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Age determination of coarse woody debris with radiocarbon analysis and dendrochronological cross-dating

Inken Krüger · Jan Muhr · Claudia Hartl-Meier · Christoph Schulz · Werner Borken

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Abstract To study the decay of coarse woody debris (CWD) in forest ecosystems, it is necessary to determine the time elapsed since tree death, which is difficult at advanced decay stages. Here, we compare two methods for age determination of CWD logs, dendrochronological cross-dating and radiocarbon analysis of the outermost tree ring. The methods were compared using samples from logs of European beech, Norway spruce and Sessile oak decomposing in situ at three different forest sites. For dendrochronological cross-dating, we prepared wood discs with diameters of 10–80 cm. For radiocarbon analysis, cellulose was isolated from shavings of the outermost tree rings. There was an overall good agreement between time of death determined by the two methods with median difference of 1 year. The uncertainty of age determination by the radiocarbon approach did not increase with decreasing carbon density, despite incomplete separation of chitin from the extracted cellulose. Fungal chitin has the potential to alter the radiocarbon signature of tree rings as the carbon for chitin synthesis originates from different sources. Significant correlations between year of tree death and carbon density of wood were found for beech and spruce, but not for oak due to relatively small decreases in carbon density within 50–60 years. Total residence times of CWD were calculated from these correlations and revealed 24 years for beech and 62 years for spruce. The uncertainty of total residence times results mainly from huge natural variability in carbon density of CWD rather than uncertainty in the age determination. The results suggest that both methods are suitable for age determination of CWD.

Keywords Radiocarbon · Coarse woody debris · CWD · Dendrochronological cross-dating · Cellulose extraction · Time of tree death

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I. Krüger (✉) · W. Borken
Department of Soil Ecology, Bayreuth Center of Ecological and Environmental Research (BayCEER), University of Bayreuth, Dr.-Hans-Frisch-Str. 1-3, 95448 Bayreuth, Germany
e-mail: inken.krueger@uni-bayreuth.de

J. Muhr
Department of Biogeochemical Processes, Max Plank Institute for Biogeochemistry, Hans-Knoell-Str. 10, 07745 Jena, Germany

C. Hartl-Meier
Faculty of Forestry, University of Applied Sciences Weihenstephan-Triesdorf, Hans-Carl-von-Carlowitz-Platz 3, 85354 Freising, Germany

C. Schulz
Bavarian State Institute of Forestry, Hans-Carl-von-Carlowitz-Platz 1, 85354 Freising, Germany

Introduction

Coarse woody debris (CWD) has several ecological functions (Harmon et al. 1986) as habitat for insects, fungi and mosses, and through its role in the nutrient and carbon (C) cycle of forest ecosystems. The decay rate of CWD is highly variable in dependence of exposure, tree species and environmental factors (Harmon et al. 1986). Residence times of few decades to centuries are common in temperate forests (Rock et al. 2008). As long-term experiments on CWD decay are rare (Stone et al. 1998), chronosequence approaches are often used to estimate residence times (Kueppers et al. 2004). One prerequisite for the estimation of decay is the age of CWD (i.e., the time elapsed since death of the tree or branch) (Harmon et al. 1986). In case the tree death is linked to distinct events like fire, storm or harvesting, historical records might be used to determine the time of tree death, but usually more sophisticated methods are needed. Dendrochronological cross-dating is commonly used for the determination of time of tree death of CWD (Daniels et al. 1997; Lombardi et al. 2008; Castagneri et al. 2010). We know of only one study by Kueppers et al. (2004) that used radiocarbon analysis.

The bomb radiocarbon approach makes use of the annual change in the atmospheric radiocarbon signature triggered by nuclear weapon testing in the 1950s and 1960s and subsequent dilution or uptake processes. Because of photosynthetic CO_2 fixation, the radiocarbon signatures of tree rings correlate with the respective atmospheric radiocarbon signatures (Worbes and Junk 1989). As the annual rate of change of the atmospheric radiocarbon signature has been bigger than the current measurement precision for the last decades, we can clearly distinguish the radiocarbon signature of two subsequent years. A limitation of the bomb radiocarbon approach arises from the 'bomb curve' that yields one radiocarbon signature for two different years, i.e., one before and one after the radiocarbon peak in the atmosphere around 1964 (Levin and Kromer 2004). Further information is needed to assign the correct year to the radiocarbon signature. For samples before 1950, radiocarbon signatures display only small annual changes as a result of radioactive decay. This feature has been traditionally used for age determination of organic materials of up to 60,000–70,000 years. In this contest, dendrochronologically dated year rings of old trees were used to estimate annual changes in the radiocarbon signature of CO_2 in the atmosphere before 1950 (Leavitt and Bannister 2009).

