

**Decoupling of nitrogen and phosphorus release from fine and coarse roots during seven years of decomposition**

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### **Data accessibility statement**

Should the manuscript be accepted, the data supporting the results will be archived in an appropriate public repository (Dryad, Figshare or Hal) and the data DOI will be included at the end of the article.

### **Authors contributions**

XW designed the experiment, JP and XW collected data, JP, FL, and XW performed data analyses.

JP wrote the first draft of the manuscript, and all authors contributed substantially to revisions.

## 1 **Abstract**

2 Belowground litter decomposition represents an important source of the limiting nutrients nitrogen  
3 (N) and phosphorus (P) to forest soils. However, the rates and drivers of nutrient immobilization and  
4 release from root litter remain poorly understood. To address this gap, we conducted a seven-year  
5 field decomposition experiment using roots from three species, across five diameter classes (up to 20  
6 mm) in a temperate forest. All roots released P to the surrounding soil within the first year of  
7 decomposition but immobilized N for much longer, particularly coarse roots. Long-term N release  
8 was mainly related to initial nutrient stoichiometry of the substrate, whereas P release was better  
9 predicted by substrate carbon (C) quality and decomposition rate. Initial root nutrients well predicted  
10 the difference between long-term N versus P release. Our results highlight the fact that N and P  
11 dynamics should be considered separately when modeling nutrient release during root  
12 decomposition.

## 13 **KEYWORDS**

14 Root decomposition; Root diameter; Nutrient release; Nutrient immobilization; Initial root quality;  
15 Nitrogen; Phosphorus

## 16 **INTRODUCTION**

17 Root litter decomposition represents a critical entry point of carbon (C), nitrogen (N), and  
18 phosphorus (P) into soil systems (e.g., Li et al. 2015; Sariyildiz 2015), but the long-term dynamics of

19 these processes remain poorly understood relative to leaf litter decomposition (Freschet et al. 2013;  
20 Keller et al. 2021). The traits controlling rates of mass loss and nutrient release of belowground  
21 tissues do not necessarily mirror those of aboveground tissues (Sun et al. 2018), even within species  
22 (Hobbie et al. 2010; See et al. 2019). Critically, the duration of most root decomposition studies is  
23 less than 3 years (diameter < 2 mm, See et al. 2019), which is shorter than the half-life of root litter  
24 in most systems (Parton et al. 2007). Furthermore, long-term studies of decay dynamics have  
25 focused exclusively on fine roots (diameter < 2 mm), but coarser roots constitute a larger biomass  
26 pool (Fahey et al. 2005), decompose more slowly (Zhang & Wang 2015), and differ from fine roots  
27 in both C chemistry and N and P concentrations. While fine roots are often a thought to be net source  
28 of nutrients to soil during the early stages of decomposition, estimates vary considerably across  
29 studies (e.g., Li et al. 2015; Zhang & Wang 2015). Thus, the controls over long-term N and P release  
30 from decomposing roots and their relationship to root diameter remain highly uncertain.

31 Ecosystem models often assume that long-term nutrient release from decomposing roots is  
32 proportional to mass (C) loss rates (e.g., Sulman et al. 2017), but empirical evidence for this is scarce.  
33 The best support comes from a 10-year global litterbag study in which N release was well correlated  
34 with mass loss in the fine roots of three species (Parton et al. 2007). However, long-term rates of N  
35 release from coarse roots have not been estimated using the litterbag approach, and studies of  
36 excavated roots from logging chronosequences suggest that N release from woody roots may be

37 decoupled from mass loss during the early stages of decay, and remain net N sinks for decades  
38 (Fahey et al. 1991; Chen et al. 2001). To our knowledge there have been no litterbag studies that  
39 have directly measured late-stage P dynamics from decomposing roots of any size. A better  
40 understanding of the relationship between long-term rates of mass loss, N release, and P release  
41 across root diameters is therefore necessary to further both conceptual understanding and modeling  
42 of forest nutrient cycles.

43 Previous research on the early stages of root decomposition suggest that the relationship  
44 between diameter class and nutrient release differs for N and P. Nitrogen release generally decreases  
45 with increasing root diameter (Goebel et al. 2011; Zhuang et al. 2018), while P release appears to be  
46 more consistent (Jing et al. 2019; Pang et al. 2022), but may be higher during the early stages of  
47 decay (Gang et al. 2019). The mechanism for this variation in nutrient dynamics with diameter size  
48 is due in large part to differences in substrate chemistry. Nutrient release tends to increase with the  
49 initial substrate concentration (Chen et al. 2002; Cusack et al. 2009; Hobbie et al. 2010) because  
50 microbial communities immobilize limiting nutrients until they have met their stoichiometric  
51 requirements. Consequently, the decomposition of higher C:N substrates can sometimes require  
52 additional import of N by the decomposer community, leading to a net immobilization of N in the  
53 decomposing root which can last for years (Parton et al. 2007). Thus, the controls over nutrient  
54 immobilization and release throughout the decomposition process are likely driven by changing

55 tradeoffs between the energy and nutrient demands of the decomposer community (Gill et al. 2021).

56       Root C chemistry is an important controlling factor of root decomposition (Berg et al. 2000;  
57 Silver & Miya 2001; Zhang et al. 2008; Fujii & Takeda 2010; Bakker et al. 2011; Jiang et al. 2021;  
58 Song et al. 2021), and its effects can be broadly categorized into those of structural and  
59 non-structural components. Structural C makes up the majority of plant C and it's dominant form  
60 influences decomposition rates, with carbohydrates degraded hydrolytically (i.e., cellulose,  
61 hemicellulose) decomposing faster than those requiring less energetically unfavorable oxidative  
62 processes. As a result, initial lignin (an acid unhydrolyzable compound) commonly predicts the rate  
63 of decomposition worldwide (Zhang et al. 2008; Harmon et al. 2009; See et al. 2019; Guo et al.  
64 2021). Non-structural C fractions such as phenolics (Sun et al. 2018), non-structural carbohydrates  
65 (NSC), and other secondary compounds also influence decomposition rate in a variety of ways, but  
66 their effects on nutrient release are less understood. A comprehensive understanding of how substrate  
67 C composition affects the long-term trajectory of mass loss and nutrient release from root litter is  
68 still lacking.

