



Wood density and carbon concentration of decomposing stumps and coarse roots of European beech, Norway spruce and Scots pine

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Abstract

Root biomass contributes a significant proportion of total biomass and carbon storage in forest ecosystems. Deadwood (including dead roots) is an essential component of the ecosystem carbon (C) balance. Currently there are some shortcomings in the reporting of deadwood regarding the completeness and the level of detail. So far it is not possible to report about dead coarse roots since there is no existing data. Therefore, we assessed wood density and C concentration of excavated stumps and dead coarse roots (≥ 2 cm) of European beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) in different stages of decay in a case study in Northeastern Germany. In total, 15 rootstocks – three for pine, four for spruce and eight for beech—could be excavated and analysed. The decay class (DC) belowground was found to be less advanced than the one aboveground in 60% of all cases where the DC above- and belowground differed. Significantly decreasing wood densities to a similar level in advanced DCs, i.e. DC 3 and 4, were observed with increasing DC for all tree species. DC has been found to be the main predictor of all variables tested; already explaining 83% of the variation in wood density as a single predictor. C concentration was highest in DC 4 for spruce and pine, but lowest for beech in the same DC. C concentration in beech was generally lower than in spruce and pine. Significantly increasing nitrogen (N) concentrations and decreasing CN ratios were observed with increasing DC for all tree species. Our results indicate that decomposing rootstocks i.e. coarse roots and stumps can be a significant sink (and source) of C. Based on this study—although it needs to be extended to more repetitions and sites in the future—a first estimation of the belowground deadwood C pool as part of the German greenhouse gas reporting can be conducted.

Keywords Coarse woody debris · Deadwood · Decay · *Fagus sylvatica* · *Picea abies* · *Pinus sylvestris*

Introduction

Deadwood, particularly in the form of coarse woody debris (CWD; generally defined to be above or equal to 10 cm in diameter (IPC 2006, Riedel et al. 2020))—above and below ground—is a significant structural and functional component of forest ecosystems. It is of particular importance for biodiversity (Stokland et al. 2012) and ecosystem carbon (C) balance (Pan et al. 2011). About 8% of the world's forest total C stock in 2007 was stored in deadwood (Pan et

al. 2011). In relation to the C stock in the living biomass, the C stock in deadwood comprised even 20% (Pan et al. 2011) (for further details see Herrmann et al. 2024). In general, increasing amounts of deadwood C are expected due to climate change and increased abiotic (storms, droughts, wildfires) and biotic (insect outbreaks) mortality events in the future (van Lierop et al. 2015; Woodall et al. 2019; Harmon et al. 2020).

Root biomass accounts for approximately 30% of the total tree biomass (Brunner and Godbold 2007) and, thus, contributes a significant proportion of total biomass and C storage in forest ecosystems (Kurz et al. 1996; Bolte et al. 2004). Woody litter (including coarse roots) can contribute up to 75% to the total soil carbon store (Hyvonen and Agren 2001). In contrast to coarse roots (mostly > 2 mm in diameter (Addo-Danso et al. 2016); but ≥ 2 cm in our study, fine roots (< 2 mm in diameter) have a very limited lifespan and high turnover rates (Brunner et al. 2013), and

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account for about 10–20% of the total amount of tree root C (Brunner and Godbold 2007). While aboveground deadwood and its estimation has received increasing attention in recent decades, very little is known about the C stock and decomposition of dead coarse roots (see also Tobin et al. 2007; Wang et al. 2012). So far, only few studies have been conducted on coarse root decomposition, mainly in boreal forests of Scandinavia (Melin et al. 2009; Palviainen et al. 2015; Shorohova and Kapitsa 2016) or in North America (Fahey et al. 1998; Chen et al. 2001; Ludovici et al. 2002) and New Zealand (Garrett et al. 2012). To our knowledge, only one study has been conducted in the temperate climate zone, in Ireland (Olajuyigbe et al. 2011) and none in Central Europe.

Since 1994, Germany has been obliged to prepare national emission inventories of greenhouse gases (GHGs) under the United Nations Framework Convention on Climate Change and, since 2005, within the Scope of the Kyoto Protocol. The latter was replaced by the Paris agreement after 2020. GHG emissions for forests are reported in the sector land use, land use change, and forestry. Carbon stock changes in forests are reported for five different pools, including the deadwood pool (IPCC 2006). The reporting obligations require full reporting of all pools. For the deadwood pool, this includes standing and lying dead wood, dead roots and tree stumps, with a minimum diameter of 10 cm. However, currently there are some shortcomings in the reporting of deadwood regarding the completeness and the level of detail. While the data basis on C content and wood density per decay stage for aboveground deadwood (i.e. CWD) has been substantially enhanced recently based on a literature analysis (Herrmann et al. 2024), it is so far

not possible to report about dead coarse roots since there is no existing data.

In this study we assessed wood density and C concentration of excavated stumps and dead coarse roots (≥ 2 cm) of European beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) in different stages of decay in a case study in Northeastern Germany, in the state of Brandenburg. Based on this, we will be able to conduct a first estimation for the belowground deadwood C pool as part of the GHG reporting.

Material and methods

Study sites and forest stands

The sampling was conducted at four different sites, all located within a radius of about 15 km north of Eberswalde (Fig. 1; Table 1). The stands consisted of pure and mixed stands of European beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) in pole and mature development stage (Table 2).

Sampling design

Dead rootstocks, i.e. stumps and dead coarse roots (≥ 2 cm) of European beech, Norway spruce and Scots pine were sampled according to diameter and decay stage (also referred to as decay class (DC)). In regard to decay stage, we aimed to include the whole decomposition spectrum between undecomposed (class 1) and heavily decomposed (class 4; assessed above ground) based on the classification

