, and a regression was applied (Fig. 2). The analysis revealed that linear regression in the form

$$\text{density}_{CWD} = 0.430180 - 0.036464 \times \text{decClass}_{CWD} \quad (3)$$

described the relationship best ($R^2 = 0.880$). The parameter density$_{CWD}$ stands for the basic wood density of coarse woody debris given in (g·cm^{-3}), and decClass$_{CWD}$ stands for the decay class (1 to 8) according to the scale of Holeksa (2001). The intercept equal to 0.430180 represents basic wood density of living trees, while the regression coefficient –0.036464 determines the reduction of basic wood density due to the deterioration. The statistical test of the regression coefficient revealed that it was highly significant from 0 ($t = -16.69$), which indicates a significant reduction of wood density in the course of decomposition process. The derived function (3) was used for the calculation of the final values of basic wood density for each decay class as given in Table 1.

The volume of coarse woody debris can then be converted to carbon stock using the following formula:

$$C_{CWDi} = V_{CWDi} \times \rho_{CWDi} \times C(\%) \times 10 \quad (4)$$

Where:

i – decay class [1 to 8 according to the applied scale of Holeksa (2001)],

C_{CWDi} – carbon stock of CWD in the i^{th} decay class in kg C·ha^{-1},

V_{CWDi} – wood volume of CWD in the i^{th} decay class in m^3·ha^{-1},

ρ_{CWDi} – wood density of CWD in the i^{th} decay class taken from Table 1 in g·cm^{-3},

$C(\%)$ – carbon concentration in percent of the dry mass taken from Weiss et al. (2000) for Norway spruce (50.1%).

RESULTS AND DISCUSSION

The results revealed that carbon storage in deadwood varies depending on the developmental stage of the forest, while the highest amount of carbon is stored in the stage of breakdown (Table 2). This stage is represented by more than 3 times higher carbon stock in deadwood than in the other two stages. The difference in carbon storage is higher than the difference in deadwood volume between the developmental stages, since the stage of breakdown is characterized by 2.6 and 2.7 higher volume of deadwood than the stage of growth and maturity, respectively (Merganičová et al. 2004). This difference results from the decomposition process, when the stage of breakdown is characterized by a significantly greater amount of the least decomposed deadwood (decay classes 1 and 2; Fig. 3a), which has higher wood density than the more decayed CWD (Fig. 2).

On the contrary, in the stage of growth the greatest timber volume of deadwood is accumulated in the last decay class 8 (Fig. 3a). Although this volume is significantly higher than the volume in all other

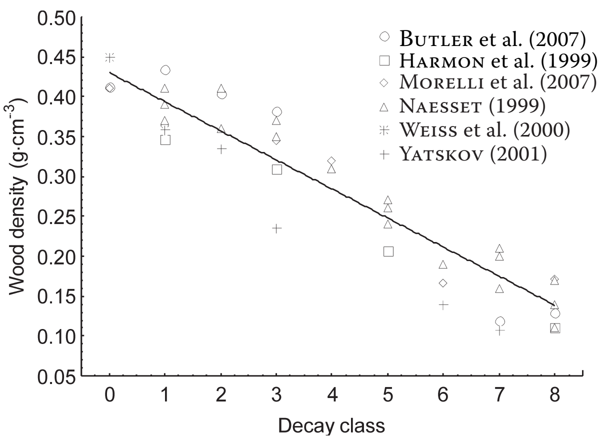

Fig. 2. Applied model for the estimation of the basic wood density of Norway spruce coarse woody debris (density$_{CWD}$ = 0.430180 – 0.036464 × decClass$_{CWD}$) using literature values for CWD decay classes (decClass$_{CWD}$) according to the scale of Holeksa (2001).