69       In addition to C chemistry, nutrient limitation of decomposer communities plays an important  
70 and complex role in determining decomposition rate and nutrient retention (Zhou & Wang 2016).  
71 Low substrate N concentrations can suppress microbial activity, reducing decomposition rate (Parton  
72 et al. 2007; Hobbie et al. 2010; Goebel et al. 2011; See et al. 2019). Conversely, N limitation can

73 enhance the decomposition of more recalcitrant substrates (i.e., N-mining), and alleviation of N  
74 limitation can inhibit ligninase activity and promote the accumulation of organic matter (Hobbie  
75 2015; Wang et al. 2019; Yang et al. 2019). Higher substrate N and P concentrations consistently lead  
76 faster decay rates during the early-stages of fine root decomposition worldwide (See et al. 2019;  
77 Jiang et al. 2021), but effects on later stages of decomposition and nutrient release remain largely  
78 unexplored. In addition, there is increasing recognition for the role of other rock-derived nutrients in  
79 regulating litter decomposition, including magnesium (Mg; Goebel et al. 2011; Wambsganss et al.  
80 2022), calcium (Ca; See et al. 2019), and silicon (Si; Schaller & Struyf 2013). A better understanding  
81 of how these less-reported elements interact to affect long-term rates of decomposition and nutrient  
82 release is therefore needed.

83       Here we present the results of a seven-year decomposition experiment conducted across roots  
84 of five diameter classes, from three temperate tree species in Northeast China. We explore patterns  
85 of short-term and long-term rates of decomposition and nutrient release, and identify the initial  
86 substrate characteristics that best predict these rates. We hypothesized that: (1) Nutrient release (as a  
87 percent of the initial pool) would be higher from lower diameter roots, (2) Decomposition rate and  
88 nutrient release would be higher from species with higher initial concentrations, and (3) The  
89 decomposition rate would predict nutrient release during both short-term and long-term stages.

## 90 **MATERIALS AND METHODS**

91 **Site description**

92 This study was conducted at the Maoershan Forest Ecosystem Research Station in northeastern  
93 China (N45°25', E127°40'). The climate is continental monsoonal, with a warm-humid summer and  
94 a dry-cold winter. The mean annual precipitation is 726 mm, and the mean annual temperature is  
95 2.1 °C during the period of 2008-2019 (Sun et al. 2021). The forest is a 70-yr old broadleaved  
96 deciduous forest, with a mean elevation of 400 m and a mean slope of 9°. The soils are classified as  
97 Alfisols (Eutroboralfs) based on the United States Soil Taxonomy.

98 **Field experiments**

99 Three dominant tree species from the site, *Betula platyphylla* (BP), *Ulmus davidiana* var. *japonica*  
100 (UJ), and *Fraxinus mandshurica* (FM), were selected to study the effects of initial root quality on  
101 decomposition of roots with different diameters. Roots from three to five mature individuals of each  
102 species were excavated in late May 2012 from the 0-20 cm soil layer, and immediately taken back to  
103 the lab for processing. The roots were cleaned with tap water, dead roots were removed, and then  
104 divided into five diameter classes: < 1 mm, 1-2 mm, 2-5 mm, 5-10 mm, 10-20 mm. A sample of 2-5  
105 g air-dried roots was placed into each 0.1 mm mesh litter-bag, and masses were later corrected to  
106 oven-dried (65 °C) mass using species- and diameter-specific correction factors. There were 720  
107 bags in total: 60 bags for each of the < 1 mm, 1-2 mm, and 2-5 mm diameter classes, and 30 bags  
108 each of the 5-10 mm and 10-20 mm diameter classes in a species. Five individual trees were

109 repeated for each species. Litter-bags were buried on June 3rd 2012 to 10 cm depth underneath five  
110 replicate trees of each species, with species corresponding to the species of root contained in the  
111 litterbag (Lin et al. 2020). After burying the bags, the litter layer was restored as much as possible to  
112 minimize disturbance.

113 Litterbags were retrieved on eight occasions during the first two years of incubation to  
114 effectively capture dynamics during the early stages of decomposition. To characterize later stage  
115 dynamics, we retrieved one set of litterbags each in the 3rd, 5th and 7th years of incubation. This  
116 resulted in a total of 11 litterbag collections, representing incubation times of 1, 2, 3, 4, 5, 11, 13, 15,  
117 27, 49, and 87 months. In total, 666 of 720 litter bags were retrieved, and the rest were lost or  
118 destroyed by wild boar (*Sus scrofa* L.). Upon removal from the field, all roots were cleaned,  
119 oven-dried it at 65 °C, massed, and analyzed for C, N and P concentrations.

