Deng *et al. Annals of Forest Science* (2023) 80:30
https://doi.org/10.1186/s13595-023-01201-y

Annals of Forest Science

RESEARCH PAPER

Open Access

Decomposition and nutrient dynamics of stumps and coarse roots of *Eucalyptus* plantations in southern China

Xiangsheng Deng[1], Xiang Liang[1,2], Lu Shen[1], Haiyu Liu[1], Mei Yang[1], Min Zeng[2], Mengqiang Liang[2] and Fei Cheng[1*]

Abstract

Key message Primary remains of *Eucalyptus* (*E. urophylla* × *E. grandis*) plantations following clear-cutting are the stumps and coarse roots. A chrono-sequence approach revealed that the biomass of coarse roots is higher than that of stumps, while they have a smaller rate of biomass loss than stumps. This implies that coarse roots serve as long-term stock for nutrients (carbon, nitrogen, and phosphorus).

Context A significant quantity of stumps and coarse roots persist in the forest floor following the clear-cutting of *Eucalyptus* plantations in China. The decomposition of these stumps and coarse roots is a crucial aspect of the nutrient stocks in plantation ecosystems.

Aims We described the stock and decomposition dynamics of stumps and coarse roots on *Eucalyptus* plantations, as well as the nutrient loss rate associated with them.

Methods We used a chrono-sequence of 0–6-year-old clear-cutting stands of *Eucalyptus* plantations in southern China. The biomass and nutrient stocks of these samples were assessed at different times of decomposition.

Results The highest biomass of stump-root system was 33.8 Mg·ha^{-1}, with nutrient stocks were 16.3 Mg·ha^{-1}, and 63.0 kg·ha^{-1}, and 6710.9 g·ha^{-1}, for C, N, and P. The coarse roots accounted for 81–96% of the biomass of the stump-root system. The loss rate of biomass and nutrients from stumps was higher than that of coarse roots. This suggests that the decomposition of coarse roots could serve as a long-term source of nutrients, thereby improving the nutrient status of the plantations.

Conclusion Stumps and coarse roots serve as significant nutrient stocks that decay at varying rates. The loss of nutrients must be considered while analyzing the decomposition dynamics following clear-cutting in *Eucalyptus* plantations.

Keywords Stumps, Coarse roots, Decomposition, Biomass, Nutrient, Stocks

Handling editor: Erwin Dreyer

*Correspondence:
Fei Cheng
feicheng@gxu.edu.cn
[1] Guangxi Key Laboratory of Forest Ecology and Conservation, College of Forestry, Guangxi University, Nanning 530004, China
[2] Guangxi State-Owned GuangMing Mountain Forestry Farm, 530600 Mashan, China

1 Introduction

Coarse woody debris (CWD), comprising logs, branches, stumps, and coarse roots, is a long-term nutrient pool that serves as a vital structural and functional component of forest ecosystems (Harmon et al. 1986; Olajuyigbe et al. 2011). In forests managed for timber production, stumps and coarse roots are produced through clear-cutting or thinning (Rabinowitsch-Jokinen and Vanha-Majamaa

2010; Hautala et al. 2011) and are the primary harvesting residues (Eufrade et al. 2020). However, their decomposition has only been discussed by a few researchers (Didion and Abegg 2022); Palviainen and Finér (2015) found that stumps decompose faster than coarse roots; and Deng et al. (2022) studied the effect of stumps substrates on microbial activity. Furthermore, the measurement of coarse roots is often overlooked owing to the considerable effort required (Palviainen and Finér 2015).

In general, the decomposition of CWD is primarily influenced by the physicochemical properties of the substrate, climatic conditions, and soil biological activity (van Geffen et al. 2010; Bradford et al. 2014; Zhu et al. 2017). The decomposition rate constant of CWD is typically expressed as k, which describes the exponential biomass losses caused by leaching, respiration, and mineralization (Olajuyigbe et al. 2014). CWD is a crucial long-term nutrient stocks due to its slow decomposition rate (Laiho and Prescott 2004). Many studies have reported an increase in the available amounts of N and P during CWD decomposition (Garrett et al. 2012). Therefore, the decomposition of stumps and coarse roots, which are crucial components of the ecosystem in clear-cutting forests, are expected to improve the nutrient status of forest soils (Shorohova et al. 2008; Melin et al. 2009) and provide nutrients for tree growth in the next rotation.

Eucalyptus exhibits a fast growth rate and is highly adaptable to environmental conditions. As a result, China planted over 5.4 million hectares of industrial *Eucalyptus*, accounting for 7% of the total planted area (National Forestry and Grassland Administration 2019; Wang et al. 2022), making it one of the most abundant tree species in China. *Eucalyptus* is often planted in areas with poor soil, has a short growth cycle, usually 5 to 7years. Two or three rotations of management are generally performed before clear cutting and replanting. In mature stands of *Eucalyptus*, stumps and root systems account for 17–38% of tree biomass (Eufrade et al. 2020). In China, the traditional plantation management model retains these stumps and coarse roots. Given the scale of *Eucalyptus* plantations, it is important to clearly understand the decomposition dynamics of nutrients in stumps and coarse roots to be able to predict nutrient cycling in plantations.

This study aimed to (1) quantify the stocks of biomass and nutrients from *Eucalyptus* stumps and coarse roots along a chrono-sequence of 0–6-year-old clear-cutting stands and (2) estimate the loss rate of biomass and nutrients, as well as the nutrient dynamics of stumps and coarse roots, to elucidate (1) if the biomass of coarse roots is higher than that of stumps and (2) if there is faster decomposition and nutrient loss rate from stumps from than coarse roots.

2 Materials and methods

2.1 Site characterization

The experiment was conducted in commercially managed *Eucalyptus* plantations located in the GuangMing mountain forest farm (23°33′ N, 108°13′ E) in southern China, using a chrono-sequence of seven second rotation stands. The area has a southern subtropical monsoon climate with a mean annual temperature of 21.8 °C, a mean precipitation of 1720 mm, and a mean altitude of 400 m. Appendix Table 4 shows the characteristics of each site immediately after clear-cutting. In general, tree characteristics, such as height, diameter at breast height, and crown size, do not differ significantly across all sites before clear-cutting. To prevent competition for nutrients within the stand due to regrowth, the stumps were treated with glyphosate to ensure their death. The same management practices were applied in all replanted stands, and the same *Eucalyptus* seedlings were planted after clear-cutting. The soil type of all stands were mainly sandy loam, originating from sandstone.