Radiocarbon analysis requires only a small quantity of wood from the outermost tree ring. The accuracy of the age determination is greater when purified cellulose of the tree ring is used for radiocarbon analysis since other components such as non-structural carbohydrates and lignin bias the radiocarbon signature. In case of CWD, the incorporation of chitin from fungal cell walls represents a potential uncertainty because fungi translocate and use organic C with distinct radiocarbon signatures for chitin synthesis. Such a 'contamination' of cellulose can be detected by elevated organic N concentration given that chitin is a N-containing polysaccharide.

Dendrochronological cross-dating exploits the similarity in weather-dependent patterns of tree ring width sequences or other growth ring characteristics in trees of the same species and from the same climatic region (Schweingruber 1988). It has proved to be a reliable age-determination technique. This method can be difficult or even impossible at advanced decay stages, as decaying CWD loses its stability and density and the formation of holes is notable (Harmon et al. 1986), making the correct identification of the outermost tree ring difficult (Schweingruber 2007; Campbell and Laroque 2007).

Here, we compare radiocarbon analysis with dendrochronological cross-dating of wood discs of European beech, Sessile oak and Norway spruce from three different study sites. Wood discs taken from logs represent a broad variety of decay stages and carbon densities ranging from 60 to 630 kg C m^{-3}. We compare the suitability of both methods and investigate how the time elapsed since tree death relates to C density of CWD calculated from C concentration and wood density. We aim at calculating total residence times of CWD, defined as the period until a piece of woody debris has been reduced by density loss and fractionation to a diameter of less than 7 cm, for each tree species. Further, we test the purity of cellulose extracts from year rings and its effect on radiocarbon dating by analysing nitrogen (N) concentrations.

Materials and methods

Study sites

Samples were collected at three unmanaged forests in Bavaria, Germany: Grübel (49°07′N 013°07′E), Ludwigshain (49°55′ 011°48′E) and Rohrberg (49°54′N 009°26′E). Grübel is a Norway spruce (*Picea abies* L.) forest reserve situated in the Bavarian Forest at an altitude of 1250 m a.s.l. Mean annual air temperature is 3–4 °C, and mean annual precipitation is 1,500 mm. The formerly managed forest has been protected since 1978 and the CWD stock amounted to 12 t C ha^{-1} in 2010 (Krüger et al., unpublished data). Ludwigshain is a beech-oak (*Fagus sylvatica* L., *Quercus petraea* (Matt.) Liebl.) forest that has been unmanaged since 1913 and is well known for ancient oaks of 450 years. Mean annual temperature is 7–8 °C, and precipitation accumulates to 650–750 mm a^{-1}. Total above-ground CWD stocks are 30 t C ha^{-1} in 2010 (Krüger et al., unpublished data). Rohrberg is a beech-oak forest that has been unmanaged since 1928. The oaks are up to 600 year old. Mean annual air temperature ranges from 7 to 8 °C and precipitation from 950 to 1,100 mm a^{-1}. The CWD stock was 24 t C ha^{-1} in 2010 (Krüger et al., unpublished data).

Sampling procedures

A total of 54 CWD logs with intact outer year ring, identified through the presence of bark or large non-decomposed surfaces, were chosen for this study. The study includes all suitable CWD logs within a representative area of the study sites. The most-decayed CWD logs were excluded from the study. The logs had diameters of

Table 1 Number and characteristics of sampled CWD logs at three study sites

Study site	Tree species	Number of logs	Log diameters (cm)	Log lengths (m)	C density (kg C m^{-3})
Grübel	Norway spruce	16	42 (16)	13.6 (9.2)	153 (69)
Ludwigshain	European beech	12	78 (61)	14.0 (8.4)	102 (33)
Ludwigshain	Sessile oak	9	76 (50)	17.5 (7.7)	134 (58)
Rohrberg	European beech	10	58 (22)	16.8 (10.2)	190 (104)
Rohrberg	Sessile oak	7	67 (31)	13.0 (8.3)	212 (35)