## 120 **Root chemistry measurements**

121 Additional root samples of each species and diameter class were collected on May 29st, 2021 to  
122 measure the initial root quality. We characterized each sample for concentrations of C, N, P, Ca, Mg,  
123 Si, soluble sugars, starch, hemicellulose, cellulose, lignin, and total phenolics. The total C  
124 concentration was determined by the dry combustion method (Multi N/C 2100 S, Analytik Jena,  
125 Jena, Germany). The N and P concentrations were determined by sulphuric acid/hydrogen peroxide  
126 digestion, followed by sodium salicylate/sodium hypochlorite colorimetric determination for N and

127 by ammonium molybdate/ascorbic acid colorimetric determination for P using continuous flow  
128 analysis (AA3, SEAL Analytical, Germany). Ca and Mg concentrations were determined by flame  
129 spectrophotometer with an Atomic Absorption Spectrophotometer (TAS-990, Pgeneral, China), Si  
130 concentration was obtained by mass method after digesting with nitric acid/perchloric acid. Soluble  
131 sugars, starch and non-structural carbohydrates (NSC, sum of soluble sugars and starch)  
132 concentrations were determined by the modified phenol sulfuric acid method (Zhang et al. 2014).  
133 Hemicellulose, cellulose, and lignin concentrations were determined by high pressure liquid  
134 chromatography (UltiMate 3000, Thermo, USA). Total phenolics concentration was determined by  
135 the Folin phenol colorimetry. Two or three repetitions were carried out in each sample to reduce the  
136 operating error. For the C quality, structural carbohydrates indicated cellulose and lignin,  
137 decomposable carbohydrates were NSC and hemicellulose, resistant carbohydrates represented  
138 cellulose, lignin, and total phenolics.

### 139 **Data analysis**

140 The Mauchly's Test of Sphericity showed that there was a significant temporal autocorrelation of  
141 mass and nutrient remaining rates, thus the two-factor repeated measurement analysis of variance of  
142 tree species and diameter and their interaction was used to test the effect of decomposition time,  
143 diameter, tree species and their interaction on nutrient remaining. Duncan post-hoc analysis was  
144 used to test significant differences in decomposition rate, nutrient release, and initial root quality

145 between root diameter within species, between species for the same root diameter.

146 We fit the proportion of mass remaining to three exponential decay models and determined the  
147 best fit among them both using Akaike Information Criterion (AIC) and considering the biological  
148 meanings of decomposition rates.

149 Single exponential model (Olson 1963):

$$150 \quad M = e^{-kt} \quad (1)$$

151 Double exponential model (Hobbie et al. 2012):

$$152 \quad M = Ce^{-k_1t} + (1 - C)e^{-k_2t} \quad (2)$$

153 Asymptotic model (Hobbie et al. 2012):

$$154 \quad M = A + (1 - A)e^{-k_a t} \quad (3)$$

155 where  $M$  is the proportion of initial mass remaining at time  $t$  (in years), and  $k$  is the decomposition  
156 rate in single exponential model. In the double exponential model,  $C$  is the fraction of the initial  
157 mass that decomposes with decomposition rate  $k_1$ , while the remaining fraction  $(1 - C)$  decomposes  
158 with rate  $k_2$ . In the asymptotic model,  $A$  is the fraction of the initial mass with a decomposition rate  
159 of zero (i.e., the asymptote), while the remaining fraction  $(1 - A)$  decomposes with rate  $k_a$ .

160 While the two pool models generally fit better based on AIC, we ultimately chose the single  
161 exponential model for comparisons with nutrient release, because the  $k_1$  based on the double  
162 exponential model and  $k$  from the asymptotic model were too large (Table S1). We thus calculated

163 separate single exponential  $k$  values to represent the short-term (0 – 15 months) and long-term (i.e.,  
164 87-months' decomposition) decomposition stages (Pan et al. 2021). For each of these time periods,  
165 we calculated rates of nutrient release, where the nutrient remaining ( $L$ , %) was calculated as:

$$166 \quad L = M_t C_t / M_0 C_0 \times 100\% \quad (4)$$

167 and the nutrient release ( $L_t$ , %) was calculated as:

$$168 \quad L_t = 1 - L \quad (5)$$

169 where  $M_t$  is residual dry mass at time  $t$  (yr),  $M_0$  is initial dry mass,  $C_t$  is the nutrient concentration at  
170 time  $t$ , and  $C_0$  is the initial nutrient concentration. The root nutrient release is the mass of nutrient lost  
171 by the roots over a time period compared with the initial nutrient mass of the roots (Parton et al.  
172 2007; Xiong et al. 2012; Freschet et al. 2021).

173 The similarities and differences in root decomposition rate and nutrient release were analyzed  
174 using principal component analysis and linear regression. Two-way ANOVA was used to determine  
175 whether the initial root quality was significantly influenced by tree species and diameter.  
176 Multi-methods were used to analyze the relationship between initial root quality and root  
177 decomposition parameters at different angles. Pearson correlation analysis was used to detect the  
178 relationship between initial root quality, decomposition rate, and nutrient release for the two stages  
179 of decomposition. We used linear regression with forward selection (based on the significance of the  
180 partial regression sum of squares) to find the best-fitting models for predicting root decomposition

181 rate and nutrient release based on initial root quality parameters. The regression procedures were  
182 conducted using the “relaimpo” package in R (Groemping 2006).

## 183 **RESULTS**

### 184 **Short-term and long-term patterns of nutrient release**

185 Nutrient release varied considerably across root diameter and tree species (Figures 1, 2, S1, and S2).

186 Short-term N and P release systematically decreased with increasing root diameter (with the  
187 exception of P release from BP), while C release generally increased. Nitrogen was immobilized  
188 during the early stages of decomposition across all species and diameters, except in the smallest  
189 diameter class (< 1 mm) of roots (Figure 1c). In contrast, C and P were generally released during this  
190 time (Figure 1b, d). Patterns in decomposition and nutrient release also varied by species and  
191 differed by element. Short-term C release was significantly higher for FM than the other two species  
192 in coarse roots (Figure 1b), and N release was also highest from fine roots of this species (Figure 1c).  
193 In contrast, short-term P release was generally highest from UJ in fine roots, while this species  
194 generally had the lowest rates of N release.