2.2 Field surveys and sampling

We utilized a chronosequence approach to evaluate the decomposition dynamics of stumps and coarse roots. The stands in these seven sites varied in age (with newly planted stands ranging from 0 to 6 years), vegetation cover, and canopy density. In November 2021, four plots (20 m × 30 m) were randomly established at each site, apart by at least 50 m (28 plots in total). Within each plot, all stumps were classified into five decay classes based on the criteria outlined in Appendix Table 5 (Hunter and Schmiegelow 1990; Naesset 1999; Paletto and Tosi 2010). Due to the difficulty in assessing decomposition in deeply buried coarse roots, we assumed that all coarse roots attached to the stumps were at the same stage of decomposition as the stumps. The distribution of stump decay classes at each site is shown in Table 1. Samples were randomly sampled in each plot and the decay class of the samples was determined. All of the coarse roots attached to the stumps as well as the lateral roots were excavated using hand tools. The fresh weights of the stump-root system were measured with a 200-kg maximum load capacity portable dynamometer (Fig. 1). In particular, soil adhering to the root samples may lead to an overestimate of root biomass. Representative stumps and coarse roots were sampled using a hand saw or knife for subsequent indoor physicochemical analyses. These samples for indoor analyses were weighed in the field using an electronic balance (USA.HZ, PTX-FA210S, accuracy ± 0.01 g). For material directly attached to the stumps, 5 to 8 cm discs were cut from the stumps using a chainsaw, and their 30 cm of vertical coarse roots with a diameter of 5 cm at the small end were collected. For

Table 1 Characteristics of the experimental sites

Decomposition time (year)	0	1	2	3	4	5	6
Year of replanting	–	2020	2019	2018	2017	2016	2015
DBH (cm)	–	4.5	8.0	13.2	13.6	15.3	16.7
TH (m)	–	4.7	10.5	13.5	17.5	18.5	20.5
Density of plantation (tree·ha^{-1})	–	1667	1667	1667	1667	1667	1667
NSH	1506	1637	1350	1343	1037	1081	1332
Distribution by decay classes of stumps	I	II	III, IV	III, IV	IV, V	IV, V	V

DBH is diameter at breast height, *TH* is tree height, *NSH* is number of stumps per hectare. – indicates that there is no data at this location. All sites had a sandy loam soil texture, were well drained, and were replanted with the same tree species

Fig. 1 Excavation and weighing of *Eucalyptus* stumps and coarse roots in harvested sites

decay classes IV and V, a sterilized vinyl bag was used to collect samples. Overall, a total of 256 samples of stumps and coarse roots were transferred to the laboratory for further analysis.

2.3 Stumps and coarse roots biomass calculation

In the laboratory, stumps and coarse roots samples were dried at 85 °C for 2 to 4 days. The volume of each sample was determined by the water displacement method. The density was calculated by dividing the dry mass by the volume of the sample.

The dry weights were calculated based on the moisture content. To obtain the stumps and coarse roots biomass yield (per hectare), the arithmetic mean of the weighted stumps and coarse roots biomass (dry matter) was multiplied by the number of stumps per hectare (Table 1).

2.4 Chemical analysis of samples

Six stumps and coarse roots samples from each decay class were used to determine the chemical composition of wood samples. For each decay class the measured sample is a mixture of at least three subsamples. The moss and soil particles were removed using a brush before grinding the samples. Residual soil dust on the surface of the samples was cleaned using deionized water before measuring the sample volume as described above to avoid contamination from the soil. The dried samples were ground to a powder using a ball mill and filtered through a 1 mm sieve. The samples were then stored in sealed polycarbonate plastic vials until analysis.

The N content using the Kjeldahl method (Uselman et al. 2012). The C and P content were determined using the dichromate oxide ferrous sulfate titration method and the Mo-Sb colorimetric method (Ashagrie et al. 2005), respectively. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) content were determined using an ANKOM A2000i automated fiber analyzer (ANKOM Technology, Macedon, NY, USA). The acid-washed lignin (ADL) content was determined according to the method described by Trofymow et al. (2002). Finally, the cellulose, hemicellulose, and lignin content of the samples was calculated using the following equations:

$$\text{Hemicellulose} = \text{NDF} - \text{ADF}$$

$$\text{Cellulose} = \text{ADF} - \text{ADL}$$

$$\text{Lignin} = \text{ADL} - \text{ash content}$$

2.5 The nutrient stocks estimation using the indirect method

The nutrient stocks of stumps and coarse roots during the decay period of 0 to 6 years was obtained by the calculation formula, as follows:

$$\text{Nutrient stocks} = \text{N}_\text{t} \times \text{B}_\text{t}$$

where B_t (Mg·ha^{-1}) is the biomass in year t; N_t (g·kg^{-1}) is the nutrient content in year t.

2.6 Decay rates of biomass and nutrients

To determine the biomass and nutrient loss rate of stumps and coarse roots, we calculated *k* values using a single negative exponential decay function (Olson 1963), as follows:

$$\frac{\text{DW}_\text{t}}{\text{DW}_0} = e^{-kt}$$

where t represents the decomposition time, DW_0 and DW_t represent the biomass or nutrient of stumps and coarse roots per year at the initial (0) and final (t) decomposition times, respectively, and k is the annual biomass or nutrient loss rate constant (year^{-1}).

Based on k values, the time required for the loss of 50% ($t_{0.5}$) and 95% ($t_{0.95}$) of the stumps and coarse roots was calculated as follows:

$$t_{0.5} = \frac{-\ln(0.5)}{k} = \frac{0.693}{k}$$

$$t_{0.95} = \frac{-\ln(0.05)}{k} = \frac{2.996}{k}$$

2.7 Statistical methods

All statistical tests were conducted with a significance level of 0.05 using the Statistical Program for the Social Sciences (SPSS Inc., Chicago, IL, USA). All results were reported as the mean ± standard error of four or six replicates. All data analyzed were normally distributed. The mean comparisons were conducted using Student's *t* tests or analysis of variance (ANOVA). Statistically significant differences among different decay classes were analyzed using one-way ANOVA, followed by Duncan's multiple range test. Differences in all variables between the coarse roots of the stumps were determined by Student's *t* test. All figures were plotted using Origin 2021 (Origin Lab Corporation Northampton, MA, USA). The data of Tables 2, 3 and Figs. 2, 3 can be referred to Deng et al. (2023).

3 Results

3.1 Changes in biomass stocks

The biomass of both stumps and coarse roots decreased with increasing decomposition time. The coarse root biomass ranged from 9.3 to 30.7·Mg ha^{-1} (Table 2), with the highest value observed after 1 year of clear-cutting, while the stump biomass decreased from 6.1 to 0.5 Mg·ha^{-1}. Similar, the stump-root system biomass ranged from 10.2 to 33.8 Mg·ha^{-1}. Across all sites, coarse root biomass accounted for 81–96% of stump-root system biomass.

3.2 Nutrient dynamics

C content of both stumps and coarse roots increased with decay class and then decreased (Fig. 2). The stump C content of decay class I was significantly higher than that of coarse roots ($P < 0.05$).