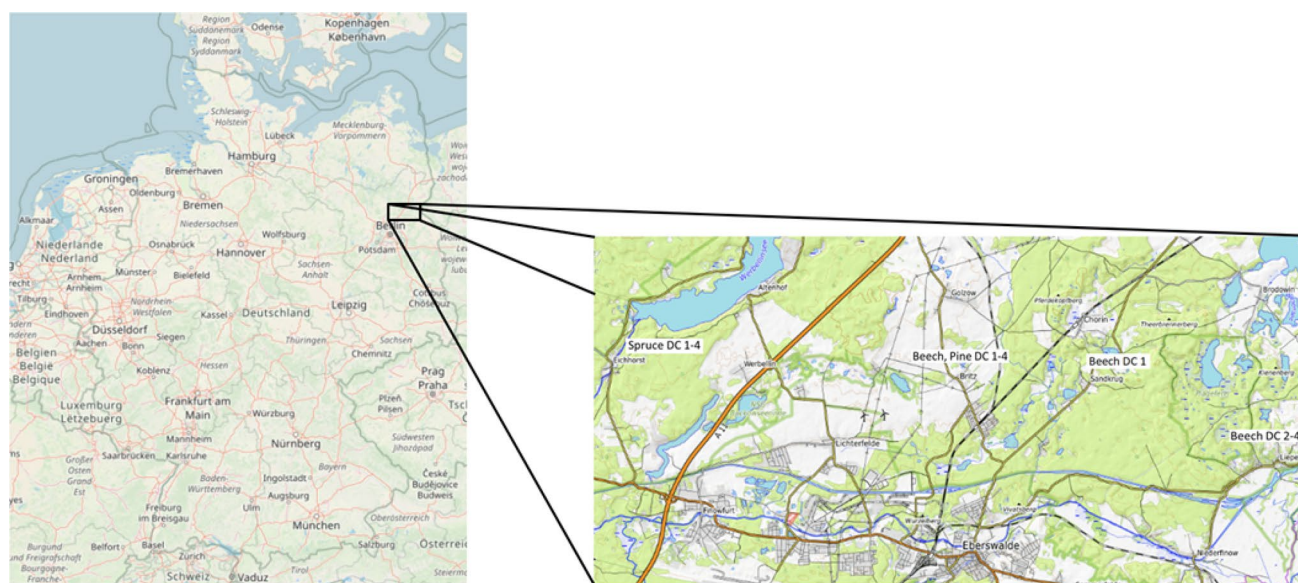


Fig. 1 Location of the study sites. DC Decay class

Table 1 Description of the study sites
(Source: State Forestry Service Brandenburg)

Site	Elevation* (m a.s.l.)	Soil type	Mean annual tempera- ture (°C)	Total annual precipita- tion (mm)
Eichhorst (EH)	52	Sandy Cambisol	8.6	590
Britz (BR)	53	Podzolic Cambisol	8.2	570
Liepe (LI)	70	Loamy haplic Albeluvisol	8.2	555
Sandkrug (SK)	40	Sandy Cambisol	8.2	555

*Source <https://de-de.topographic-map.com/maps/6jd7/Eberswalde/>

system used within the German national forest inventory (NFI) (Riedel et al. 2020; Table 3).

We started with small stumps of beech (< 20 cm in diameter at the cutting surface) at the research site of the Thünen Institute of Forest Ecosystems in Britz, in order to establish the measurement procedure, in a first step (Fig. 2). Following this, we focused on stumps between 20 and 50 cm in diameter, as this diameter range is the most frequent in terms of volume according to the German NFI (<https://bwi.info/Tabellenauswahl.aspx>. Accessed 10 Sept 2018.).

After a suitable rootstock was found, we first assessed the decay stage (Table 3) and the main stand characteristics i.e. stand type and canopy cover as well as the distance to and the diameter at breast height of the nearest neighboring trees (Table 2). For each rootstock, we measured the average stump height with a measuring tape and the average diameter at the soil surface and at the cutting surface via

Table 3 Deadwood classification system used within the German national forest inventory

Decay class	Description
1	Undecomposed: bark still on the trunk
2	Beginning decomposition: bark loosening to missing, wood can still be cut with an axe, in the case of heartrot < 1/3 of the diameter
3	Advanced decomposition: sapwood soft, heart can only partly be cut with an axe, in the case of heartrot > 1/3 of the diameter
4	Heavily decomposed: wood soft all the way through, crumbly if trodden on, contours disintegrated

cross callipering. Following this, the below ground rootstock was excavated using spades and small shovels and the root parameters were measured. These include: (1) the measurement of the diameter at the base, in the middle and at the end of each root up to a minimum diameter of 2 cm, (2) the assessment of length, decay stage and maximum depth (in relation to the soil surface) of each root and (3) the documentation of the position of each root at the rootstock. After this, rootstock and roots were roughly cleaned and the total weight was measured based on the minimum diameters of 2 and 10 cm. The latter was achieved after the weight for 2 cm was assessed, by cutting every root below 10 cm using a chainsaw. The weight was usually assessed with a scale attached to a tripod (Fig. 3). Smaller rootstocks that could be transported to the laboratory were weighed with a laboratory balance (Soehnle Tischwaage 7742 (max. 30 kg), Soehnle Professional, Backnang, Germany) at the Thünen Institute of Forest Ecosystems. For very small rootstocks and individual roots or root parts a more precise laboratory balance (Kern Präzisionswaage 572–35 (max. 2400 g),

Table 2 Description of forest stands

Site and species ID	Stand type	Tree species	Development phase	Canopy density degree ¹	Average DBH ² (in cm) and number of living trees (in brackets) within a 5 m radius
BR-Bu1	Pure stand	Europ. beech	Pole stage	8	13.3 (4)
BR-Bu2	Pure stand	Europ. beech	Pole stage	10	12.5 (2)
BR-Bu3	Pure stand	Europ. beech	Pole stage	9	13.6 (2)
BR-Ki1	Pure stand	Scots pine	Mature stand	7	20.0 (4)
BR-Ki2	Mixed stand	Scots pine with oak	Mature stand, two storied	4	18.1 (4)
BR-Ki3	Pure stand	Scots pine	Mature stand	5	27.7 (1)
EH-Fi1	Pure stand	Norway spruce	Mature stand	5	38.8 (4)
EH-Fi2	Pure stand	Norway spruce	Mature stand	5	30.5 (3)
EH-Fi3	Pure stand	Norway spruce	Mature stand	8	37.2 (5)
EH-Fi4	Pure stand	Norway spruce	Mature stand	3	36.8 (5)
LI-Bu1	Pure stand	Europ. beech	Mature stand	9	29.7 (2)
LI-Bu3	Pure stand	Europ. beech	Mature stand	10	43.3 (3)
LI-Bu4	Mixed stand	Europ. beech, oak	Mature stand	5	21.1 (4)
LI-Bu5	Pure stand	Europ. beech	Mature stand	6	56.1 (1)
SK-Bu1	Mixed stand	Europ. beech with oak, Scots pine	Mature stand, two storied	10	21.6 (6)

¹(in tenths); ²diameter at breast height

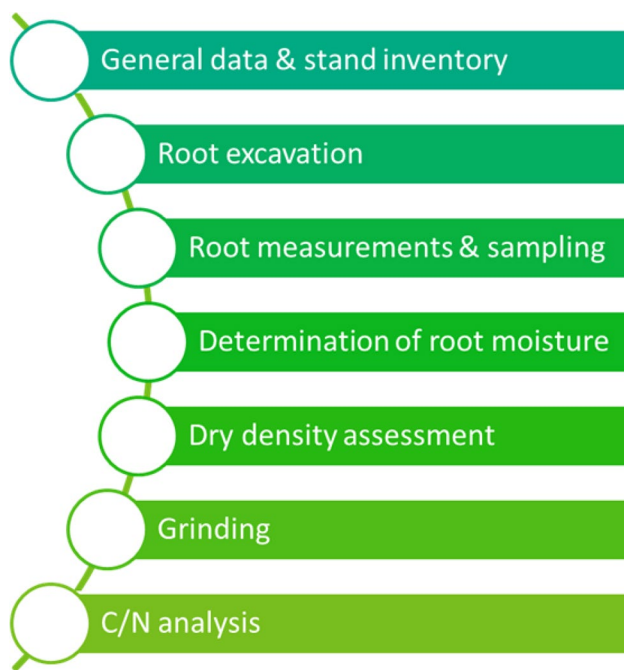


Fig. 2 Procedure of the belowground dead wood sampling in the field (1–3) as well as in the laboratory (4–7)