195 After seven years of decomposition, we observed a wide range in net source-sink dynamics  
196 across species and diameter classes, with a much wider range observed for N than P. In general,  
197 long-term decomposition rate, C loss, and P release in coarse roots was higher than in fine roots.  
198 Nitrogen release roughly decreased with root diameter and varied strongly among species. Most

199 diameter classes released N during the later stages of decomposition, but the coarsest roots of BP  
200 and UJ still immobilized N at the end of the experiment. The greatest N release was observed in < 1  
201 mm FM roots (40.1% of initial N), while the coarsest roots of UJ had still immobilized 25.3% of  
202 initial N at the end of the experiment. In contrast, all roots released P, but net release still varied by a  
203 factor of three, with coarse roots of FM (5-10 mm diameter) releasing 69.6% of initial P, and UJ  
204 releasing 15.4% of initial P. Long-term nutrient release of FM was generally higher than that of the  
205 other two species (Figure 2).

206 Principal component analysis showed that short-term N and P release diverged from long-term  
207 decomposition rate (Figures 3 and S3). In general, long-term C and P release were similar to  
208 long-term decomposition rate (Figure 3), and C and P release were significantly positively correlated  
209 with long-term decomposition rate (Figure S3). Notably, rates of long-term N release were unrelated  
210 to mass loss, C loss, and P release.

### 211 **Chemical drivers of short-term and long-term nutrient release**

212 Our analysis of initial substrate chemistry revealed that the strongest predictors of short-term  
213 decomposition rates and C losses differed from those driving nutrient release (Figures 4 and S4).  
214 Short-term C release, P release, and decomposition rate were largely driven by C fractions and  
215 structural components (i.e. Si), while short-term N release was directly related to N, Mg, and total C  
216 concentrations. The initial substrate effects on long-term root decomposition and C losses largely

217 mirrored those predicting short-term rates (Figures 5, S4, and S5). In contrast, none of the predictors  
218 of short-term N and P release remained predictors in the long-term model. Surprisingly, there were  
219 no significant relationships between long-term root decomposition rate and lignin. Higher initial N  
220 and P concentrations increased N but not C and P release.

221 The contributions of initial root quality to decomposition rate and nutrient release diverged  
222 during short-term and long-term stages (Figure 4, Table S5). Based on the multiple linear regression,  
223 initial root quality explained more than 80% of the variation in short-term root decomposition  
224 parameters. The major contributors of short-term decomposition rate, C release, and P release, were  
225 C quality and their ratios, but the primary predictors of N release generally nutrient concentrations.  
226 Surprisingly, initial Si concentrations predicted 54% of the variability in short-term P release. The  
227 major contributors of long-term decomposition rate, C and P releases were C quality and their ratios,  
228 while variability in N release was mainly driven by initial nutrient concentrations (Figure 4). For  
229 example, the contributions of soluble sugars:lignin to long-term P release and decomposition rate  
230 explanations were up to 60% and 56%, respectively. The top predictors of long-term C and N release  
231 were cellulose:phenolics (46% of variability) and P (29% of variability), respectively.

232 Sensitivities of decomposition during the short-term and long-term to the first two major  
233 contribution factors were shown in Figures S6 and S7. Short-term root decomposition parameters  
234 (except short-term N release) were consistently more sensitive to and increased with increasing the

235 first principal factor, and decreased with the increase of the second principal factor. Short-term N  
236 release was positively correlated with the initial concentration of C and N. However, long-term  
237 decomposition rate and long-term N release increased with increasing the first principal factor  
238 (soluble sugars:lignin and P, respectively), and decreased with increasing the second principal factor  
239 (phenolics and Ca, respectively), and were more sensitive to the first principal factor. Long-term C  
240 release increased with increasing cellulose:phenolics (more sensitive) and NSC:phenolics, and P  
241 release increased as soluble sugars:lignin and C:NSC (more sensitive) increase, respectively.

242 The relative difference in N release and P release at the end of the study was well related to  
243 initial and final nutrient concentrations (Figure 5). Initial N and N:P were good single predictors of  
244 the difference from N release and P release during long-term stage. And the difference between  
245 long-term N and P release well predicted the final N:P in root litter with a linear model. The multiple  
246 linear regression revealed that initial C:N, N:P and resistant carbohydrates concentration together  
247 explained 89% of the variation (Figure S8). However, the difference between N and P release during  
248 short-term stage was exclusively related to structural carbohydrates ( $R^2 = 0.39$ , Figure S9).

## 249 **DISCUSSION**

### 250 **Nitrogen and phosphorus dynamics during root decomposition**

251 Our results represent the most detailed study of the long-term N and P dynamics in decomposing  
252 roots to date, and highlight the fact that N release is decoupled from P release during all stages of

253 decomposition. These findings have clear implications for forest nutrient cycling, as root necromass  
254 represents a significant nutrient pool in soils, and soil N and P availability commonly co-limit  
255 productivity in terrestrial ecosystems (Elser et al. 2007; Harpole et al. 2011). Importantly, we found  
256 opposite relationships between root diameter and nutrient retention for these two elements, with  
257 greater proportional P release from coarse roots (diameter  $\geq 2$  mm), and greater proportional N  
258 release from fine roots (diameter  $\leq 2$  mm). Furthermore, our data strongly suggest that while  
259 long-term rates of P release during decomposition can be predicted as a function of mass loss, N  
260 release cannot (Figure S3), challenging the assumption that these fluxes are linearly related to  
261 decomposition (Parton et al. 2007; Cusack et al. 2009). These contrasting long-term dynamics are  
262 not explicitly represented in ecosystem models but are likely important, because the ability of  
263 ecosystems to redistribute stocks of N and P in synchrony between above and belowground pools in  
264 response to plant demand will be critical to determining future C sequestration under global change  
265 (e.g., Rastetter et al. 2022).