N content of stumps in decay class II was significantly higher than the other decay classes. In contrast, the N content of the coarse roots decreased with increasing decay class and reached a minimum in decay class III. Meanwhile, the N content of decay class I and II of coarse roots were significantly higher than those of stumps, while decay class III of coarse roots had a significantly lower N content than that of stumps.

P content of both stumps and coarse roots in decay class I were significantly higher than the other decay classes (Fig. 2). In addition, the P content of stumps of decay class I was significantly lower than that of coarse roots.

3.3 Changes in nutrient stocks

The highest total C, N, and P stocks were found in the stumps at the year of the clear-cutting and then declined to 0.2 Mg·ha^{-1}, 0.7 kg·ha^{-1}, and 36.0 g·ha^{-1}, respectively, as decomposition time increased (Table 2). Coarse roots reached the maximum total C, N, and P stocks at the 1 year after clear-cutting, while they reached a minimum after the 5th year of decomposition. The biomass and nutrient stocks of the coarse roots were significantly higher than that of the stumps in all years investigated.

3.4 Biomass and nutrient loss rate

The single exponential decay model was used to explain the rate of biomass and nutrient loss rate for each of the stumps and coarse roots. The biomass loss rate for stumps and coarse roots were 0.36 and 0.19 year^{-1}, the R^2 of the exponential model were 0.44 and 0.62, respectively, and the turnover time was 8 and 16 years, respectively (Appendix Table 6, Fig. 3). Among all nutrient element fitting models, the coarse roots were better

Table 2 Changes in biomass and nutrient stocks of *Eucalyptus* stumps and coarse roots during 0–6 years of decomposition time

Component	Decay time (year)	Biomass (Mg·ha^{-1})	Residual biomass (%)	C (Mg·ha^{-1})	Residual C (%)	N (kg·ha^{-1})	Residual N (%)	P (g·ha^{-1})	Residual P (%)
Stumps	0	6.1 ± 2.8Aa (19)	100	2.8 ± 1.2Aa	100	7.4 ± 3.3Aa	100	975.8 ± 438.2Aa	100
	1	3.1 ± 0.2Aab (9)	50	1.5 ± 0.1Aab	54	4.9 ± 0.3Aab	66	333.4 ± 18.0Ab	34
	2	2.2 ± 0.2Ab (10)	36	1.1 ± 0.1Ab	39	3.1 ± 0.3Ab	43	185.4 ± 19.5Ab	19
	3	1.4 ± 0.1Ab (8)	24	0.7 ± 0.1Ab	26	1.2 ± 0.1Ab	17	79.3 ± 6.0Ab	8
	4	1.3 ± 0.7Ab (11)	22	0.6 ± 0.3Ab	23	1.3 ± 0.7Ab	18	97.7 ± 49.9Ab	10
	5	0.8 ± 0.2Ab (8)	14	0.4 ± 0.1Ab	14	0.7 ± 0.1Ab	9	36.0 ± 7.4Ab	4
	6	0.5 ± 0.0Ab (4)	9	0.2 ± 0.0Ab	9	0.8 ± 0.0Ab	11	73.4 ± 4.2Ab	8
Coarse roots	0	26.3 ± 4.9Bab (81)	100	11.5 ± 2.2Bb	100	55.2 ± 10.3Ba	100	5735.1 ± 1070.7Ba	100
	1	30.7 ± 2.7Ba (91)	116	14.8 ± 1.3Ba	129	58.1 ± 5.2Ba	105	3384.7 ± 300.8Bb	59
	2	20.9 ± 1.4Bbc (90)	79	9.0 ± 0.7Bbc	78	23.5 ± 1.6Bb	43	1585.8 ± 104.9Bc	28
	3	15.6 ± 1.1Bcd (92)	59	7.6 ± 0.6Bcd	66	13.0 ± 1.0Bbc	24	1079.6 ± 78.7Bc	19
	4	10.5 ± 1.4Bd (89)	40	5.0 ± 0.7Bd	43	11.9 ± 1.6Bbc	22	962.6 ± 128.8Bc	17
	5	9.3 ± 1.6Bd (92)	35	4.4 ± 0.8Bd	38	7.7 ± 1.4Bc	14	439.1 ± 77.5Bc	8
	6	11.8 ± 1.7Bd (96)	45	5.1 ± 0.7Bd	44	13.5 ± 1.9Bbc	25	1763.4 ± 250.4Bc	31
Stump-root system	0	32.5	100	14.3	100	62.6	100	6710.9	100
	1	33.8	104	16.3	114	63.0	101	3718.0	55
	2	23.1	71	10.1	71	26.7	43	1771.2	26
	3	17.1	53	8.3	58	14.3	23	1158.8	17
	4	11.8	36	5.6	39	13.2	21	1060.3	16
	5	10.2	31	4.8	34	8.4	13	475.1	7
	6	12.3	38	5.3	37	14.3	23	1836.8	27

Lower case letters represent differences between stumps and coarse roots at different times of decomposition ($P < 0.05$), while capital letters represent differences between stumps and coarse roots during the same years ($P < 0.05$). Data are presented as means ± S.E., n = 4. Values in parentheses indicate the percentage of stumps and coarse roots biomass in the same years. Residual percentages (%) for biomass, C, N, and P indicate the ratio of decomposition time relative to 0 year