Standard deviation of the mean is given in parenthesis

20–180 cm and lengths between 4 and 32 m (Table 1). For determination of CWD characteristics (wood density, C concentration), up to 10 wood discs or segments were taken evenly distributed per log using a power drill with a diameter of 2 cm and a depth of up to 25 cm. Wood shavings of each drilling were entirely collected and subsequently dried at 60 °C until constant mass. Wood density was calculated from dry mass and the volume of the drill hole. Subsamples were ground with a ball mill for C and N analysis (Elementar Vario EL, Hanau, Germany).

For radiocarbon analysis, we took samples of the outermost tree ring with a utility knife. The blade was exchanged between two samplings to avoid cross-contamination. The samples were ground before the cellulose extraction. One wood disc or segment of each log was taken with a motor saw for dendrochronological cross-dating.

Radiocarbon analysis

Cellulose is commonly isolated from wood for isotope analysis (Gaudinski et al. 2005). While non-structural wood compounds might cross tree ring boundaries, cellulose is synthesized with C fixed in the year of ring formation (Mazany et al. 1980). Lignification of wood tissue occurs after cellulose formation (Fritts 1976). We thus assume that contamination with lignin-containing compounds has no or little impact on radiocarbon signatures. For cellulose extraction, we used a method adapted from the Jayme–Wise protocol (Green 1963). Forty to fifty milligrams of wood was processed for extraction of α-cellulose. The milled samples were processed in cuvettes with glass fibre filters. Extractable wood substances were extracted with a 1:1 toluene–ethanol mixture in a soxhlet extractor. Subsequently, the remaining samples were treated with a CH_3COOH-$NaClO_2$ mixture and subsequently 5 % NaOH solution at 80 °C. Between extraction steps, the samples were rinsed with a 15 % NaCl solution. These extraction steps were repeated at least three times and until the remaining sample had a white colour. The samples were then rinsed with 1 % HCl and subsequently with distilled water for a period of at least 12 h. The cellulose was freeze-dried until mass constancy. To assess the quality of cellulose, total C and N was measured with a CN analyser (Elementar Vario EL, Hanau, Germany) by the Central Analytics of the Bayreuth Center of Environmental and Ecological Research (BayCEER). Further, $\delta^{13}C$ of the cellulose was measured with a MAT 252 IRMS at the stable isotope laboratory of the Max Planck Institute for Biogeochemsitry in Jena. Industrial cellulose (Sigma chemicals, St Louis, USA), chitin and chitinase (Acros organics, New Jersey, USA) as well as Heidelberger Nullholz and the wood standards C-4 and C-5 from the International Atomic Energy Agency (IAEA) (Rozanski et al. 1992) were used as standards for radiocarbon analysis. The yield of cellulose is calculated from the difference of the original sample weight and the weight of the extracted cellulose.

Radiocarbon signatures of cellulose were measured by accelerator mass spectrometry (AMS). Subsamples of 0.7–1.1 mg C were combusted in sealed quartz tubes with CuO as oxidizer and silver wire for 2 h at 900 °C. The resulting CO_2 was cryogenically purified from water and non-condensable compounds and converted to graphite targets using the modified sealed-tube zinc reduction method described by Xu et al. (2007). Radiocarbon data are expressed as $\Delta^{14}C$, which is the per mil deviation from the $^{14}C/^{12}C$ ratio of oxalic acid standard in 1950. The sample $^{14}C/^{12}C$ ratio has been corrected to a $\delta^{13}C$ value of −25 ‰ to account for any mass-dependent fractionation effects (Stuiver and Polach 1977). $\Delta^{14}C$ signatures were dated to calendar years using the CALIBomb Radiocarbon calibration online tool (Reimer et al. 2004). For post-bomb radiocarbon signatures, two calendar years are possible. The younger age was attributed to the time of tree death. The cellulose extraction and sample combustion were processed at the laboratory of ^{14}C analyses at the Max Planck Institute for Biogeochemistry in Jena. Graphite targets were prepared at the Department of Soil Ecology at the University of Bayreuth. The AMS measurements were performed by the Keck-CCAMS facility of the University of California, Irvine with a precision of 2–5 ‰.