266 Short-term patterns of N and P release were correlated with mass loss in our dataset, consistent  
267 with previous work, but the magnitude of these fluxes varied by species and root size. Rates of N  
268 release decreased with root diameter and varied widely among species (Usman et al. 2000; Lin et al.  
269 2010; Jani et al. 2015; Xu et al. 2022). Only the finest diameter ( $< 1$  mm) roots immediately released  
270 N during the first 15 months of decomposition (Figure 1; Parton et al. 2007; Sun et al. 2013).

271 Conversely, while short-term rates of P release also differed across diameter and species, there was  
272 considerably less variation, and all roots were net source of P to soil within the first 15 months (with  
273 the exception of the coarsest FM roots), suggesting that root necromass may be a more important  
274 long-term sink for N than P in soils. Similar to the relationships observed across diameters, N release  
275 also varied more across species than P, though we also found (smaller) interspecific differences in P  
276 release (between UJ and FM) that corroborate a previous study of these species (Zhuang et al. 2018).  
277 These interspecific differences support the idea that fine scale variation in rhizosphere species  
278 composition may have considerable afterlife effects on localized N and P availability (Tong et al.  
279 2012; Freschet et al. 2013), ultimately leading to plant-driven feedbacks on rates of stand-scale  
280 nutrient cycling (Hobbie 2015). The fact that species differed in their relative rates of N and P release  
281 warrants further investigation (Figure S10). If within-species N:P stoichiometry of nutrient release is  
282 decoupled from with the N:P stoichiometry of annual plant demand, it could provide a previously  
283 overlooked reinforcing mechanism for maintaining community-level N and P colimitation (Bloom  
284 1985).

### 285 **Effects of initial substrate quality on nitrogen, phosphorus, and carbon release**

286 Our results strongly suggest that differences in initial C chemistry and nutrient stoichiometry were  
287 the underlying mechanism for the observed differences in nutrient release among species and  
288 diameter class (Figures S11 – S16). Critically, the main drivers of nutrient release differed between

289 the early and late stages of decay. Initial concentrations of N and P predicted the release of these  
290 elements reasonably well during the first 15 months of decomposition, but P release was better  
291 predicted by initial Si and C chemistry than by initial P (Figure 4). Moreover, initial P concentrations  
292 were completely unrelated to the rate of P released at the end of the study (Figure S5), which was  
293 instead a function of initial C chemistry (i.e., the ratio of soluble sugars to lignin, and initial  
294 non-structural carbohydrates; Figure 4). Similarly, although long-term rates of N release were  
295 correlated with initial N, the best model for predicting N release did not include initial substrate N.  
296 Instead, N retention was best explained by initial concentrations of the other nutrients (P, Mg, Ca),  
297 and labile C fractions. Given that most roots had still retained over half of initial N and P after seven  
298 years, our results suggest that N and P cycles cannot be considered in isolation from other elements.

299 Our findings clearly demonstrate that rates of N and P release during root decomposition are  
300 not directly proportional, and vary widely across species and diameters. Critically however,  
301 long-term dynamics appear to be relatively predictable based on initial substrate chemistry. The  
302 differences in long-term N and P release were well predicted by initial C:N:P stoichiometry (Figures  
303 5 and S8). In contrast, short-term differences were less predictable, but were correlated with initial  
304 structural carbohydrates (Figure S9). The effect of initial N (Figure 5) was overshadowed by the  
305 indirect effect of initial P and C quality during long-term decay. Taken together, our results indicate  
306 that the effects of root litter inputs on soil N and P availability could potentially be modeled based on

307 initial root traits, but further research is needed.

308         While our results are ultimately correlational, they strongly suggest multiple element control  
309 over long-term nutrient release, likely due to a combination of decomposer nutrient demands and  
310 nutrient-related stabilization of the decomposing substrates. The N immobilization we observed in  
311 most roots may be explained by root N concentrations being lower than the N concentration of the  
312 surrounding soil (6.3 vs 7.6 mg/g), facilitating the transfer of N from soil into the decomposing  
313 substrate. Previous nutrient manipulations (Zhou & Wang 2016) and foliar dynamics (Wang et al.  
314 2022) suggest that our site it is not strongly N limited. Intriguingly, P was the most important initial  
315 nutrient controlling the long-term N immobilization, perhaps suggesting that the rate of N  
316 investment by the decomposer community may be in part controlled by P demand. This is further  
317 supported by the strong negative relationship between root N:P and C losses during the early stages  
318 of decomposition (Figure S4). In contrast, Ca had a significant inhibitory effect on N release, which  
319 might be caused by Ca stabilization of the cell wall in cortex parenchyma cells, which tend to have  
320 high N concentrations (Fujii & Takeda 2010). This may be a more likely explanation than Ca  
321 limitation, as Ca is not thought to be limiting to decomposer communities in this region (Gao et al.  
322 2022). Mechanisms for the relationship between Si and P release are less understood, but Si enables  
323 plants to mitigate P stress (Tombeur et al. 2020), so may reflect the correlations between initial  
324 substrate P and Si.