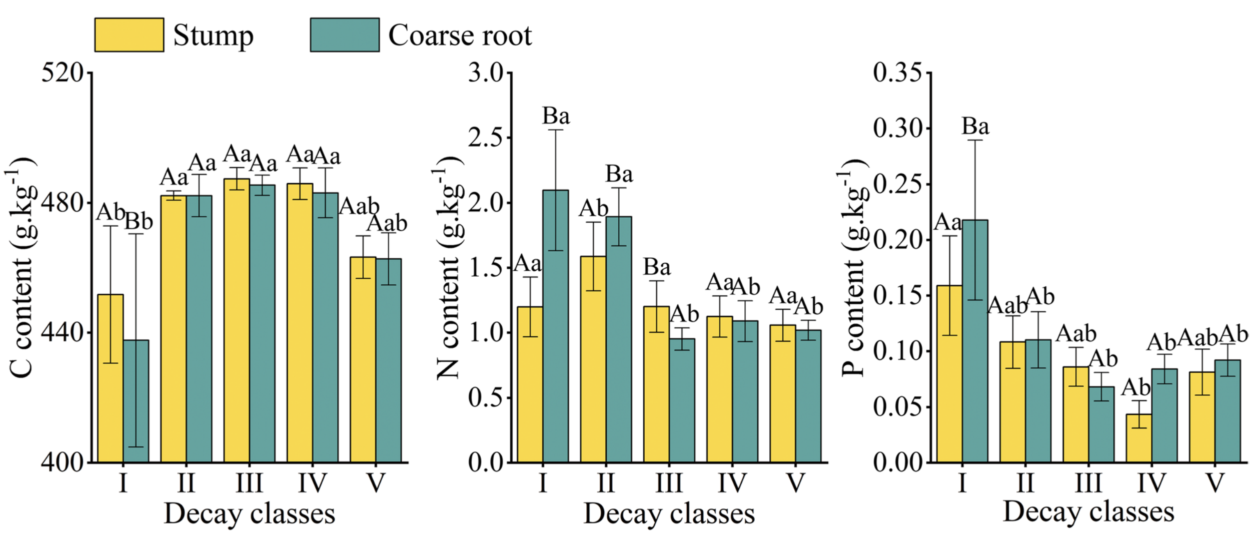

Fig. 2 Contents of C, N, and P of stumps and coarse roots in different decay classes (mean ± S.E., $n = 6$). Different lowercase letters indicate that means are significantly different ($P < 0.05$) among different decay classes within stumps or coarse roots, whereas different uppercase letters indicate that means are significantly different ($P < 0.05$) between stumps and coarse roots

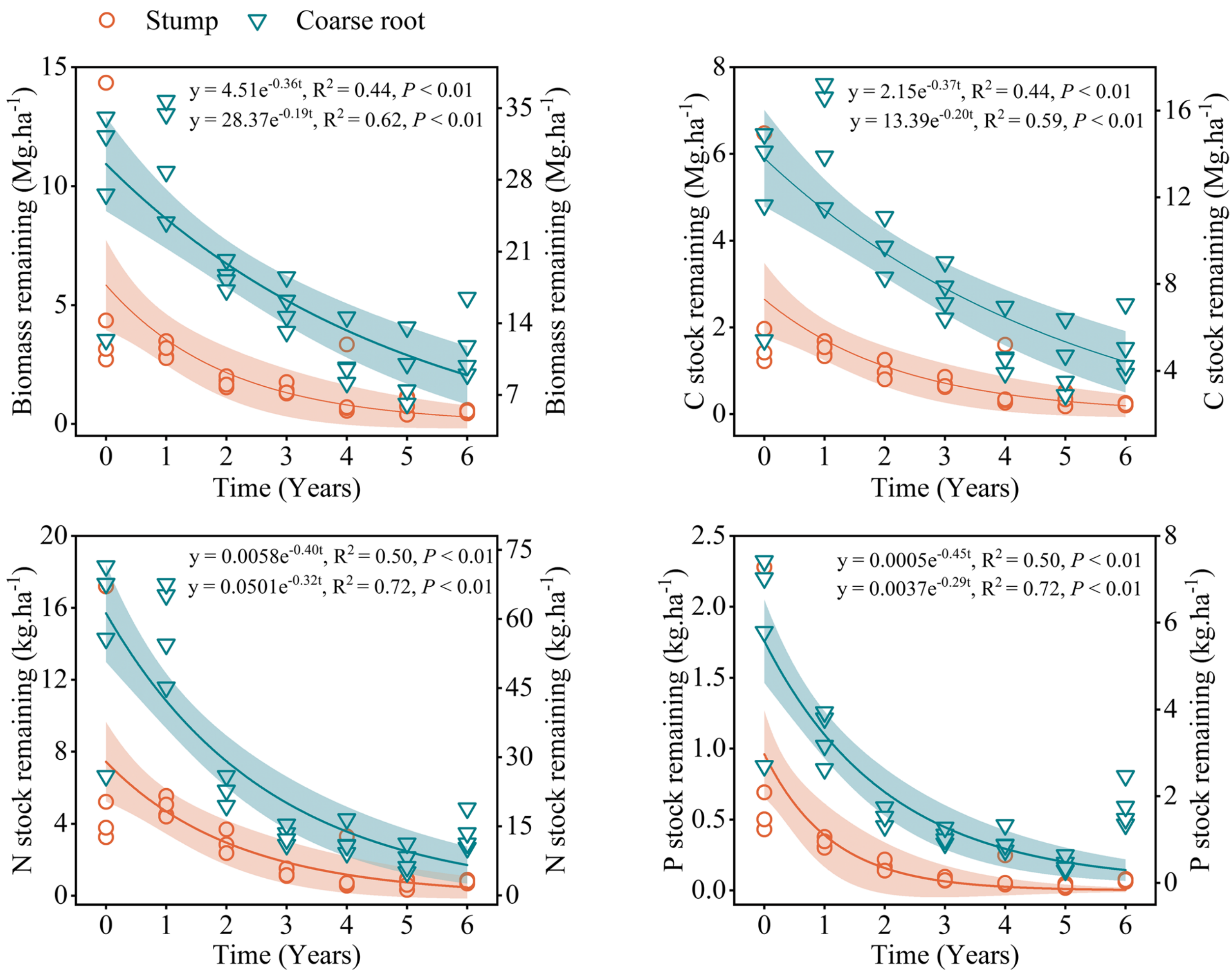

Fig. 3 A single exponential decay model fit for biomass and nutrient stocks ($n = 28$). The colored areas are the 95% confidence intervals of the model. Triangles indicate coarse roots, and circles indicate stumps. For a given year, different numbers of points indicate the remaining biomass or nutrient stocks in the survey sample plots

fitted than the stumps; however, the stumps nutrient loss rate more rapidly (Fig. 3).

3.5 Decomposition processes of stumps and coarse roots

Stump density decreased and moisture content increased with increasing decay class, while coarse root density increased and moisture content decreased with increasing decay class (Table 3). The cellulose content of the stumps decreased from 49.79 to 37.45%, and the hemicellulose content decreased from 17.30 to 12.74%, while lignin increased from 19.54 to 29.80%. Cellulose was significantly higher in the stumps than that in coarse roots in decay class I, whereas it was significantly lower than that in coarse roots in decay classes IV and V. Stump hemicellulose was significantly higher than coarse roots in decay classes I and II. However, there were no significant differences in the cellulose and hemicellulose contents of coarse roots of different decay classes. The lignin content in the coarse roots remained relatively consistent, with only decay class IV was significantly lower than decay class III. In addition, lignin was significantly higher in the stumps of decay classes IV and V than that in coarse roots.