Kern & Sohn GmbH, Balingen, Germany) was used. After completion of the field work, rootstock and roots were cleaned from the remaining impurities. Following weight assessment small samples i.e. discs or cylinders (in the case of a diameter < 5 cm) were cut with a chainsaw or hand-saw at the base, in the middle and at the end of a particular root – corresponding to the diameter range of 2–5, 5–10 and > 10 cm—as well as from the above and below ground root stock (Fig. 4) for further moisture, density and chemical analysis. For each sample the decay stage was recorded. The samples were selected visually in order to represent the condition of the rootstock in terms of decay stage and size. The number of samples varied depending on decay stage and size of the individual rootstock. In total, 348 samples from 15 different rootstocks were included in the analysis. These samples were treated as separate samples even if they were not completely independent (see also Brosius 2011; Wang et al. 2012).

In order to determine the root moisture content, the fresh weight of the samples was measured in the first step. After that, the samples were dried in a fan-forced oven at 105 °C until constant weight was achieved, which took about 5 days (depending on the size and decay stage), and the dry weight was recorded.

Density assessment

Wood density was assessed as dry density (DD), independently from the water content of the wood. The latter varied

between 32 and 60% for our samples and would also influence the basic i.e. field density. In addition, sample handling was easier. For application in the context of the GHG inventory, a conversion method was applied to account for the lower field density (see also Herrmann et al. 2024 and formula 1 below).

DD was measured for each sample via the water displacement method. The samples were wrapped in foil bags of 10 × 10 cm and vacuum-sealed with a Caso VC10 vacuum sealer (CASO DESIGN, Arnsberg, Germany) before they were submerged into the water in order to prevent water absorption into the wood. The weight of the empty foil bag and of the submerged part of the tweezers were subtracted from the total value.

Chemical analysis

Following density assessment, a subset of all samples was ground and analysed for C and nitrogen (N) concentrations at the central laboratory of the Thünen Institute of Climate-Smart Agriculture in Braunschweig, Germany. C and N concentrations were determined by macro elemental analysis via combustion of the sample material at 1350 °C (TRU-MAC, LECO, St. Joseph, MI, USA).

Data analysis

Conversion of dry density to basic density

Dry density (=dry weight/dry volume) was converted to basic density (=dry weight/fresh volume) according to Formula 1 (Niemz and Sonderegger 2017).

$$Bd = Ddx \frac{100 - \beta v}{100} \quad (1)$$

Where Bd =basic density, Dd =dry density and βv =volume swelling or shrinkage (%; 17.9, 11.9 and 12.1 for beech, spruce and pine, respectively).

Here it should be noted that this conversion was developed for intact wood. With increasing decomposition and depending on rot type and tree species (and corresponding decomposition of cell wall components) this should be viewed as an approximation.

Statistical analysis

Statistical and model analyses were conducted using R 3.5.1 (R Core Team 2018). All significance testing was performed using an alpha level of 0.05. The assumption of normality was assessed graphically using residual QQ-plots and scatter plots of residuals vs. fitted values, as well as via parametric



Fig. 3 Weighing of rootstock and roots with a scale attached to a tripod. Photo: S. Herrmann

tests (the Kolmogorov–Smirnov test and, for sample sizes below 50 (Brosius 2011), the Shapiro–Wilk test (Dormann 2012)).

To test for significant differences in DD and C concentration (CC) between the different DCs at the species level, adjusted (i.e. estimated marginal) means were calculated and compared with the Tukey HSD test. In addition, the 95% confidence interval and the root mean square error (RMSE%; =standard error in relation to mean DD value) were calculated as well.

Results

In total, 15 rootstocks – three for Scots pine (*Pinus sylvestris* L.), four for Norway spruce (*Picea abies* (L.) Karst.) and eight for European beech (*Fagus sylvatica* L.)—could be excavated and analysed (Table 4). The average diameter across species was 26 cm, the average dry weight was 21 kg. The DC assessed aboveground was different from

that belowground by one class at the maximum for about 50% of all rootstocks across all species and DCs. The belowground DC was less than the one aboveground, which indicates less advanced decomposition, for the majority of these cases (60%).

Density variation and influencing variables

With increasing DC significantly decreasing wood densities to a similar level in advanced DCs, i.e. DC 3 and 4, were observed for all tree species (Fig. 5; Table 5). The difference between maximum and minimum values was largest in DC 2 for all species. Overall, the mean wood density of spruce was significantly different from the one of beech and pine ($p < 0.001$, Tukey HSD). The latter were not different to each other. Specifically, the mean wood density of beech was significantly different from the one of pine for DC 1 and 2 ($p < 0.001$ and $p < 0.05$, Tukey HSD) and from the one of spruce for DC 1 ($p < 0.001$, Tukey HSD) (Table 5).