325 Beyond nutrient release, this experiment also represents one of the longest-running studies of C  
326 losses across root diameters and species during root decomposition. Our findings support the  
327 emerging idea that lignin alone is not sufficient to predict long-term C dynamics, and the effects of  
328 lignin have been previously shown to weaken over time (Figures. 4, S4 and S5; Harmon et al. 2009),  
329 and with increasing diameter class (Zhang & Wang 2015). Our results highlight the importance of  
330 negative effects of phenolics (Sun et al. 2018) in combination with the positive effects of more labile  
331 C fractions (i.e., soluble sugars, NSC, cellulose; Harmon et al. 2009; Fan & Guo 2010; Sun et al.  
332 2013; Wang et al. 2019) in controlling the long-term trajectory of C losses from root litter.  
333 Nevertheless, the greater C losses from coarser roots were likely due in part to lower acid-insoluble  
334 compounds (mainly composed of lignin; Figure S12e; Harmon et al. 2009; Fan & Guo 2010; Sun et  
335 al. 2013; Cotrufo et al. 2015; Wang et al. 2019). However, coarser roots also had much lower  
336 concentrations of phenolics, which emerged as a more important control over C losses with time  
337 (Figure 4), suggesting that C lost during the early stages was primarily composed of relatively labile  
338 materials. Importantly, the variation in initial lignin concentrations across species was considerably  
339 lower than the variation in phenolics and labile C fractions (Figures S11 and S12), likely driving the  
340 patterns we observed. A better understanding of this variability will be critical to elucidating the role  
341 of root traits in long-term soil C sequestration, as more than half of initial root C remained at the end  
342 of the study.

343 Beyond influencing the residence time of C retention in decomposing litter pools, substrate  
344 chemistry differences across species and diameter classes likely impact the formation of new  
345 stabilized C in surrounding soil. Recent evidence suggests that arbuscular mycorrhizal roots  
346 decompose faster than ectomycorrhizal roots (See et al. 2019), and these more labile litter inputs  
347 lead may result in more efficient C transfer to mineral associated soil pools with longer residence  
348 time (Cotrufo et al. 2015; Craig et al. 2022). Our long-term C loss patterns support the idea that  
349 arbuscular mycorrhiza species (FM) lose C more rapidly than ectotrophic mycorrhiza species (UJ,  
350 BP), and suggests that these differences amplify with time, and with increasing diameter size  
351 (Figures 1 and 2). Although the proportion of soil minerals in direct contact with decomposing root  
352 litter is likely lower for coarse roots than fine roots (due to a smaller lower surface area to volume  
353 ratio), the redistribution C from litter into mineral soils via fungal hyphae is common (Frey et al.  
354 2003; See et al. 2022). Thus, relatively low concentrations of lignins and phenolics and relatively  
355 high concentrations of carbohydrates in coarse roots likely represents a labile source of C for  
356 microbial transfer to mineral-associated C pools.

#### 357 **DECLARATION OF COMPETING INTEREST**

358 The authors declare that they have no conflicts of interest.

#### 359 **ACKNOWLEDGEMENTS**

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362

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537           in root decomposition of three common subalpine tree species in southwestern China.  
538           *Geoderma*, 311, 1–8.

539

1 **Figure captions**

2 **FIGURE 1** Short-term decomposition rate ( $k$ ) and nutrient release in different root  
3 diameter classes of three species. BP, *Betula platyphylla*; UJ, *Ulmus davidiana* var.  
4 *japonica*; FM, *Fraxinus mandshurica*. Different lower-case letters indicate significant  
5 differences between root diameter within species; different capital letters indicate  
6 significant difference between species within root diameter ( $P < 0.05$ ). Short-term  
7 decomposition rate ( $k$ ) based on Eq. (1).

8 **FIGURE 2** Long-term decomposition rate ( $k$ ) and nutrient release in different root  
9 diameter classes of three species. BP, *Betula platyphylla*; UJ, *Ulmus davidiana* var.  
10 *japonica*; FM, *Fraxinus mandshurica*. Different low-case letters indicate significant  
11 differences between root diameter within species; different capital letters indicate  
12 significant difference between species within root diameter ( $P < 0.05$ ). Long-term  
13 decomposition rate ( $k$ ) based on Eq. (1).

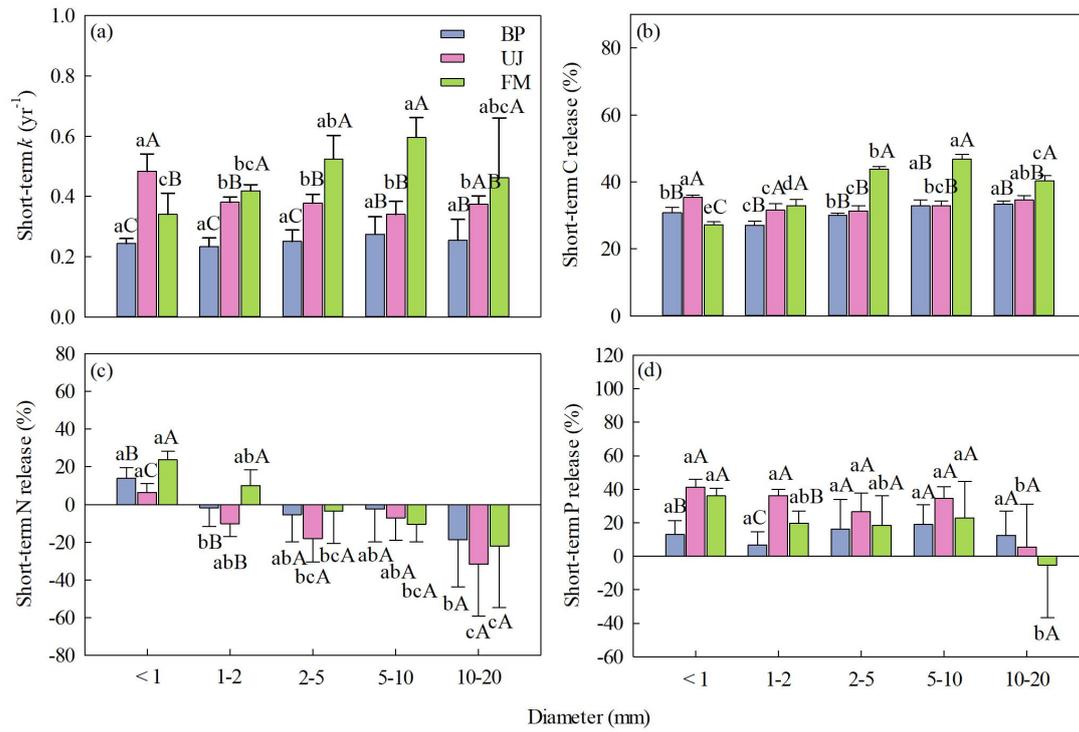
14 **FIGURE 3** The first two principal components of the PCA for decomposition rates  
15 and nutrient release showing their similarities and differences.  $Lk$ , Long-term  
16 decomposition rate; LCR, Long-term C release; LNR, Long-term N release; LPR,  
17 Long-term P release;  $Sk$ , Short-term decomposition rate; SCR, Short-term C release;  
18 SNR, Short-term N release; SPR, Short-term P release. BP, *Betula platyphylla*; UJ,  
19 *Ulmus davidiana* var. *japonica*; FM, *Fraxinus mandshurica*.