4 Discussion

4.1 Biomass stocks

The biomass of stumps and coarse roots in our study was significantly reduced over the 6-year decomposition period (Table 2), which was similar to the studies conducted by Palviainen and Finér (2015) and Grelle et al. (2012). In addition, the coarse roots accounted for 81–96% of the stump-root system stocks in all the surveyed stands and were the largest stock component of the stump-root system. Our findings regarding coarse root stocks are consistent with studies from other regions. For instance, Merila et al. (2014) estimated that coarse roots accounted for 83% of the stump-root system, with stumps accounting

Table 3 Variation characteristics of density, moisture, cellulose, lignin, and hemicellulose of the stumps and coarse roots of *Eucalyptus* from the different decay classes (mean ± S.E., $n = 6$)

Component	Decay classes	Density ($g \cdot cm^{-3}$)	Moisture (%)	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Stumps	I	0.40 ± 0.01Aa	33.98 ± 0.98Ac	49.79 ± 1.02Aa	17.30 ± 0.33Aa	19.54 ± 0.85Ab
	II	0.39 ± 0.01Aa	33.37 ± 0.91Ac	45.83 ± 1.57Ab	17.27 ± 0.72Aa	21.02 ± 0.78Ab
	III	0.34 ± 0.01Ab	37.03 ± 1.48Ac	46.66 ± 0.69Ab	13.12 ± 0.50Ab	21.12 ± 1.17Ab
	IV	0.31 ± 0.01Ac	41.36 ± 1.18Ab	40.50 ± 0.40Ac	13.42 ± 0.52Ab	22.68 ± 1.06Ab
	V	0.28 ± 0.01Ad	54.80 ± 1.61Aa	37.45 ± 0.54Ad	12.74 ± 0.34Ab	29.80 ± 2.78Aa
Coarse roots	I	0.35 ± 0.01Bc	59.59 ± 1.01Ba	44.09 ± 1.02Ba	14.43 ± 0.78Ba	22.26 ± 1.82Aab
	II	0.47 ± 0.03Bc	46.68 ± 1.40Bb	42.78 ± 1.11Aa	13.85 ± 1.52Ba	23.21 ± 1.17Aab
	III	0.48 ± 0.04Bb	33.36 ± 1.48Bcd	45.58 ± 1.53Aa	12.00 ± 0.47Aa	25.38 ± 2.16Aa
	IV	0.50 ± 0.03Bb	30.54 ± 0.86Bd	45.48 ± 0.86Ba	11.68 ± 1.10Aa	19.92 ± 0.45Bb
	V	0.62 ± 0.04Ba	37.42 ± 1.70Bc	42.37 ± 1.94Ba	12.61 ± 1.00Aa	21.43 ± 1.72Bab

Lowercase letters represent differences between stumps and coarse roots at different decay classes ($P < 0.05$), while capital letters represent differences between stumps and coarse roots during the same decay classes ($P < 0.05$)

for the remaining 17%. In particular, this study found that coarse root stocks was higher after 1 year of decomposition than the year of clear-cutting. This may be due to the fact that the root system remained alive after cutting, as similarly reported by Garrett et al. (2008) in *Pinus radiata* roots. However, the stocks of coarse roots after 6 years of decomposition in this study was higher than that at 5 years of decomposition, which may be due to more stumps in the decomposed 6-year-old stand (Table 1). This difference in the number of stumps formed may be due to the natural death of the trees, the differences in the number of branch sprouting in the second-generation budding stands, or the uncertainty of the chrono-sequence approach.

After 6 years of decomposition, the percentage of stump stocks decreased from 19 to 4%, and these results are lower than those reported by Varik et al. (2013), but similar to those observed by Kaarakka et al. (2018) in managed *Picea abies* forests. Moreover, the stump stocks were higher than those found in commercially managed *Sitka spruce* forests in northeastern Wicklow Ireland (Kaarakka et al. 2018). Overall, our results highlight the importance of stumps and coarse roots as nutrient reserves in Chinese *Eucalyptus* plantations.

4.2 Nutrient stocks

Stumps and coarse roots, being the main harvesting residues of plantation forests, are also the main source of nutrients in the forest soil (Hautala et al. 2011). In our study, the stump C stocks are similar to those of Nanjenshan Reserve (3.3 to 4.7 $Mg \cdot ha^{-1}$) in the tropics (Chao et al. 2017) and lower than commercial *Sitka spruce* stands (8.0 to 25.0 $Mg \cdot ha^{-1}$) in Ireland (Tobin et al. 2021). The regional climate and forest type differences between studies may account for the differences observed in C stocks. In addition, Paletto et al. (2014) emphasized that the stocks of C in dead wood were strongly influenced by forest management. At the same time, the C stocks of the coarse roots was higher than that of the stumps. This was expected because coarse roots generally have a higher biomass than stumps (Palviainen and Finér 2015). Nutrient stocks in *Eucalyptus* differed across structures (Shammas et al. 2003). Our results showed that the coarse roots contained more N and P compared to the stumps (Fig. 2). At the beginning of tree growth, nutrient storage in leaves and branches is higher (Rocha et al. 2019), while the coarse root portion of *Eucalyptus* provides higher biomass and nutrient storage as the tree grows (Guimaraes et al. 2015).

4.3 Biomass and nutrient loss rate

The decomposition of wood in forest ecosystems is influenced by various factors, including temperature, moisture content of the wood, physicochemical properties of the substrate, and the abundance of decomposing fungi and animals (Beets et al. 2008). The rate of biomass loss from stumps observed in this study was higher than the k value (0.25 $year^{-1}$) reported by Shammas et al. (2003) for the rapid phase of decomposition of *Eucalyptus globulus* branches. The rate of biomass loss of coarse roots observed in our study is comparable to those reported by Garrett et al. (2012) for decomposing roots of *Pinus radiata* in golden down soil types in New Zealand (0.174 $year^{-1}$). The observed differences in the k values for stumps and coarse roots support the hypothesis that stumps tend to decompose more rapidly compared to coarse roots (Appendix Table 6). However, previous studies comparing the decay rates of stems and roots of the same tree species showed that the decay rate of dead roots was similar to or faster than that of stems (Garrett et al. 2008, 2019). This could be explained by temperature differences as indicated by previous studies claiming that mean annual temperature is the main driver of decomposition (Shorohova et al. 2012). The higher water content of stumps may also contribute to their faster decomposition (Table 3). Some studies have shown that the water content favors the decomposition of microbial activity and accelerates decomposition processes (Jomura et al. 2015). The coarse root stocks increased after 1 year of clear-cutting, while the stump stocks decreased by 50% (Table 2). This indicates that the coarse roots remained alive after cutting and were not immediately decomposed, which also resulted in a higher water content of the coarse roots in decay classes I and II. In addition, due to the fact that we are using a chrono-sequence approach, it may introduce uncertainty in the estimation of k values.

Nutrient loss rate from stumps and coarse roots are often overlooked, although they are probably the most important CWD in managed forests (Harmon et al. 2011). Our findings are consistent with Martinez-Garcia et al. (2015), which reported an annual C loss that ranged from 0.1 to 1.3 Mg·ha^{-1} year^{-1}, but was less than that reported by Palviainen et al. (2004). Meanwhile, the loss of C from stumps and coarse roots decreased with increasing decomposition times (Table 2). Those are consistent with the findings of Tobin et al. (2021), who found higher C losses in the youngest site plots (4 years of decomposition) than in the oldest site (16 years of decomposition). The N loss from the stumps in this study was similar to the results of Palviainen and Finer (2015) on *Norway spruce* coarse roots and stumps (0.9 to 1.3 kg·ha^{-1}). However, the loss of N from stumps and coarse roots in our study were faster than that in the study by Palviainen et al. (2010) on *Scots pine* stumps in Norway. This difference in nutrient dynamics may be attributed to differences in substrate chemistry, decomposition biology, and microenvironmental conditions.