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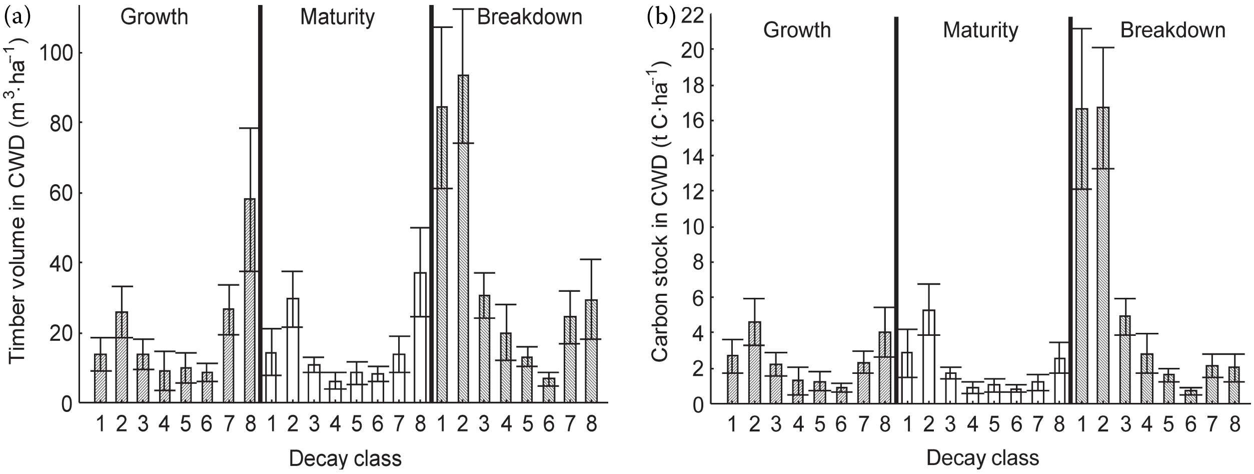

Fig. 3. Timber volume (a) and carbon storage (b) in coarse woody debris in particular developmental stages distributed along 8 decay classes defined by Holeksa (2001), where represents 95% confidence interval

classes in the stage of growth (Fig. 3a), the carbon stock in decay class 8 and the stage of growth is slightly lower than the carbon stock in decay class 2 in the same developmental stage (Fig. 3b) due to lower wood density (Table 1). The same pattern can be observed in the stage of maturity and decay classes 2 and 8 (Figs. 3a and 3b). In the stage of breakdown, large differences in the deadwood volume in early and late decay stages become even more profound in carbon stock.

If the elevation as a significant factor is accounted for in the analyses, both deadwood volume and carbon stock of CWD show a decline in all three developmental stages with increasing elevation (Fig. 4). This reduction follows the pattern of decreasing dimensions of trees with increasing elevation (Merganič et al. 2003). At upper elevations, climate characteristics are less favourable, which negatively affects forest productivity, and hence also the amount of CWD accumulated in the forest (Feller 2003). The highest deadwood volume as well as the highest carbon storage was found in the stage of breakdown and the first elevation category (Fig. 4). The other two stages, i.e. the stage of growth and maturity, are characterized by a very similar volume or carbon stock of coarse woody debris. As the elevation increases, the differences between the stage of breakdown and the other two stages diminish, and in the last elevation category become insignificant (Fig. 4).

The absolute values of carbon stock in CWD vary from 1.6 to 64.4 t C·ha^{-1} depending on the developmental stage and the elevation category as it can be seen in Fig. 4. The values are higher than those reported by Krankina et al. (2002) for Russian boreal forests (0.1–0.7 t C·ha^{-1}) or by Woodall et al. (2008) for the USA (from 2.16 to 11.35 t C·ha^{-1}), since in our study we addressed natural forests excluded from forest management practice. However, our overall average value for the whole nature reserve (23.4 t C·ha^{-1}; Table 2) corresponds with the values from natural forests from other parts of the world, e.g. Chen et al.

Table 2. Average carbon stock in coarse woody debris in particular developmental stages. In the calculation we applied weights derived from the spatial proportion of the developmental stages in individual elevation categories, i.e. we used 12 weights as follows: 1st elevation category – stage of growth (G) 0.026, maturity (M) 0.051, breakdown (B) 0.026; 2nd elevation category – G 0.095, M 0.238, B 0.143; 3rd elevation category – G 0.058, M 0.25, B 0.077; 4th elevation category – G 0.012, M 0.012, B 0.012

Developmental stage	Average (Ø) carbon stock in CWD (t C·ha^{-1})	Confidence interval 95%	
		Ø – 2 × SE	Ø + 2 × SE
Growth	12.9^{S}	5.0	20.9
Maturity	12.0^{S}	4.1	20.0
Breakdown	44.5^{S}	36.5	52.4
Together	23.4^{W}	15.5	31.3

SE – Standard error; ^{S}standardized for an average of a covariate variable elevation equal to 1,352.7 m a.s.l.; ^{W}weighted average