Dendrochronological cross-dating

All wood segments were dried prior to further preparation. Heavily decomposed wood was immersed in paraffin at 60 °C to prevent rupture and breaking (Hall 1939). Less decomposed wood was polished with sandpaper with granulation of 100 grit. Wet chalk was used to increase the visibility of tree ring boundaries (Schweingruber 1983). Ring widths were measured to the nearest 0.01 mm using a measuring device (LINTAB 6; Rinntech, Heidelberg, Germany) with a stereomicroscope (MZ 6; Leica, Wetzlar; Germany) and the TSAP-Win software package (Rinn 2003). Tree ring widths were measured along two radii following the longest and shortest radius.

Site chronologies were compiled from 6 to 12 wood discs of living trees for each tree species and study site, in order to build up reference chronologies for the CWD. The quality of the site chronologies was tested with three methods using the dplR package for R (Bunn 2008): series inter-correlation (Rbar), which examines the signal strength between throughout the chronology (Cook et al. 2000), expressed population signal (EPS), which is a measure of the mean correlation between series (Wigley et al. 1984) and the Gleichläufigkeit (Glk), which compares the difference in width of successive tree rings (Schweingruber 1988).

Tree ring sequences were measured along at least two radii with a surely identified outermost tree ring and the smallest amount of major constraints including softness of wood or holes. All measurements were conducted at the Faculty of Forestry, University of Applied Science Weihenstephan-Triesdorf.

The dating of tree death was obtained through visual cross-dating of CWD samples with the corresponding site chronology with the software Corina 1.1 β (The Cornell Tree Ring Analysis System). Additionally, the software was used to calculate correlation analyses based on student's *t* test (t values), series inter-correlation (Rbar) as well as Gleichläufigkeit (Glk) to cross-date the tree ring sequence with the site chronologies. All results that gave an end of the sequence set after 2009 were excluded. Based on what is known about the decay rate of the observed tree species (Rock et al. 2008) as well as site history, we also excluded all results that gave end dates before 1935. If uncertainties on the correct date remained, the tree ring sequences were visually compared with other sequences of CWD of the same tree species and the same study site. Precision of the method depends on the number of overlapping years and by consequence the length of the individual tree ring sequences.

Data analysis

The C density of CWD is calculated from the density and the C concentration of CWD. CWD decay functions were calculated by reduced major axis regression with the lmodel2 package in R 2.9.2 (R Development Core Team 2009) using C density and year of tree death. When not otherwise specified, year of tree death describes the mean of the year determined by radiocarbon analysis and dendrochronological cross-dating. Total residence times are calculated as the time difference between sampling year (2010) and the intersection of the decay function with the *x*-axis. Differences between tree species were tested with a Student's *t* test with a confidence interval of $p < 0.05$.

Results

Properties of cellulose and radiocarbon dating

We found cellulose yields, defined as mass % of the original sample after extraction, of 17–38 % for the different wood standards with a good reproducibility (data not shown). Pure industrial cellulose had a recovery rate of 81.2 ± 0.3 % (SD, $n = 4$). For the CWD samples, cellulose yields ranged between 6 and 39 % (Fig. 1a). We found significant differences between tree species ($p < 0.001$), but no correlations with C density of CWD.

Mean C concentration (±SD) in the extracted cellulose was lower in oak (39.5 ± 3.9 %) than in beech (42.1 ± 0.7 %) and spruce (42.2 ± 0.6 %). In 6 out of 54 samples, the C concentration was below 40 %. Thirteen samples contained measurable N concentrations (>0.05 %), whereas the N concentration of the remaining samples was below the detection limit (Fig. 1b). Mean $\delta^{13}C$ of cellulose was −23.2 ± 1.3 ‰ without significant differences between the three tree species. $\Delta^{14}C$ signatures of the outermost tree rings ranged between −34 and 660 ‰. Five samples were dated to the time period before the bomb peak. Forty-nine samples could be attributed to calendar years between 1959 and 2006.

Dendrochronological cross-dating

The length of the site chronologies was between 94 and 244 years. The Rbar values range between 0.45 and 0.65 and EPS between 0.82 and 0.93; therefore, the reference chronologies provide good data quality (Table 2). With respect to wood characteristics and tree age, between 43 and 286 rings were measured per CWD segment. Figure 2 shows samples of the wood anatomy at different stages of decay and the tree species-specific changes in CWD. Beech CWD becomes soft, and tree rings gradually less visible. Oak CWD is marked by the formation of holes and spruce CWD by cracks along tree ring boundaries.