4.4 Decomposition dynamics

The C content may increase slightly (Preston et al. 2012; Lombardi et al. 2013; Romashkin et al. 2018), decrease (Wu et al. 2005; Palviainen and Finér 2015), or even remain constant (Palviainen et al. 2010) during CWD decomposition. Our results are consistent with Garrett et al. (2008), who found that the C concentration in stumps increased during decomposition. Similar, our results are consistent with those of Palviainen et al. (2010), who found that the N content during *Scots pine* stump decomposition first increased and then decreased. Previous studies have suggested that increased N during CWD decomposition may be due to atmospheric N deposition and other organisms associated with CWD, particularly epiphytes and nitrogen-fixing bacteria (Shorohova et al. 2016; Hu et al. 2018). In this study, the N content of stumps was significantly lower than that of coarse roots during the early stages of decomposition (Fig. 2). And the higher N content also indicated that the coarse roots had more viable cells than the stumps (Apostolov 2006).

5 Conclusions

This study represents the first attempt to quantify the loss rate of biomass and nutrients from stumps and coarse roots in Chinese *Eucalyptus* plantations during the same decomposition periods. Single exponential decay model confirmed the hypothesis that stumps have a faster loss rate of biomass and nutrient loss rate compared to coarse roots. Additionally, the biomass of coarse roots was significantly higher than that of stumps. Based on the nutrient loss rate estimated by the single exponential decay model, the decomposition of the stumps and coarse roots may meet some of the nutrient requirements in the subsequent rotations. Our results suggest that when conducting studies on the stump-root system of *Eucalyptus* related to decomposition dynamics, it is necessary to separate the stumps from the coarse roots.

Appendix

Table 4 Description of each *Eucalyptus* sites before clear-cutting

Year of tree clear-cutting	2021	2020	2019	2018	2017	2016	2015
Species	*E. uro × E. gran*	*E. uro × E. gran*	*E. uro × E. gran*	*E. uro × E. gran*	*E. uro × E. gran*	*E. uro × E. gran*	*E. uro × E. gran*
DBH (cm)	17.5	17.8	16.7	17.7	17.0	16.3	16.2
TH (m)	21.5	20.0	18.5	19.5	20.0	17.5	17.5
Rotation	2th	2th	2th	2th	2th	2th	2th
Year of last coppice harvest	2014	2013	2012	2011	2010	2009	2008
Tree age at clear-cutting (year)	7	7	7	7	7	7	7
Year of stump harvesting	2021	2021	2021	2021	2021	2021	2021

E.uro × E. gran is E. urophylla × E. grandis, *DBH* is diameter at breast height, *TH* is tree height

Table 5 Description of stumps decay classes

Decay class	Description	Characteristics
I	Intact	Stumps intact and hard with intact bark
II	Slightly decayed	Stumps still intact and hard and with some signs of decay
III	Intermediate	Most bark missing in places and fragmentation is evident; hardness intermediate
IV	Slightly rotten	Decay at advanced stage, stumps is soft overall and become fragments when pressed hard
V	Rotten	Stumps becomes fragments with little force

The coarse roots attached to the stumps were assigned to the same decay class

Table 6 Single exponential decay model between remaining biomass or remaining nutrient and time for stumps and coarse roots of *Eucalyptus*

Component	Element	Regression equation	Loss rate, k (year^{-1})	R^2	P value	t_{50} (year)	t_{95} (year)
Stumps	Biomass	$y=4.51e^{-0.36t}$	0.36	0.44	< 0.01	2	8
	C	$y=2.15e^{-0.37t}$	0.37	0.44	< 0.01	2	8
	N	$y=0.0058e^{-0.39t}$	0.40	0.50	< 0.01	2	8
	P	$y=0.0005e^{-0.44t}$	0.45	0.50	< 0.01	2	7
Coarse roots	Biomass	$y=28.37e^{-0.19t}$	0.19	0.62	< 0.01	4	16
	C	$y=13.39e^{-0.20t}$	0.20	0.59	< 0.01	3	15
	N	$y=0.0501e^{-0.31t}$	0.32	0.72	< 0.01	2	10
	P	$y=0.0037e^{-0.29t}$	0.29	0.72	< 0.01	2	10

Acknowledgements
We are grateful to Miss Wang for the constructive comments, which helped improved the manuscript. Our deepest gratitude also goes to the editors and anonymous reviewers for their careful work and constructive suggestions that help improve this paper substantially.

Code availability
Not applicable.

Authors' contributions
XSD planned and conducted the study including field sampling and analysis and wrote the majority of the manuscript. FC conceived and guided the study and co-wrote the manuscript. Experimental assistance was provided by XL, LS, and HYL. MY for the constructive comments, which helped improved the manuscript. MZ and MQL provide site support. All authors read and approved the final manuscript.

Funding
This research was provided by the "Characteristics of microbial communities during decomposition of underground coarse roots of *Eucalyptus* stumps" (32160359) from the National Natural Science Foundation of China.

Availability of data and materials
The datasets generated and analyzed during the current study are available in the Zenodo repository (https://zenodo.org/record/7934507#.ZGDWgOxBzdo, https://doi.org/10.5281/zenodo.7934507).

Declarations

Ethics approval and consent to participate
The authors declare that the study was not conducted on endangered, vulnerable, or threatened species.
Not applicable.

Consent for publication
All authors gave their informed consent to this publication and its content.

Competing interests
The authors declare that they have no competing interests.