20 **FIGURE 4** The relative importance (%) of the main contributors of the initial root  
21 quality to short-term and long-term decomposition constant ( $k$ ) and nutrient release  
22 rates.  $Lk$ , Long-term decomposition constant; LCR, Long-term C release rate; LNR,

23 Long-term N release rate; LPR, Long-term P release rate;  $S_k$ , Short-term  
24 decomposition constant; SCR, Short-term C release rate; SNR, Short-term N release  
25 rate; SPR, Short-term P release rate. SS, Soluble sugars; NSC, Non-structural  
26 carbohydrates; Hemi, Hemicellulose; Cell, Cellulose; Lign, Lignin; Phe, Phenolics; C,  
27 Carbon; P, Phosphorus; Ca, Calcium; Mg, Magnesium; Si, Silicon.

28 **FIGURE 5** The relationship of the difference from long-term N release and P release  
29 with initial and final nutrients in roots. Each point within a species represents a  
30 diameter class.

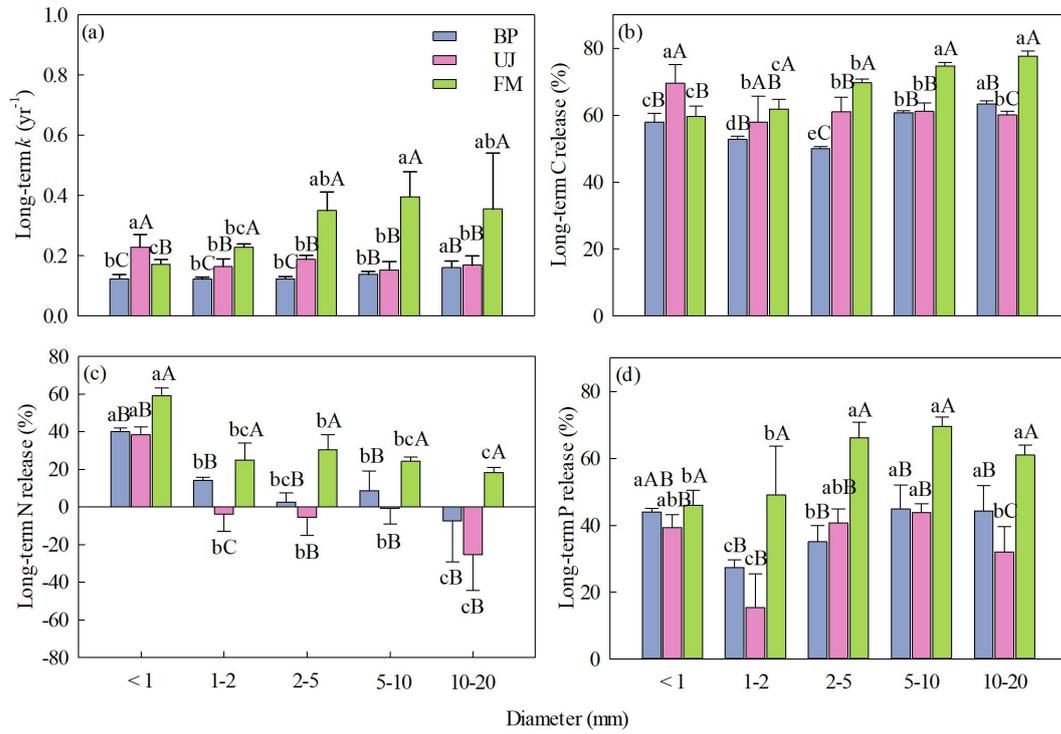
31 FIGURE 1



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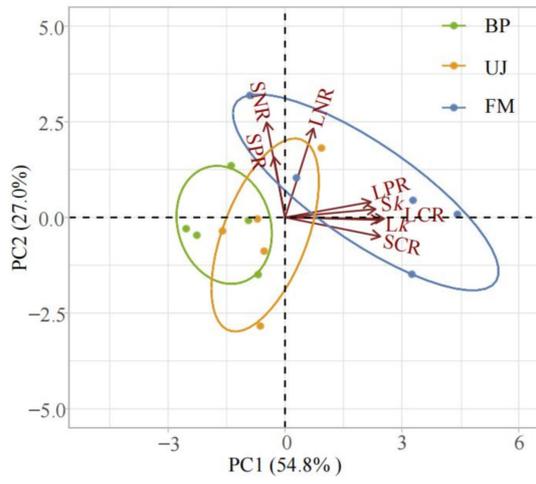
34 FIGURE 2