Based on dendrochronological cross-dating, the investigated trees had died between 1942 and 2006. The distribution differed between the tree species: for beech the oldest CWD originated from 1981, while four samples of oak and one sample of spruce were dated to the period prior to the bomb peak in the 1950s.

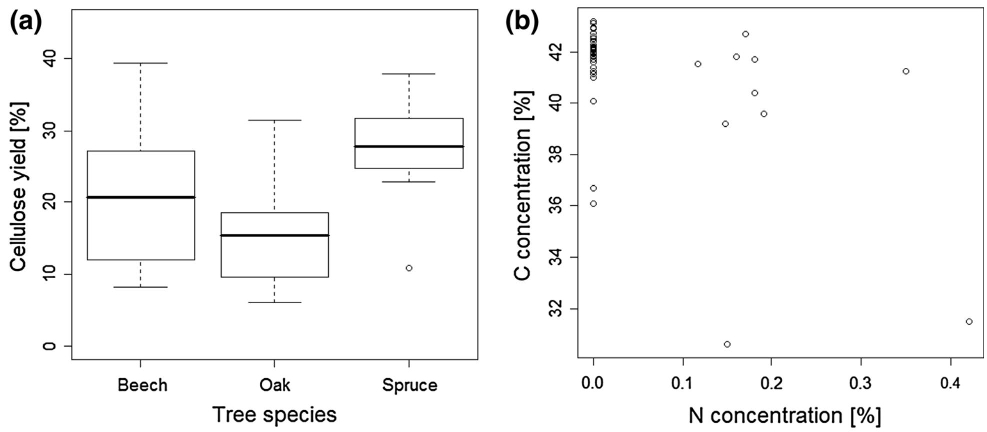

Fig. 1 Properties of extracted cellulose: Yields of cellulose extraction in % per tree species (**a**) and C and N concentration of extracted cellulose in % (**b**)

Table 2 Dendrochronological characteristics of site chronologies for living trees at the study sites

Study site	Tree species	Period	Number of trees	Series inter-correlation (rbar)	Expressed population signal (EPS)	Gleichläufigkeit (GLK) [%]
Grübel	Norway spruce	1759–2010	6	0.50	0.82	52
Ludwigshain	European beech	1916–2009	12	0.51	0.91	63
Ludwigshain	Sessile oak	1907–2009	8	0.65	0.93	64
Rohrberg	European beech	1938–2009	7	0.45	0.84	68
Rohrberg	Sessile oak	1848–2009	10	0.46	0.93	64

Comparison of radiocarbon and dendrochronological dating

We found a good positive relationship between year of death as determined by radiocarbon dating versus dendrochronological cross-dating ($R^2 = 0.96$, $p < 0.001$) (Fig. 3). The average difference between radiocarbon and dendrochronological dating was 2.05 years with a median value of 1 year. Radiocarbon dating showed a younger time of death in 13 cases and an older death year in 17 cases. No differences between radiocarbon analysis and dendrochronological cross-dating were found for tree species, study sites or C density of CWD.

CWD density varied between 80 and 630 kg m^{-3} for beech, 140 and 480 kg m^{-3} for oak and 60 and 510 kg m^{-3} for spruce. C concentration ranged between 46 and 56 % for all species, resulting in C densities of CWD of 29–307 kg C m^{-3}. Positive correlations between average time of tree death and C density were found for beech and spruce, but not for oak (Fig. 4). In case of oak, correlations were also not significant for the single study sites. Differences in decay functions between dendrochronological data and radiocarbon data were small (Table 3). Total residence times are estimated at 24 years for beech and about 62 years for spruce.