Received: 15 May 2023 Accepted: 14 July 2023
Published online: 31 July 2023

References
Apostolov SA (2006) New handbook of chemists and technologists (Novyi spravochnik khimika i tekhnologa) raw materials and products of the industry of organic and inorganic substances, vol. 2. Professional Publisher, Saint-Petersburg, p 1142 (**in Russian**)
Ashagrie Y, Zech W, Guggenberger G (2005) Transformation of a Podocarpus falcatus dominated natural forest into a monoculture Eucalyptus globulus plantation at Munesa, Ethiopia: soil organic C, N and S dynamics in primary particle and aggregate-size fractions. Agr Ecosyst Environ 106:89–98. https://doi.org/10.1016/j.agee.2004.07.015
Beets PN, Hood IA, Kimberley MO, Oliver GR, Pearce SH, Gardner JF (2008) Coarse woody debris decay rates for seven indigenous tree species in the central north island of new zealand. Forest Ecol Manag 256:548–557. https://doi.org/10.1016/j.foreco.2008.05.036
Bradford MA, Warren RJ, Baldrian P, Crowther TW, Maynard DS, Oldfield EE, Wieder WR, Wood SA, King JR (2014) Climate fails to predict wood decomposition at regional scales. Nat Clim Change 4:625–630. https://doi.org/10.1038/NCLIMATE2251
Chao K, Chen Y, Song G, Chang Y, Sheue C, Phillips OL, Hsieh CF (2017) Carbon concentration declines with decay class in tropical forest woody debris. Forest Ecol Manag 391:75–85. https://doi.org/10.1016/j.foreco.2017.01.020
Deng X, Cheng F, Li M, He P, Shen L, Liu H (2022) Effect of different decay classes of Eucalyptus stump substrates on microbial resource limitation and carbon-use efficiency. Plant Soil 478:651–669. https://doi.org/10.1007/s11104-022-05499-x
Deng X, Liang X, Shen L, Liu H, Zeng M, Liang M, Cheng F (2023) Decomposition and nutrient dynamics of stumps and coarse roots of Eucalyptus plantations in southern China. Zenodo. [Data set]. https://doi.org/10.5281/zenodo.7934507
Didion M, Abegg M (2022) Tree stumps - an important but undervalued dead wood pool. Ann Forest Sci 79:34. https://doi.org/10.1186/s13595-022-01155-7
Eufrade HD, Leonello EC, Spadim ER, Rodrigues SA, de Azevedo GB, Guerra SPS (2020) Stump and coarse root biomass from eucalypt forest plantations in a commercial-scale operation for bioenergy. Biomass and Bioenerg 142:105784. https://doi.org/10.1016/j.biombioe.2020.105784
Forestry N, Administration G (2019) China Forest Resources Report (2014–2018). China Forestry Publishing House, Beijing, pp 206–208
Garrett LG, Oliver GR, Pearce SH, Davis MR (2008) Decomposition of Pinus radiata coarse woody debris in New Zealand. Forest Ecol Manag 255:3839–3845. https://doi.org/10.1016/j.foreco.2008.03.031
Garrett LG, Kimberley MO, Oliver GR, Pearce SH, Beets PN (2012) Decomposition of coarse woody roots and branches in managed Pinus radiata plantations in New Zealand - A time series approach. Forest Ecol Manag 269:116–123. https://doi.org/10.1016/j.foreco.2011.12.030
Garrett LG, Kimberley MO, Oliver GR, Parks M, Pearce SH, Beets PN, Paul T (2019) Decay rates of above- and below-ground coarse woody debris of common tree species in New Zealand's natural forest. Forest Ecol Manag 438:96–102. https://doi.org/10.1016/j.foreco.2018.12.013

Grelle A, Stromgren M, Hyvonen R (2012) Carbon balance of a forest ecosystem after stump harvest. Scand J Forest Res 27:762–773. https://doi.org/10.1080/02827581.2012.726371

Guimaraes CC, Schumacher MV, Witshoreck R, Souza HP, Santo JC (2015) Biomass and nutrients of eucalyptus dunnii maiden stand in pampa gaucho. Rev Arvore 39:873–882. https://doi.org/10.1590/0100-67622015000500010

Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR, Lienkaemper GW, Cromack JK, Cummins KW (1986) Ecology of coarse woody debris in temperate ecosystems. Adv Ecol Res 15:133–302. https://doi.org/10.1016/S0065-2504(08)60121-X

Harmon ME, Bond-Lamberty B, Tang JW, Vargas R (2011) Heterotrophic respiration in disturbed forests: A review with examples from North America. J Geophys Res-Biogeo 116:G00504. https://doi.org/10.1029/2010JG001495

Hautala H, Laaka-Lindberg S, Vanha-Majamaa I (2011) Effects of Retention Felling on Epixylic Species in Boreal Spruce Forests in Southern Finland. Restor Ecol 19:418–429. https://doi.org/10.1111/j.1526-100X.2009.00545.x

Hu Z, Michaletz ST, Johnson DJ, Mcdowell NG, Huang Z, Zhou X, Xu C (2018) Traits drive global wood decomposition rates more than climate. Global Change Biol 24:5259–5269. https://doi.org/10.1111/gcb.14357

Hunter ML, Schmiegelow FK (1990) Wildlife, Forests and Forestry: Principles of Managing Forests for Biological Diversity 2(nd) edition. Forest Chron 87:570

Jomura M, Akashi Y, Itoh H, Yuki R, Sakai Y, Maruyama Y (2015) Biotic and abiotic factors controlling respiration rates of above- and belowground woody debris of Fagus crenata and Quercus crispula in Japan. Plos One 10:e0145113. https://doi.org/10.1371/journal.pone.0145113

Kaarakka L, Vaittinen J, Marjanen M, Hellsten S, Kukkola M, Saarsalmi A, Palviainen M, Helmisaari HS (2018) Stump harvesting in Picea abies stands: Soil surface disturbance and biomass distribution of the harvested stumps and roots. Forest Ecol Manag 425:27–34. https://doi.org/10.1016/j.foreco.2018.05.032

Laiho R, Prescott CE (2004) Decay and nutrient dynamics of coarse woody debris in northern coniferous forests: a synthesis. Can J Forest Res 34:763–777. https://doi.org/10.1139/X03-241

Lombardi F, Cherubini P, Tognetti R, Cocozza C, Lasserre B, Marchetti M (2013) Investigating biochemical processes to assess deadwood decay of beech and silver fir in Mediterranean mountain forests. Ann Forest Sci 70:101–111. https://doi.org/10.1007/s13595-012-0230-3

Martinez-Garcia E, Lopez-Serrano FR, Dadi T, Garcia-Morote FA, Andres-Abellan M, Rubio E (2015) Carbon loss during the early decomposition stages of tree stumps in a post-wildfire Spanish black pine forest. Forest Ecol Manag 358:321–334. https://doi.org/10.1016/j.foreco.2015.09.022

Melin Y, Petersson H, Nordfjell T (2009) Decomposition of stump and root systems of Norway spruce in Sweden-A modelling approach. Forest Ecol Manag 257:1445–1451. https://doi.org/10.1016/j.foreco.2008.12.020

Merila P, Mustajarvi K, Helmisaari HS, Hilli S, Lindroos AJ, Nieminen TM, Nojd P, Rautio P, Salemaa M, Ukonmaanaho L (2014) Above- and below-ground N stocks in coniferous boreal forests in Finland: Implications for sustainability of more intensive biomass utilization. Forest Ecol Manag 311:17–28. https://doi.org/10.1016/j.foreco.2013.06.029

Naesset E (1999) Relationship between relative wood density of Picea abies logs and simple classification systems of decayed coarse woody debris. Scand J Forest Res 14:454–461. https://doi.org/10.1080/02827589950154159