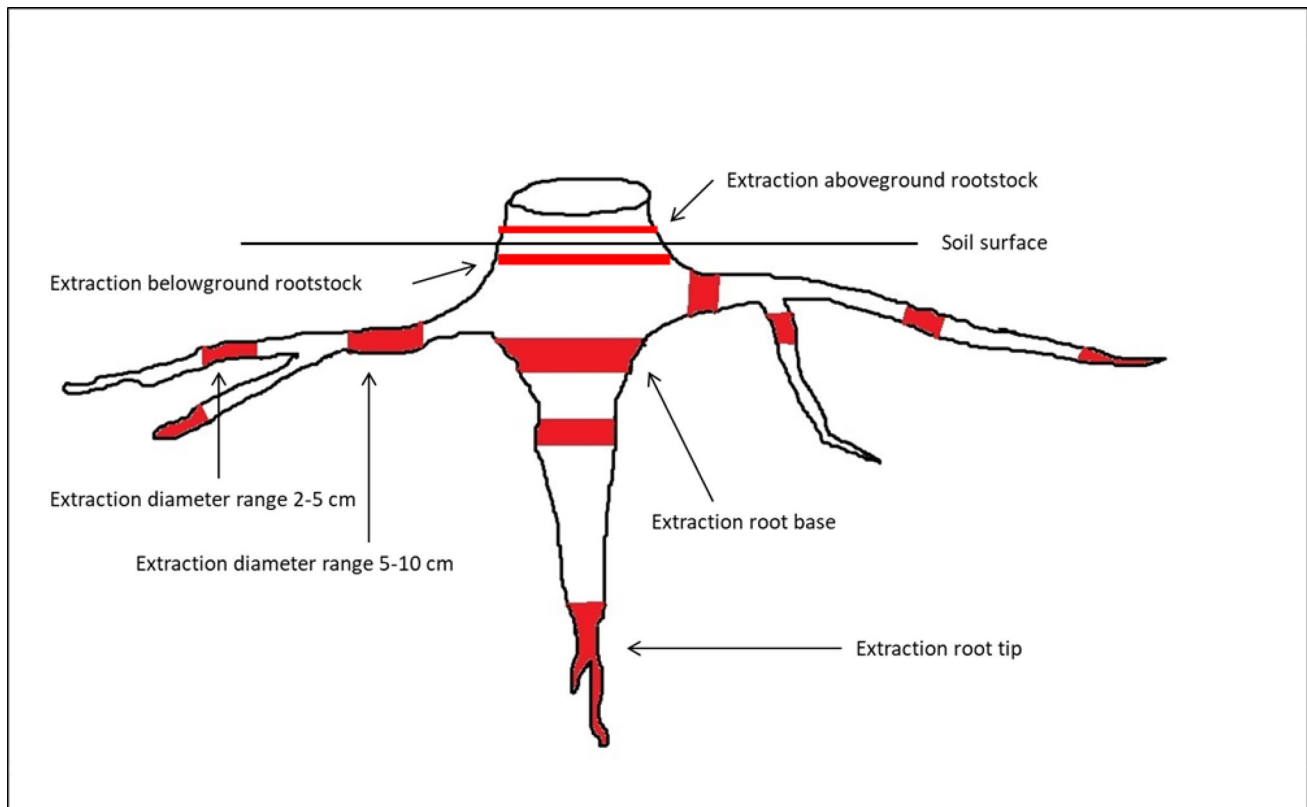


Fig. 4 Sampling design for the extraction of wood samples

Table 4 Excavated root stocks of *Picea abies*, *Pinus sylvestris* and *Fagus sylvatica* (Sites (ID): EH=Eichhorst, BR=Britz, LI=Liepe, SK=Sandkrug; + over bark, under bark)

Tree species	ID	Decay class		Diameter at cutting surface (cm)	Stump height (cm)	Dry weight ≥ 2 cm (kg)
		Above ground	Below ground			
<i>P. abies</i>	EH-Fi1	3	2	26	20	11.7
<i>P. abies</i>	EH-Fi2	4	4	22.5	17.5	2.33
<i>P. abies</i>	EH-Fi3	2	3	25.9	20	8.41
<i>P. abies</i>	EH-Fi4	1	1	42.7 ⁺	27	86.8
<i>P. sylvestris</i>	BR-Ki1	1	1	21.5 ⁺	12	19.3
<i>P. sylvestris</i>	BR-Ki2	3	3	14.95	10	6.55
<i>P. sylvestris</i>	BR-Ki3	4	3	17.5 ⁺	6.5	4.9
<i>F. sylvatica</i>	BR-Bu1	1	1	13.5 ⁺	10	6.85
<i>F. sylvatica</i>	BR-Bu2	2	3	9	4	0.49
<i>F. sylvatica</i>	BR-Bu3	3	4	11.9	8	0.68
<i>F. sylvatica</i>	LI-Bu1	4	4	35	13	5.51
<i>F. sylvatica</i>	LI-Bu3	3	2	44	20	60
<i>F. sylvatica</i>	LI-Bu4	4	3	45.9	13	32.9
<i>F. sylvatica</i>	LI-Bu5	2	1	35.1 ⁺	15	32.2
<i>F. sylvatica</i>	SK-Bu1	1	1	27 ⁺	15	37

Up to 92% of the variation in DD could be explained with a linear mixed effects model, mainly by the variables DC—with the biggest share (about 50%) followed by C (14%), tree species (8%), the interactive term between tree species and C (7%), and N (4%) as well as ID—consisting of site and rootstock—as a random factor (Table 7). If the chemical constituents were not considered, 85% at the

maximum could be predicted by DC, tree species and their interactive effect. However, already 83% of the variation in density values could be explained with only DC as predictive variable (Table 7).