Discussion

Properties of cellulose and constraints of radiocarbon analysis

The observed cellulose yields for CWD samples between 6 and 39 % were considerably lower than the values reported for fresh wood samples of up to 68 % (Gaudinski et al. 2005). These differences can be explained only partly by incomplete extraction due to the method, as we measured a recovery rate of about 80 % for the extraction of pure cellulose. Decay of wood usually results in the preferential loss of cellulose and thus a relative increase in lignin, resins and waxes (Preston et al. 1990), which could explain the low cellulose yields in the CWD samples. The lowest yield was found for oak CWD, likely for two reasons: (1) Live oak wood is known to have a smaller initial cellulose concentration (ca. 40 %) than beech (43 %) and spruce (49 %) (Thygesen et al. 2005; Pettersen 1984; Kollmann and Fengel 1965; Fengel and Wegner 1983); (2) decomposition of oak wood is dominated by brown-rot fungi, which preferentially decompose cellulose while leaving lignin mostly intact, whereas beech and spruce wood are known to be decomposed by white-rot fungi, which decompose cellulose and lignin at a nearly equal rate (Leonowicz et al. 1999).

Fig. 2 Samples of CWD of Sessile oak (**a**), European beech (**b**) and Norway spruce (**c**) with increasing stages of decay

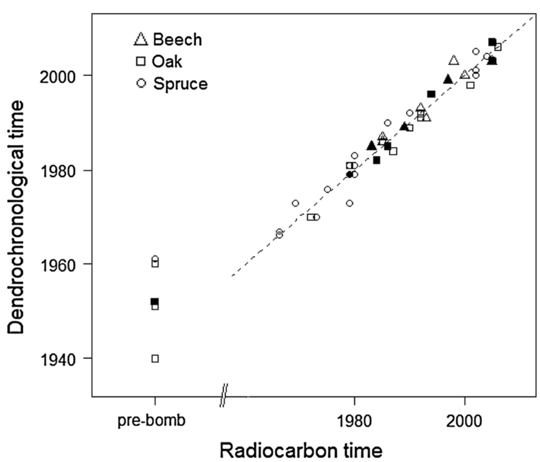

Fig. 3 Time of tree death as determined by dendrochronological cross-dating (dendrochronological time) and radiocarbon analysis of the uttermost year ring (radiocarbon time) for the tree species European beech, Sessile oak and Norway spruce. Full symbols designate enhanced N concentration in the cellulose extracts

With an average of 41 %, the C concentration of the extracted cellulose is lower than the 44 % C of pure cellulose polymer. Other methods of cellulose extraction do not have this problem, reporting C concentration in the extracted cellulose closer to the expected values (Brendel et al. 2000). The lower C concentrations in our measurements are most likely to be explained by a dilution effect: Weighing of the glass fibre filters that we used, before and after the extraction procedure, indicates a weight loss of the filters. As the filters are C-free, the addition of filter material to the samples would result in a decrease in the C concentration without affecting any of the isotopic measurements. The measured weight losses were high enough to explain the observed differences in C concentration. We found no relationship between ^{13}C signatures and C concentration, affirming that isotope measurements were not affected by a presumed contamination of the samples.

We speculate that chitin produced by fungi during the decay of CWD could explain the increased N concentrations found in some of the samples. The treatment of industrial chitin revealed that chitin is not at all removed by the procedure we used (data not shown). The presence of chitin in wood samples is a problem for age determination by radiocarbon analysis of CWD samples as chitin has a different radiocarbon signature than cellulose of the outermost tree ring. Undecayed wood contains only small amounts of chitin (Jones and Worrall 1995). Because of