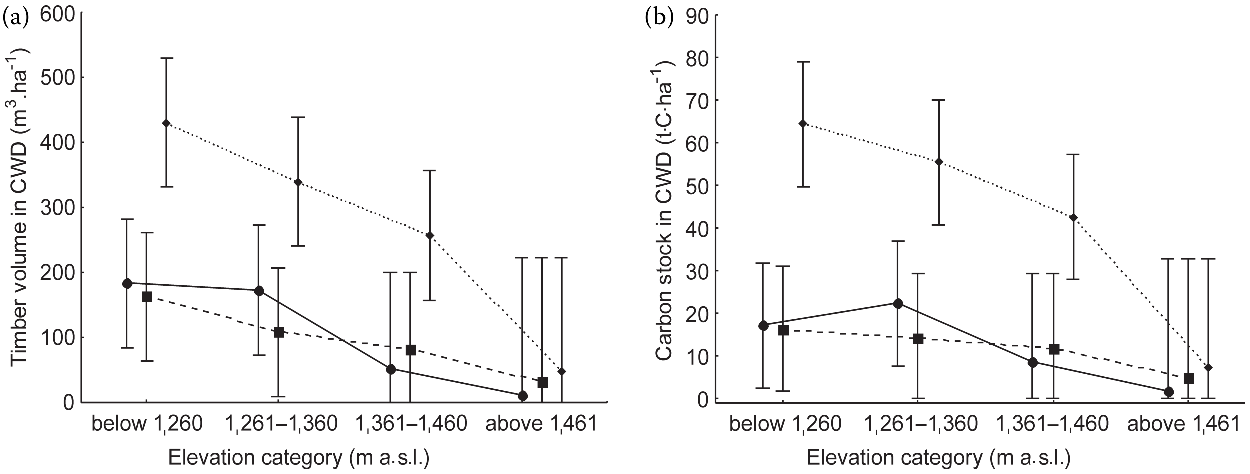

Fig. 4. Deadwood volume (a) and carbon storage (b) in developmental stages (● growth, ■ maturity, ◆ breakdown) and elevation categories, where represents 95% confidence interval

(2005) and Coomes et al. (2002) reported 17.3 ± 3.0 and 28.9 ± 8.5 t $C{\cdot}ha^{-1}$ from old-growth riparian forests in Canada, and indigenous forests in New Zealand, respectively. Unfortunately, we have not found any information about CWD carbon stock in other virgin forests of Europe.

Expressed in relative values, in the area of interest the highest amount of carbon stored in CWD is present in standing dead trees and snags (61 ± 6.5%), followed by lying dead wood (38 ± 6.5%) and naturally formed stumps, in which on average only 1% (0–5%) of aboveground CWD carbon is stored. This distribution of carbon stock differs from the distribution of CWD volume among individual categories (50% dead standing trees, 48% lying deadwood, 2% stumps, Merganič et al. 2003) due to the effect of the decomposition process.

In order to examine whether it is important to account for the changes in wood density due to wood deterioration, we estimated carbon storage in deadwood in the Babia hora nature reserve in three different ways: (1) using the basic wood density of living trees (i.e. 0.430 $g{\cdot}cm^{-3}$, see Table 1) for all decay classes, or (2) by applying the derived basic wood densities for each decay class (from Table 1), or (3) using the average basic wood density of coarse woody debris (i.e. 0.266 $g{\cdot}cm^{-3}$) calculated from the derived linear regression (3).

The results show that if the deterioration is not accounted for and the basic wood density of living trees is used in the calculations, the estimated carbon stock in coarse woody debris can be as much as twice higher than if the effect of wood decomposition is included in the estimation of carbon storage (Table 2; Fig. 5a). Although the overestimation of carbon stock differs between the developmental stages and the elevation categories, it is significant in all cases (the ratio is always significantly different from 1, see Fig. 5a). In the stage of breakdown, the overestimation is the lowest although the absolute values of carbon stock are the greatest (Fig. 4), because this stage is characterized by a large input of deadwood in early stages of deterioration (Fig. 3). On average, carbon storage is overestimated by 35%, 65%, and 66% in the stage of breakdown, growth, and maturity, respectively.

If the average basic wood density of coarse woody debris is used for the conversion of deadwood volume to carbon stock, the results show that carbon stock is underestimated in the stage of breakdown (Fig. 5b). This is so because the highest proportion of CWD is in early decay classes 1 to 4 (Fig. 3) with greater basic wood density than the applied average density. The underestimation is significant in all but the first elevation category, where a large amount of CWD was also observed in decay classes 7 and 8 (Fig. 6a).