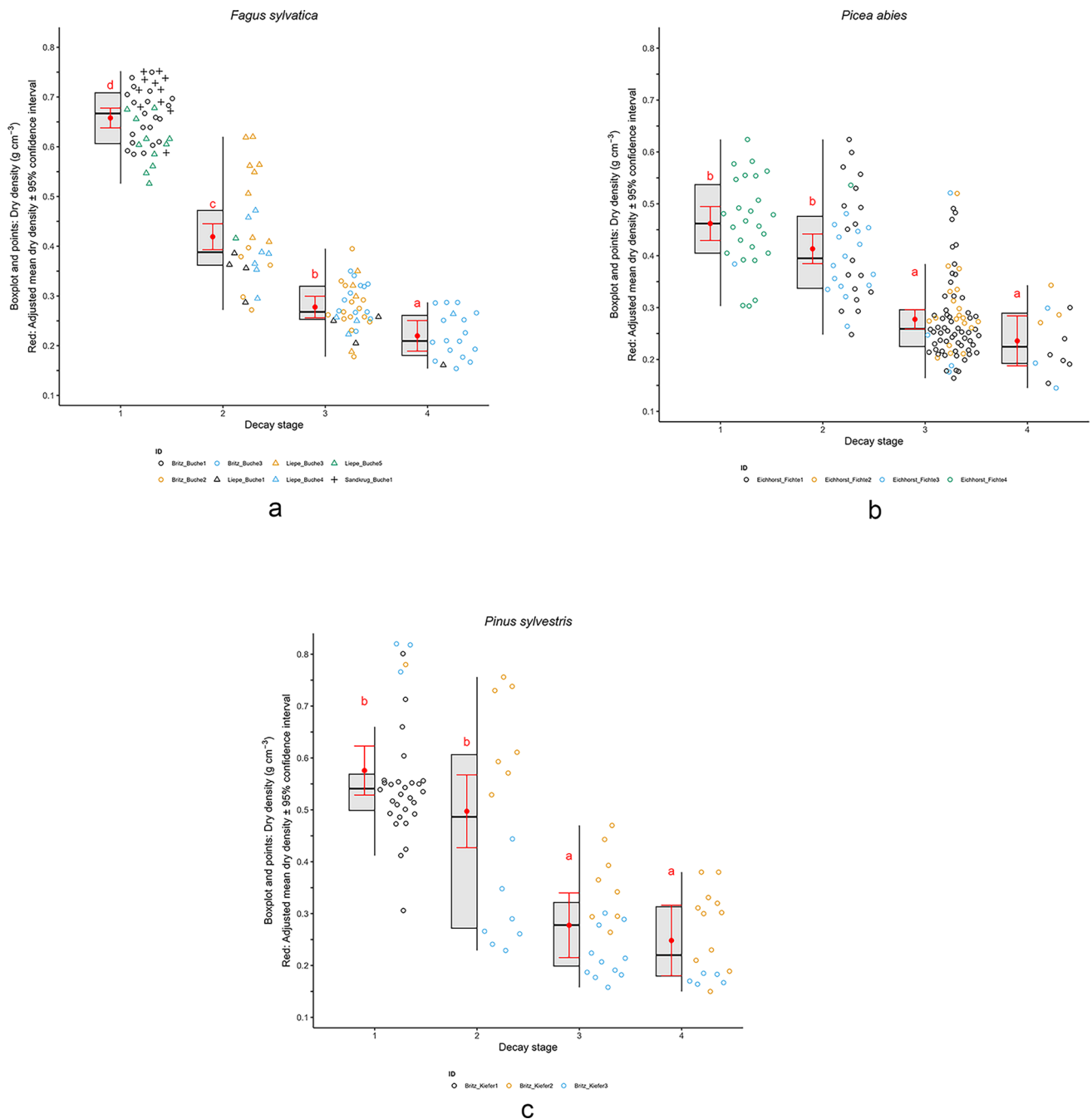


Fig. 5 Dry densities (g cm⁻³) in dead coarse roots and rootstocks of *Fagus sylvatica*, *Picea abies* and *Pinus sylvestris*; boxplots display median, lower and upper quartile, minimum and maximum values;

points outside boxplots represent outliers; different letters indicate significant differences between group means ($p < 0.05$; Tukey HSD method)

Carbon concentration

We observed a trend towards the highest C concentration in DC 4 for spruce and pine. (Fig. 6, Table 6). In contrast, the lowest CC was observed for rootstocks of beech in DC 4 (Fig. 6, Table 6). The CC in beech was generally about 3% lower than in spruce and pine. However, the variation around the mean value was large, particularly for spruce and

pine. Overall, the mean CC of beech was significantly different from the one of spruce and pine ($p < 0.001$, Tukey HSD). The latter were not different to each other. Specifically, the mean CC of beech was significantly different from the one of spruce and pine for all DCs ($p < 0.01$, Tukey HSD; pine-beech, DC1: $p < 0.05$), except for DC 1 where the mean CC of beech and spruce were not different to each other.

Table 5 Estimated marginal means (emmean) and corresponding confidence limits (CL; from lowest to highest) for deadwood basic density (derived from dry density) per decay class of excavated root stocks of *Picea abies*, *Pinus sylvestris* and *Fagus sylvatica*. Different letters indicate significant differences between group means ($p < 0.05$; Tukey HSD method)

Tree species	Decay class	Emmean	SE	RMSE%	df	Lower CL	Upper CL	Group
<i>P. abies</i>	4	0.208	0.021	10.3	148	0.153	0.262	a
<i>P. abies</i>	3	0.244	0.008	3.4	148	0.224	0.265	a
<i>P. abies</i>	2	0.364	0.013	3.5	148	0.332	0.396	b
<i>P. abies</i>	1	0.407	0.015	3.6	148	0.370	0.444	b
<i>P. sylvestris</i>	4	0.218	0.030	13.8	79	0.142	0.294	a
<i>P. sylvestris</i>	3	0.244	0.028	11.3	79	0.174	0.314	a
<i>P. sylvestris</i>	2	0.437	0.031	7.1	79	0.358	0.516	b
<i>P. sylvestris</i>	1	0.506	0.021	4.1	79	0.453	0.559	b
<i>F. sylvatica</i>	4	0.181	0.013	7.0	118	0.149	0.213	a
<i>F. sylvatica</i>	3	0.228	0.009	4.0	118	0.205	0.251	b
<i>F. sylvatica</i>	2	0.344	0.011	3.2	118	0.317	0.371	c
<i>F. sylvatica</i>	1	0.540	0.008	1.5	118	0.519	0.561	d

Confidence level used: 0.95

N and CN

Significantly increasing N concentrations and decreasing CN ratios were observed with increasing DC in all species (Figs. 7 and 8). The highest N concentration was observed for beech (Fig. 7) while initial CN ratios were highest in spruce and pine (Fig. 8).

Discussion

Rootstock decomposition

We found the DC belowground to be less advanced than the one aboveground in 60% of all cases where the DC above- and belowground differed. Coarse roots decomposed slower than stumps also in the studies by Olajuyigbe et al. (2011) and Palviainen and Finér (2015). The decomposition process i.e. microbial activity depends on climatic i.e. temperature and moisture conditions, which might both be modified negatively belowground such that temperature is usually reduced and moisture is increased. Therefore, decomposition is slowed down belowground compared to aboveground in moist and cool environments, whereas wood decomposition is limited by low moisture levels in xeric forests and belowground wood decomposes faster than aboveground wood (Moroni et al. 2015). This was also confirmed in a study using a laboratory and field experiment (Herrmann and Bauhus 2012). According to this study, CWD respiration rates were dependent on tree species and decay stages and were strongly controlled by wood temperature and wood moisture content (Herrmann and Bauhus 2012). In addition, the chemical and physical properties also differ between Norway spruce (*Picea abies* (L.) Karst.) stumps and coarse roots. The latter have higher lignin and lower carbohydrate

contents (see also Palviainen and Finér (2015) for further details). The same applies also to the differences between the three tree species. The generally higher initial nutrient concentrations for N, P, S, Ca, K and Mg in European beech (*Fagus sylvatica* L.) (Herrmann and Bauhus 2018), the lack of resin channels (in contrast to Norway spruce and Scots pine (*Pinus sylvestris* L.)), the generally lower lignin content which also belongs to a different type (syringyl instead of guaiacyl lignin) in angiosperm wood when compared to gymnosperm wood (Cornwell et al. 2009), as well as the presence of extractive compounds (like tannins and flavanoids) in the latter (Weedon et al. 2009), lead to a higher decay susceptibility in beech compared to spruce and pine (see also Weedon et al. 2009). Furthermore, brown-rot fungi (with minimal lignin degrading capacity) are more commonly associated with conifer forests than lignin-degrading white-rot fungi, which preferentially attack angiosperm wood (Weedon et al. 2009).