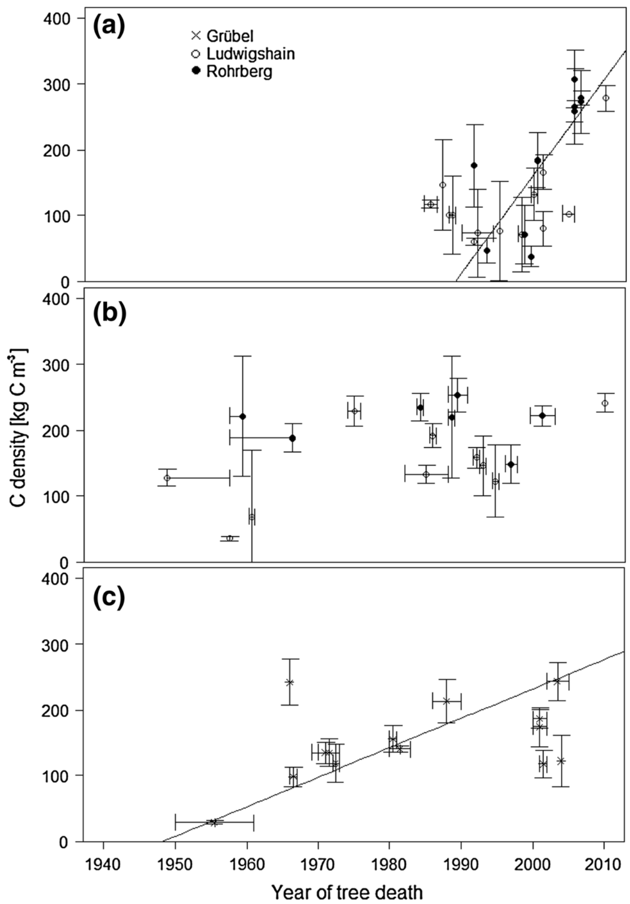

Fig. 4 Relationship between time since tree death and C density of CWD for the tree species European beech (**a**), Sessile oak (**b**) and Norway spruce (**c**). Time since tree death represents the mean of radiocarbon and dendrochronological dating

increasing colonization by fungi, both the chitin and N concentration of CWD increase with decay (Holub et al. 2001). CWD from our study sites displays also an increase in total N concentration with progressing decay (not shown). However, we found no relationship between N concentration in cellulose extracts and C density (not shown). The increased amount of chitin or other organic N compounds indicates an incomplete purification of cellulose. The presence of carbon molecules besides cellulose might harm the accuracy of radiocarbon analysis of heavily decayed CWD samples. The C:N ratio of 210–80 found in the cellulose would be explained by a dilution of cellulose with about 3–8 % chitin. An increase in N concentration during cellulose extraction is commonly observed in most extraction methods (Gaudinski et al. 2005). As no N-containing chemicals were utilized during sample preparation, the N must originate from the CWD sample.

The five CWD samples with negative $\Delta^{14}C$ signatures that correspond to calendar years before 1955 belong to the tree species spruce and oak. The CWD logs must have resided in the forests for at least 65 years, which is common for CWD of spruce and oak (Holeska et al. 2008; Harmon et al. 1986).

Constraints of dendrochronological cross-dating

Dendrochronological studies of CWD are more challenging than studies of living trees. The changes due to the decay of CWD affect the completeness of the outermost tree ring, the choice of radii position and the visibility of the tree rings. With advancing decay, density and stability of CWD decrease (Harmon et al. 1986). This affects the correct identification of tree ring boundaries, resulting in missing tree rings or incorrect tree ring widths.

By extracting wood segments like discs instead of increment cores, the difficulties resulting from decay were remediated to some extent. As a disadvantage, segments are larger and more difficult to handle than core samples, but allow choosing the best suited radii after examination of the entire section. Nonetheless, the significance of the correlation analysis was affected by decay. Calculated algorithms are on the lower scale of what is commonly considered statistically significant for some of the CWD measurements.

We found the effects of decay on wood anatomy to be species dependent. Samples of beech often showed

Table 3 CWD decay functions calculated with reduced major axis regression between time of tree death and C density for the tree species European beech, Sessile oak and Norway spruce

Tree species	Method	CWD decay function	Adjusted R^2	p	Total residence time (a)
European beech	Average	$y = 1{,}986.0 + 0.08x$	0.62	<0.001	24
	Dendrochronology	$y = 1{,}985.6 + 0.08x$	0.63	<0.001	24
	Radiocarbon	$y = 1{,}986.4 + 0.08x$	0.61	<0.001	24
Sessile oak	Average	$y = 1{,}956.8 + 0.11x$	0.14	0.10	
	Dendrochronology	$y = 1{,}957.0 + 0.11x$	0.13	0.08	
	Radiocarbon	$y = 1{,}958.5 + 0.10x$	0.12	0.08	
Norway spruce	Average	$y = 1{,}948.4 + 0.22x$	0.59	<0.001	62
	Dendrochronology	$y = 1{,}948.6 + 0.22x$	0.56	<0.001	61
	Radiocarbon	$y = 1{,}948.2 + 0.22x$	0.61	<0.001	62

Time of tree death was determined by dendrochronology and radiocarbon method; average represents the mean time of tree death of both methods symptoms of white-rot decay that disintegrates wood structure and reduces it to its components cellulose, hemicelluloses and lignin (Schweingruber 2007). Discoloration of wood, often the first visible effect of decay, does not affect the identification of tree rings. At later stages of decay, however, tree ring boundaries become difficult to see or even invisible. This process usually occurs from the outside to the inside, in consequence of reducing the length of the usable sequence. In spruce CWD, the formation of cracks along tree ring boundaries was often noted and restricted the positioning of the recorded radii. Decay of oak CWD leads to the formation of holes, but it does not affect the visibility of tree ring boundaries until advanced stages of decay.