In the stage of growth and maturity, carbon stock is highly overestimated in the first elevation category (Fig. 5b). In the second elevation category, the estimation of CWD carbon stock using an average CWD density is equal to the estimation using individual values of CWD densities from Table 1. In upper elevation categories, CWD C stock was underestimated both in the stage of growth and in the stage of breakdown (Fig. 5b). This corresponds with the distribution of coarse woody debris in the decay classes, when with the increasing elevation the shift in the proportion of CWD in decay classes has been observed (Fig. 6). While in the first elevation category and the developmental stages of growth and breakdown the highest amount of deadwood is in the last decay class 8 (Fig. 6a), in the second elevation category the differences between the decay classes are much smaller with starting prevalence

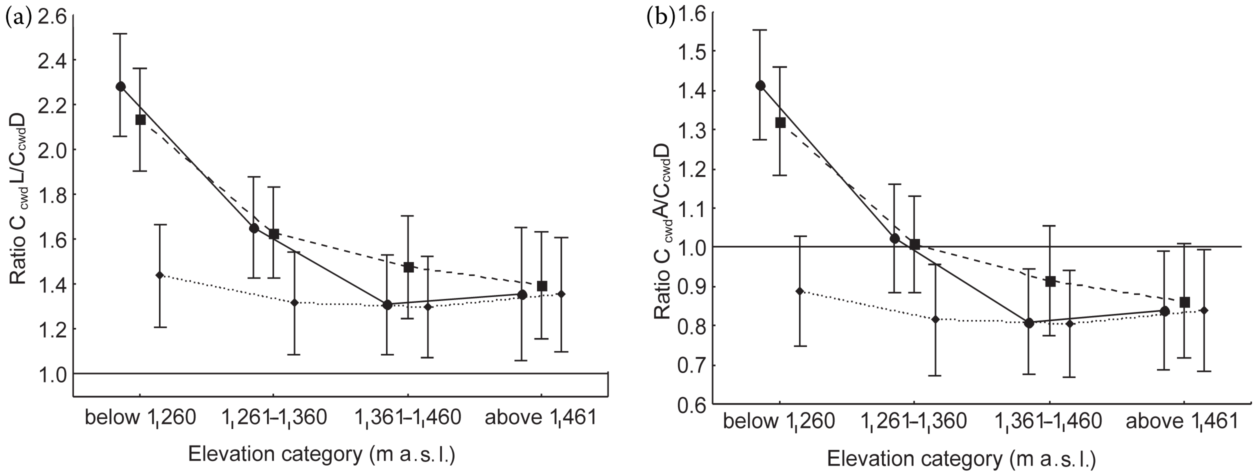

Fig. 5. Relative deviation of CWD carbon stock estimation when the decrease of deadwood density is not incorporated in the calculation (● growth, ■ maturity, ◆ breakdown, ⊥ represents 95% confidence interval). (a) represents the ratio between the carbon stock of coarse woody debris calculated with fresh wood basic density (i.e. 0.430 g·cm^{-3}, $C_{cwd}L$) and carbon stock of CWD using the decreasing wood densities from Table 1 ($C_{cwd}D$); (b) represents the ratio between the carbon stock of coarse woody debris calculated with average wood density of deadwood (i.e. 0.266 g·cm^{-3}, $C_{cwd}A$) and carbon stock of CWD using the decreasing wood densities from Table 1 ($C_{cwd}D$)

of early decomposed CWD (Fig. 6a). In the third elevation category, decay class 2 is the most abundant in both developmental stages of growth and breakdown (Fig. 6c), and the fourth elevation category is also characterized by higher CWD volume in early decay classes 1 to 4 (Fig. 6d).