Density variation and influencing variables

Significantly decreasing wood densities with similar values in advanced DCs as observed in our study, were also found in other studies for aboveground deadwood (Yatskov et al. 2003; Müller-Using and Bartsch 2009; Herrmann et al. 2015, 2024). In Detail, our mean density values for beech were in between the values found in the study by Müller-Using and Bartsch (2009) and Herrmann et al. (2015). The density values for spruce observed in our study were in the range of variation of the values found by Palviainen and Finér (2015) for spruce coarse roots and stumps and somewhat lower than the values observed by Herrmann et al. (2015) for aboveground CWD. The latter was also the case for the mean density values observed for pine in our study. Our density values of spruce and pine were somewhat

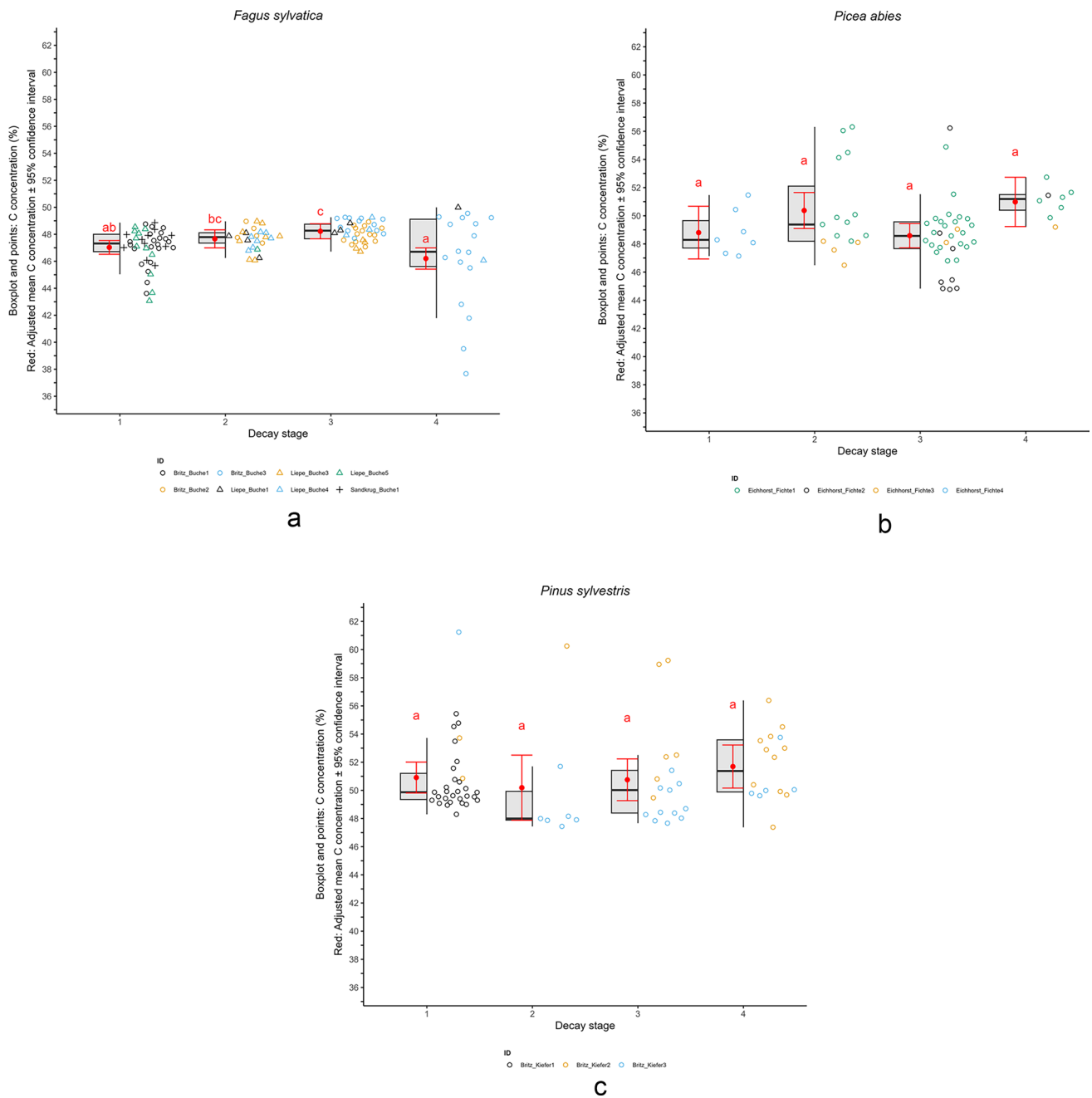


Fig. 6 Carbon concentrations (%) in dead coarse roots and rootstocks of *Fagus sylvatica*, *Picea abies* and *Pinus sylvestris*; boxplots display median, lower and upper quartile, minimum and maximum values;

points outside boxplots represent outliers; different letters indicate significant differences between group means ($p < 0.05$; Tukey HSD method)

higher than the values observed by Yatskov et al. (2003). In comparison to a meta-analysis for the same tree species that included 41 different data sets from 14 European countries (Herrmann et al. 2024), our density values for spruce and pine were mostly higher (in particular for pine) and lower for beech than the values derived in that study.

Similar to Seedre et al. (2013), were DC alone accounted for 81% of the variation in deadwood density for aboveground CWD, DC alone accounted for 83% (or 71% without

random factor) of the variation in our study. Up to 86% of the variation in deadwood density could be explained by DC, tree species and their interactive effect in the study by Seedre et al. (2013), while 81% of the variation associated with (aboveground) CWD density could be explained by the same variables in the study by Yatskov et al. (2003); compared to up to 92% (or 84% without random factor) in our study. However, in contrast to our study, chemical constituents were not considered in the studies by Yatskov

Table 6 Estimated marginal means (emmean) and corresponding confidence limits (CL; from lowest to highest) for carbon concentration per decay class of excavated root stocks of *Picea abies*, *Pinus sylvestris* and *Fagus sylvatica*. Different letters indicate significant differences between group means ($p < 0.05$; Tukey HSD method)

Tree species	Decay class	Emmean	SE	RMSE%	df	Lower CL	Upper CL	Group
<i>P. abies</i>	3	48.6	0.431	0.89	59	47.5	49.7	a
<i>P. abies</i>	1	48.8	0.935	1.92	59	46.4	51.2	a
<i>P. abies</i>	2	50.4	0.639	1.27	59	48.7	52	a
<i>P. abies</i>	4	51	0.874	1.71	59	48.7	53.2	a
<i>P. sylvestris</i>	2	50.2	1.159	2.31	67	47.2	53.2	a
<i>P. sylvestris</i>	3	50.8	0.743	1.46	67	48.8	52.7	a
<i>P. sylvestris</i>	1	50.9	0.551	1.08	67	49.5	52.3	a
<i>P. sylvestris</i>	4	51.7	0.766	1.48	67	49.7	53.7	a
<i>F. sylvatica</i>	4	46.2	0.398	0.86	118	45.2	47.2	a
<i>F. sylvatica</i>	1	47	0.257	0.55	118	46.4	47.7	ab
<i>F. sylvatica</i>	2	47	0.338	0.72	118	46.8	48.5	bc
<i>F. sylvatica</i>	3	48.2	0.281	0.58	118	47.5	48.9	c