While sequences are statistically compared with standardized methods, dendrochronological cross-dating necessitates the restriction to a certain time interval. While such restrictions are based on scientific observations and reliable accounts, they remain to some extent subjective and might differ between users.

Comparison of analytical methods and CWD C density

We found a good relationship between radiocarbon analysis and dendrochronological cross-dating that was not affected by the state of decay, tree species and the study sites. This indicates that despite constraints, both methods are equally reliable techniques to estimate the year of tree death. Radiocarbon analysis can be the favourable method for standing CWD that cannot be sampled by motor saw and for CWD where the outermost tree ring is only intact on a small area or decay occurs from the inner to the outer wood. Dendrochronological cross-dating is more suitable for CWD that is expected to have slow decay rates owing to resistant wood properties or to unfavourable site conditions for decomposing organisms.

Besides practicability, the decision to apply a method is based on factors like time and cost. Both methods are time intensive and require special equipment. Which method is more efficient partially depends on the number of samples, age as well as their diversity regarding geographical origin and tree species. For dendrochronological cross-dating, each region and tree species requires an individual site or reference chronology that needs to be compiled from trees of known age. The compilation of a site chronology requires a need to record a certain number of tree ring width sequences in addition to the CWD samples. This is more worthwhile that the more samples need to be dated. If a reference chronology is existent, dendrochronological cross-dating represents a cheaper way to date a large number of samples than radiocarbon analysis.

Age determination of tree rings by radiocarbon analysis is barely dependent on the geographical region and the tree species. In mixed forests with many tree species, classification of heavily decayed CWD logs to tree species is problematic if wood characteristics are similar. In such cases, radiocarbon analysis is an alternative method of age determination. Radiocarbon analysis can be more time efficient if the number of CWD samples is small.

Positive slopes between year of tree death and C density allowed estimates of CWD total residence times for European beech and Norway spruce. CWD of European beech exhibits a relatively short total residence time of 24 years compared to Norway spruce with 62 years. For Sessile oak, no relationship was found, but the small decrease in C density with increasing CWD age points to a long total residence time at both study sites. More data of logs from before 1950 would make it possible to estimate total residence time of Sessile oak. The variation in C density at similar age emphasizes that CWD decay of a specific tree species is a heterogeneous process, controlled by some factors. Decay rates can greatly vary depending on the decomposition conditions and the contact of CWD to soil fungi (Holeska et al. 2008). Further, large branches or even parts of the stem of oak trees can die and decay while other parts of the trees are still alive for many decades, resulting in a nonuniform year of death for different parts of these trees (Ranius et al. 2009). In such a tree, some parts would already decay and lose C, while new tree rings could still be formed in others. Other possible explanations for varying decay rates of CWD within a single log are differences in wood density, diameter, chemical composition and anatomy. However, we found no relationship between decay rates or carbon density and the length or diameter of the sampled logs. Despite differences of up to 5 years between radiocarbon analysis and dendrochronological cross-dating, both methods yield similar decay functions and total residence times for beech and spruce. Overall, the variations in CWD characteristics cause a greater uncertainty for the calculation of decay rates than the both studied methods of age determination.

Conclusions

Radiocarbon analysis and dendrochronological cross-dating revealed similar year of tree death and are in most cases suitable for age determination of CWD logs. Both methods are constrained by strong decay of CWD within and among logs, though we found these not to affect the quality of the dating procedure. Radiocarbon analyses are less destructive and only require small samples. On the other hand, radiocarbon dating of outer year rings from periods before the 1950s is much less accurate because of small changes in the radiocarbon signature by radioactive decay. In both cases, for periods before and after the 1950s, radiocarbon dating of consecutive year rings could improve the age determination of CWD. High variability in CWD decay as for oak logs excludes the estimate of total residence times by regression analysis of C density and year of tree death.

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