Olajuyigbe SO, Tobin B, Gardiner P, Nieuwenhuis M (2011) Stocks and decay dynamics of above- and belowground coarse woody debris in managed Sitka spruce forests in Ireland. Forest Ecol Manag 262:1109–1118. https://doi.org/10.1016/j.foreco.2011.06.010

Olajuyigbe SO, Tobin B, Nieuwenhuis M (2014) The role of brash in augmenting forest site carbon capital and maintaining site nutrition in a Sitka spruce forest in Ireland. Eur J Forest Res 133:563–572. https://doi.org/10.1007/s10342-014-0785-7

Olson JS (1963) Energy-storage and balance of producers and decomposers in ecological-systems. Ecology 44:322–331. https://doi.org/10.2307/1932179

Paletto A, Tosi V (2010) Deadwood density variation with decay class in seven tree species of the Italian Alps. Scand J Forest Res 25:164–173. https://doi.org/10.1080/02827581003730773

Paletto A, De Meo I, Cantiani P, Ferretti F (2014) Effects of forest management on the amount of deadwood in Mediterranean oak ecosystems. Ann Forest Sci 71:791–800. https://doi.org/10.1007/s13595-014-0377-1

Palviainen M, Finer L (2015) Decomposition and nutrient release from Norway spruce coarse roots and stumps - A 40-year chronosequence study. Forest Ecol Manag 358:1–11. https://doi.org/10.1016/j.foreco.2015.08.036

Palviainen M, Finer L, Kurka AM, Mannerkoski H, Piirainen S, Starr M (2004) Decomposition and nutrient release from logging residues after clear-cutting of mixed boreal forest. Plant Soil 263:53–67. https://doi.org/10.1023/B:PLSO.0000047718.34805.fb

Palviainen M, Finer L, Laiho R, Shorohova E, Kapitsa E, Vanha-Majamaa I (2010) Carbon and nitrogen release from decomposing Scots pine, Norway spruce and silver birch stumps. Forest Ecol Manag 259:390–398. https://doi.org/10.1016/j.foreco.2009.10.034

Preston CM, Trofymow JA, Nault JR (2012) Decomposition and change in N and organic composition of small-diameter Douglas-fir woody debris over 23 years. Can J Forest Res 42:1153–1167. https://doi.org/10.1016/j.catena.2019.03.025

Rabinowitsch-Jokinen R, Vanha-Majamaa I (2010) Immediate effects of logging, mounding and removal of logging residues and stumps on coarse woody debris in managed boreal norway spruce stands. Silva Fenn 44:51–62. https://doi.org/10.14214/sf.162

Rocha JH, Toit BT, Gonçalves JL (2019) Ca and Mg nutrition and its application in Eucalyptus and Pinus plantations. Forest Ecol Manag 442:63–78. https://doi.org/10.1016/j.foreco.2019.03.062

Romashkin I, Shorohova E, Kapitsa E, Galibina N, Nikerova K (2018) Carbon and nitrogen dynamics along the log bark decomposition continuum in a mesic old-growth boreal forest. Eur J Forest Res 137:643–657. https://doi.org/10.1007/s10342-018-1131-2

Shammas K, O'Connell AM, Grove TS, Mcmurtrie R, Damon P, Rance SJ (2003) Contribution of decomposing harvest residues to nutrient cycling in a second rotation Eucalyptus globulus plantation in south-western Australia. Biol Fert Soils 38:228–235. https://doi.org/10.1007/s00374-003-0654-x

Shorohova E, Kapitsa E, Vanha-Majamaa I (2008) Decomposition of stumps 10 years after partial and complete harvesting in a southern boreal forest in Finland. Can J Forest Res 38:2414–2421. https://doi.org/10.1139/X08-083

Shorohova E, Ignatyeva O, Kapitsa E, Kauhanen H, Kuznetsov A, Vanha-Majamaa I (2012) Stump decomposition rates after clear-felling with and without prescribed burning in southern and northern boreal forests in Finland. Forest Ecol Manag 263:74–84. https://doi.org/10.1016/j.foreco.2011.09.006

Shorohova E, Kapitsa E, Kazartsev I, Romashkin I, Polevoi A, Kushnevskaya H (2016) Tree species traits are the predominant control on the decomposition rate of tree log bark in a mesic old-growth boreal forest. Forest Ecol Manag 377:36–45. https://doi.org/10.1016/j.foreco.2016.06.036

State Forestry and Grassland Administration (2019) The Ninth Forest Resources Survey Report (2014–2018). China Forestry Press, Beijing, p 206–208.

Tobin B, Pastore G, Nieuwenhuis M (2021) Carbon Losses from Decomposing Windrowed Sitka Spruce Woody Debris Over a 16-Year Chronosequence. Forests 12:244. https://doi.org/10.3390/f12020244

Trofymow JA, Moore TR, Titus B, Prescott C, Morrison I, Siltanen M, Smith S, Fyles J, Wein R, Camirt C, Duschene L, Kozak L, Kranabetter M, Visser S (2002) Rates of litter decomposition over 6 years in Canadian forests: influence of litter quality and climate. Can J Forest Res 32:789–804. https://doi.org/10.1139/X01-117

Uselman SM, Qualls RG, Lilienfein J (2012) Quality of soluble organic C, N, and P produced by different types and species of litter: Root litter versus leaf litter. Soil Biol Biochem 54:57–67. https://doi.org/10.1016/j.soilbio.2012.03.021

van Geffen KG, Poorter L, Sass-Klaassen U, van Logtestijn R, Cornelissen J (2010) The trait contribution to wood decomposition rates of 15 Neotropical tree species. Ecology 91:3686–3697. https://doi.org/10.1890/09-2224.1

Varik M, Aosaar J, Ostonen I, Lohmus K, Uri V (2013) Carbon and nitrogen accumulation in belowground tree biomass in a chronosequence of silver birch stands. Forest Ecol Manag 302:62–70. https://doi.org/10.1016/j.foreco.2013.03.033

Wang J, Deng Y, Li D, Liu Z, Wen L, Huang Z, Jiang D, Lu Y (2022) Soil aggregate stability and its response to overland flow in successive Eucalyptus

plantations in subtropical China. Sci Total Environ 807:151000. https://doi.org/10.1016/j.scitotenv.2021.151000
Wu J, Guan D, Han S, Zhang M, Jin C (2005) Ecological functions of coarse woody debris in forest ecosystem. J Forestry Res 16:247–252 ((in chinese))
Zhu J, Hu H, Tao S, Chi X, Li P, Jiang L, Ji C, Zhu J, Tang Z, Pan Y, Birdsey RA, He X, Fang J (2017) Carbon stocks and changes of dead organic matter in China's forests. Nat Commun 8:151. https://doi.org/10.1038/s41467-017-00207-1

Publisher's Note