Confidence level used: 0.95

Table 7 Linear mixed effects model (ANOVA table) to predict the dry density of dead coarse roots and rootstocks of *Fagus sylvatica*, *Picea abies* and *Pinus sylvestris*: Dry density ~ Tree species + Decay class + C + N + Tree species x C + (1 | ID)

Source	Sum of squares	df	F	Sig	Eta squared
(1) Maximum model ^a					
Tree species	0.12682	2	20.173	<0.001	8.02
Decay class	0.78544	3	83.291	<0.001	49.66
C	0.23635	1	75.19	<0.001	14.94
N	0.07088	1	22.549	<0.001	4.48
Tree species x C	0.11011	2	17.514	<0.001	6.96
(2) Without chemical analysis ^b					
Source	Sum of Squares	df	F	Sig	Eta squared
Decay class	1.89056	3	106.7303	<0.001	54.17
Tree species	0.00549	2	0.4647	0.638	0.18
Decay class x Tree species	0.26790	6	7.5620	<0.001	17.52
(3) ^c					
Source	Sum of Squares	df	F	Sig	Eta squared
Decay class	2.5327	3	125.41	<0.001	71.12

^aConditional R²: 0.922 (Marginal R²: 0.841)^bConditional R²: 0.851 (Marginal R²: 0.713)^cConditional R²: 0.832 (Marginal R²: 0.711)

et al. (2003) and Seedre et al. (2013). Up to 92% (or 86% without random factor) of the variation in deadwood density could also be explained in the meta-analysis by Herrmann et al. (2024) based on a linear mixed effects model with DC, CWD type, tree species, the interactive effects between DC and CWD type and DC and tree species as the main explaining variables. Up to 84% (or 71% without random factor) of the variation in (aboveground) deadwood density could be explained by DC alone in that study; which is very similar to the result obtained here.

Carbon concentration

The C concentrations observed in our study were lower for beech when compared to spruce and pine, and comparable to the values by Herrmann and Bauhus (2018). Compared to the results of the meta-analysis by Herrmann et al. (2024), our CCs were similar but showed higher variation, which is not surprising given the small sample size. Lower CCs in CWD of angiosperms when compared to gymnosperms were also found by Harmon et al. (2013) as well as by Thomas and Martin (2012) for live trees.

N and C/N

We found significantly increasing N concentrations and decreasing C/N ratios for spruce as well as for beech and pine in our study. In contrast, only a tendency of increasing N concentrations was observed for spruce in the study by Palviainen and Finér (2015), compared to a fourfold increase between DC 1 and 4 in our study. Even a ninefold increase in N concentration was found for aboveground spruce CWD in the study by Herrmann and Bauhus (2018). Increasing N concentrations were also observed in the study by Müller-Using and Bartsch (2007) for beech and by Köster et al. (2015) for pine. In the study by Palviainen and Finér (2015), C/N ratios for spruce decreased from 278 at the maximum (in > 10 cm roots) to 79 in stumps while in our study, C/N decreased from 1136 in DC 1 to 115 in DC 4. The C/N ratios for spruce observed in our study were very similar to those found by Herrmann and Bauhus (2018) for aboveground CWD. In that study, the C/N ratio for spruce decreased from 1088 at 8 years to 178 at 36 years of decomposition.

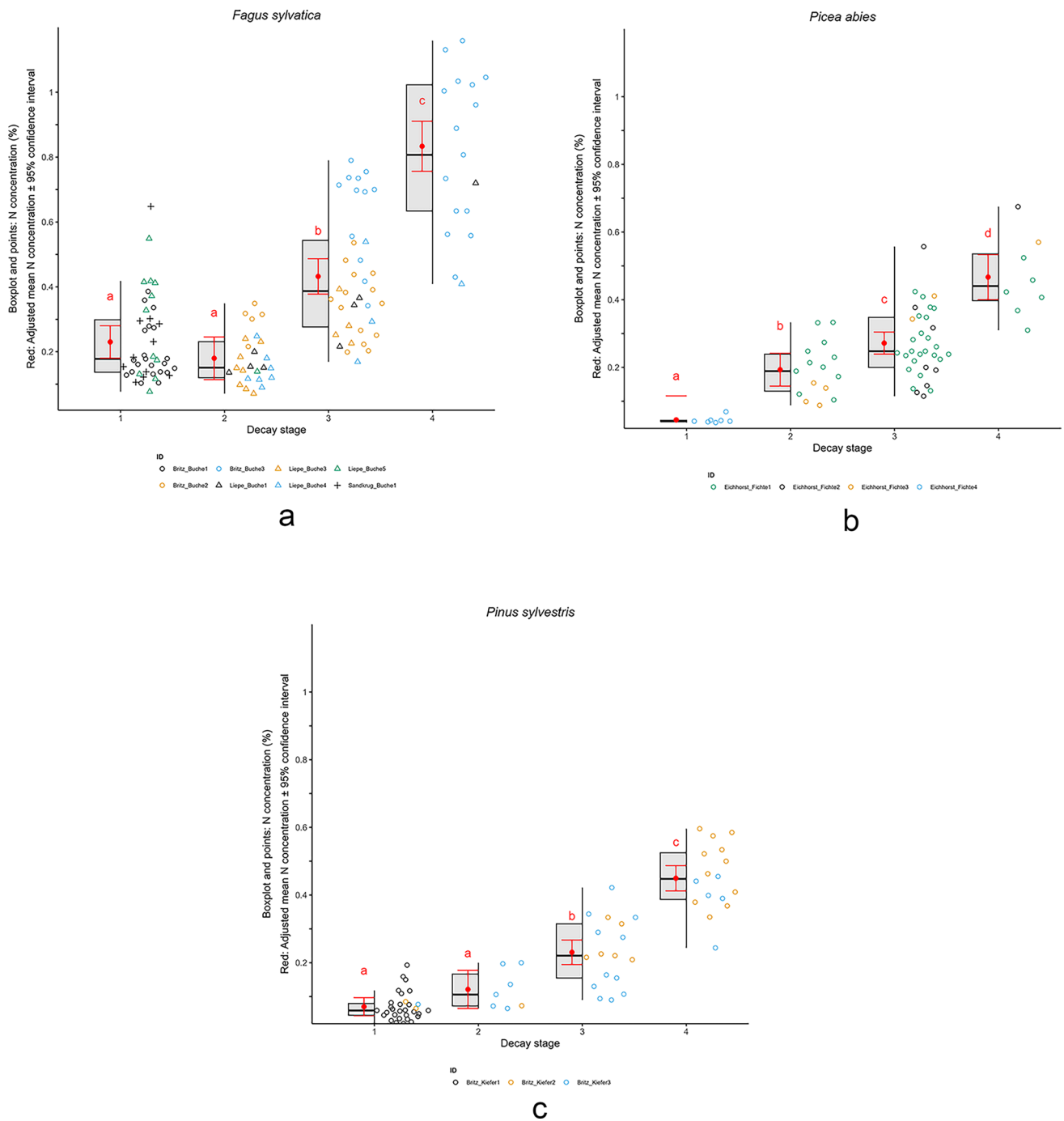


Fig. 7 Nitrogen concentrations (%) in dead coarse roots and rootstocks of *Fagus sylvatica*, *Picea abies* and *Pinus sylvestris*; boxplots display median, lower and upper quartile, minimum and maximum values;

points outside boxplots represent outliers; different letters indicate significant differences between group means ($p < 0.05$; Tukey HSD method)

Study limitations and future research

We are aware, that the study and analysis presented here is a first attempt to estimate the carbon pool in decomposing coarse roots. Our results should be mainly viewed as preliminary, as the majority of the samples were not independent and very few repetitions i.e. rootstocks per tree species

and DC could be sampled. Unfortunately, the decomposition rates could not be calculated as part of this study; as we did not know the specific dates of cutting. The calculation of the decomposition rates would have been too imprecise based on the available information.