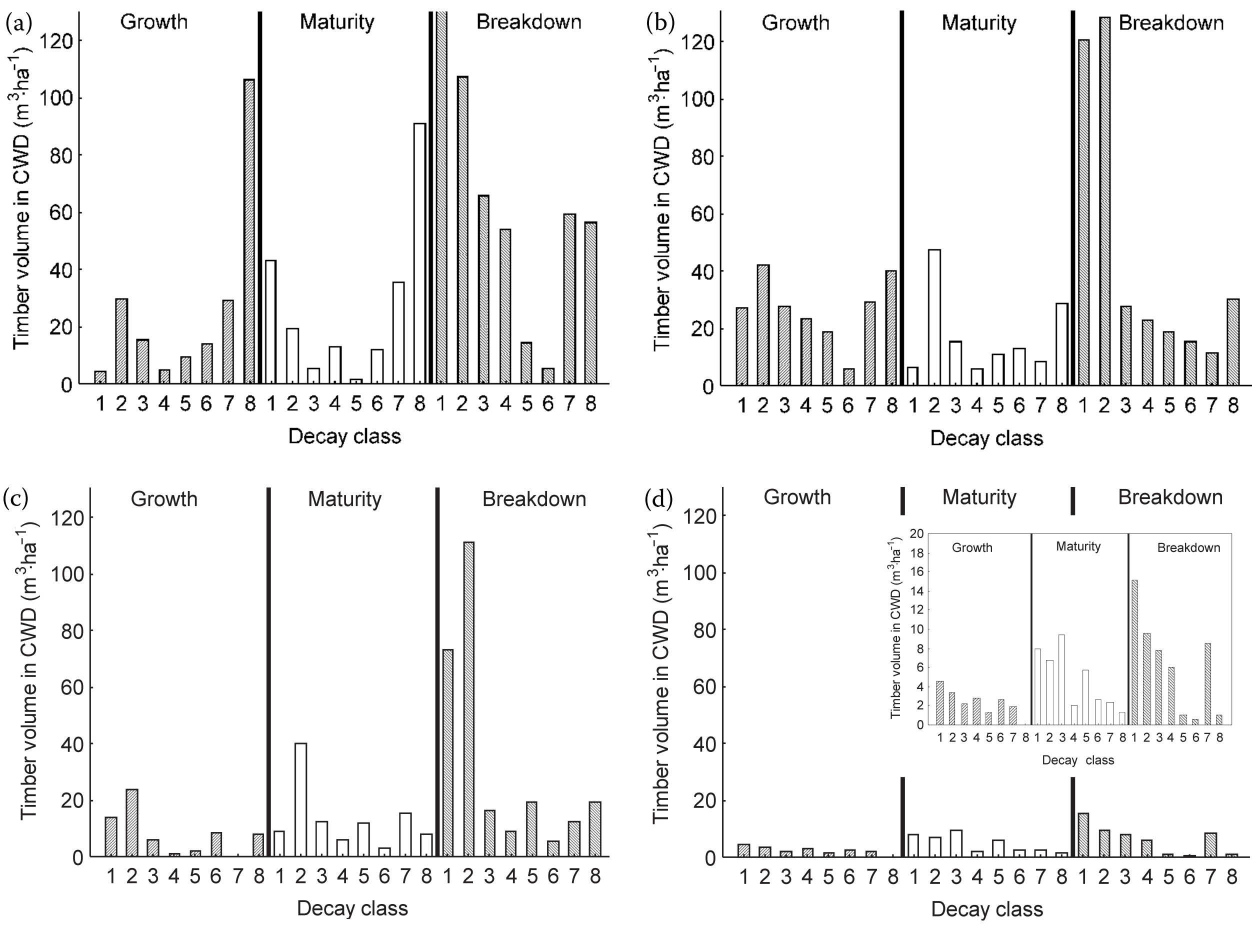

Fig. 6. Distribution of coarse woody debris volume between 8 decay classes separately in three developmental stages and four elevation categories (a) below 1,260 m; (b) 1,261–1,360 m; (c) 1,361–1,460 m, (d) above 1,460 m a.s.l.

CONCLUSION

In the presented study we estimated the carbon stock in coarse woody debris in spruce virgin forests of the nature reserve Babia Hora in Slovakia, which has been found to be highly dependent on the developmental stage and the elevation. CWD carbon stocks are the greatest in the stage of breakdown characterized by the largest amount of the least decayed deadwood. As the elevation increases, CWD carbon stocks decrease due to lower forest productivity expressed in lower tree dimensions at the upper timberline, and the differences between the developmental stages diminish.

The current lack of exact information and knowledge of the decay process of coarse woody debris in Central Europe can hinder precise carbon inventories. We demonstrated that the carbon stock could be highly overestimated if the decay process of the deadwood is not accounted for. There is an urgent need for further research in the field of coarse woody debris decomposition in order to better understand the nutrient cycle of forest ecosystems, and to be able to provide reliable data on greenhouse gas emissions which are countries obliged to report under the United Nations Framework Convention on Climate Change.

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