Due to the severe drought in 2019, it was very difficult to manually dig out the roots in the severely hardened soil.

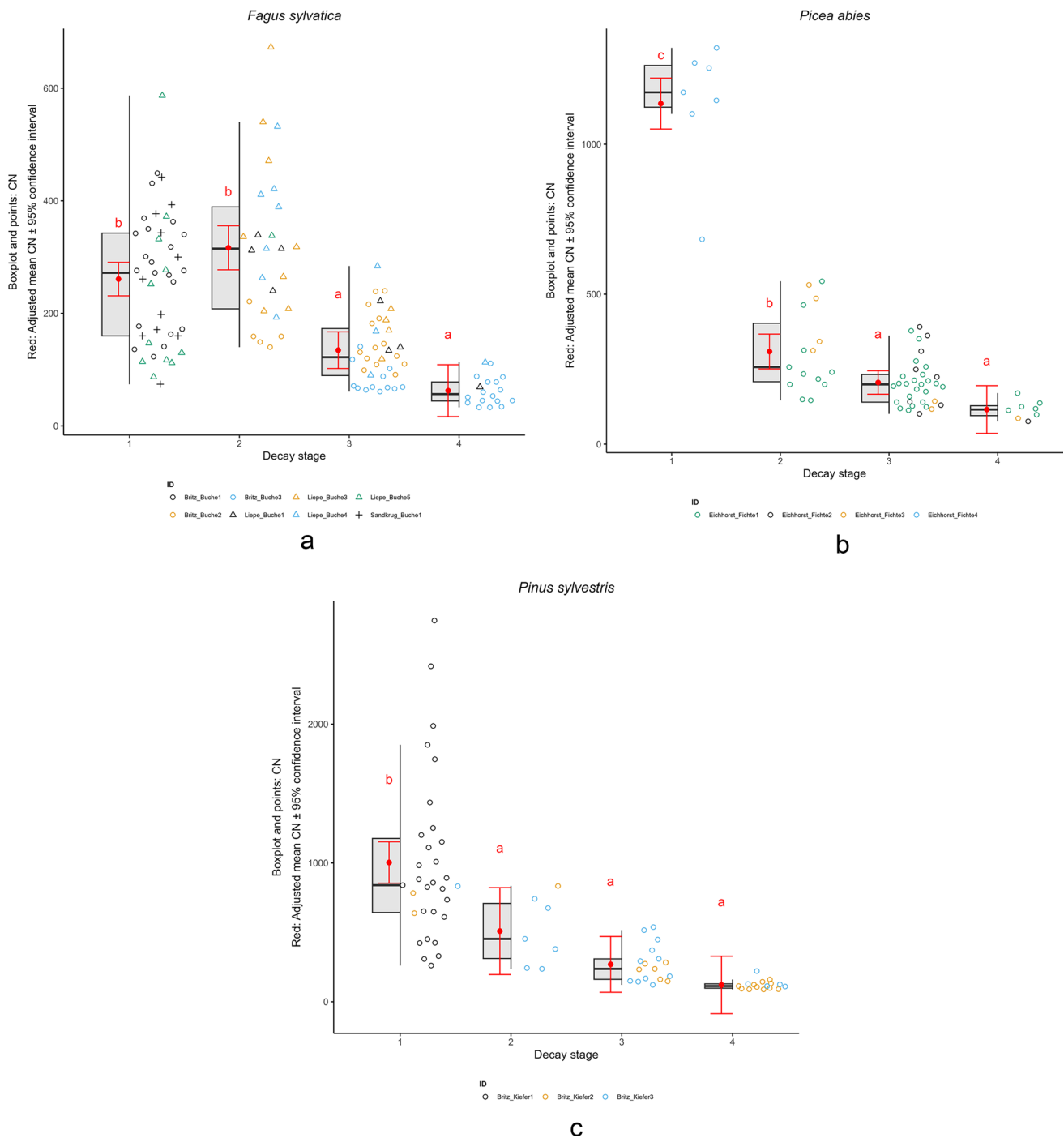


Fig. 8 C to N ratios of dead coarse roots and rootstocks of *Fagus sylvatica*, *Picea abies* and *Pinus sylvestris*; boxplots display median, lower and upper quartile, minimum and maximum values; points out-

side boxplots represent outliers; different letters indicate significant differences between group means ($p < 0.05$; Tukey HSD method)

This was one reason why the excavation of dead rootstocks with a diameter above 40 cm was only possible to a very limited extent, depending on tree species and soil conditions, with the equipment available in this project. Therefore, our sampling was restricted to rootstocks from very

few sites and to average diameters at the cutting surface usually far below 50 cm.

The current study and analysis should be verified and extended based on a larger sample size and more sites in the future. In addition, the assessment of the decomposition rate

should be included in a future study. With this, our results can be understood in further detail.

Conclusions

To our knowledge, no comparable study is known in Germany and central Europe in which an attempt was made to directly inventory the biomass and estimate wood density and C storage of dead coarse roots. The data collected here are currently the only data of this kind available.

Our results indicate that decomposing rootstocks i.e. coarse roots and stumps can be a significant sink (and source) of carbon. We found the DC belowground (and hence decomposition) to be less advanced than the one aboveground for the majority of cases where DC above- and belowground differed. Wood density can be predicted with high accuracy based on DC alone. The wood densities and C concentrations of stumps and dead coarse roots determined in our study, although they need to be further refined, provide a basis for a first estimation of the belowground deadwood C pool as part of the German GHG reporting. However, this data set should be extended to a larger sample size and more sites in the future. Only then can the representativeness and the range of variation of the study results obtained here be assessed. This is a prerequisite to include the carbon balance of dead coarse roots in the German GHG reporting.

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Author contributions SH conducted field sampling and analysis and wrote the majority of the manuscript. SD conducted field sampling and contributed to the manuscript. KO guided the study and contributed to the manuscript. WS conceived and co-guided the study and contributed to the manuscript. All authors read and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no Conflict of interests.

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