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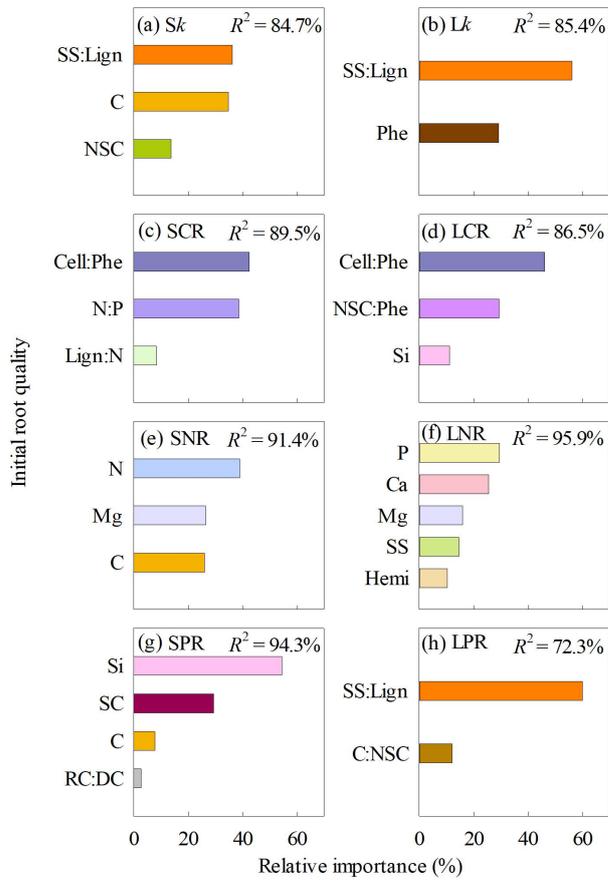
37 FIGURE 3



38

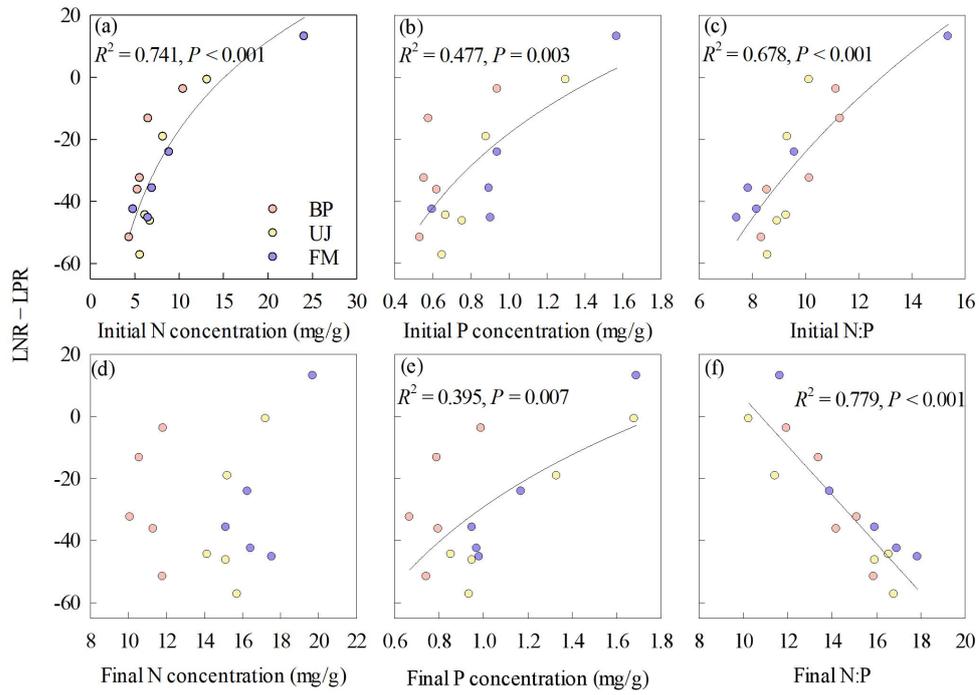
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40 FIGURE 4



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## Supporting Information

**Table S1** Decomposition parameters obtained from fitting double exponential, single exponential, and asymptotic model and its Akaike Information Criterion (AIC) for roots with various diameter of three species

**Table S2** Repeated measurements analysis of variance for carbon, nitrogen, phosphorous concentrations for the three species

**Table S3** Repeated measurements analysis of variance for carbon, nitrogen, phosphorous remaining for the three species

**Table S4** Results of two-way analysis of variance for initial root quality for the three tree species

**Table S5** Forward multiple linear regressions between the initial root quality and root decomposition rate ( $k$ ), nutrient release

**FIGURE S1** Carbon, nitrogen and phosphorous concentrations dynamic in different root diameter classes of three species during the seven years' decomposition

**FIGURE S2** Carbon, nitrogen and phosphorous dynamics in different root diameter classes of three species during the seven years' decomposition

**FIGURE S3** Linear regression of long-term and short-term decomposition rates ( $k$ ) against long-term and short-term nutrient release for the three species

**FIGURE S4** Correlations between initial root quality and short-term decomposition rate ( $k$ ),

nutrient release for the three species.

**FIGURE S5** Correlations between initial root quality and long-term decomposition rate ( $k$ ), nutrient release of the three tree species.

**FIGURE S6** Sensitivities of short-term decomposition rate ( $k$ ) and nutrient release to their two major contribution factors.

**FIGURE S7** Sensitivities of long-term decomposition rate ( $k$ ) and nutrient release to their two major contribution factors.

**FIGURE S8** The relative importance (%) of the main contributors of the initial root quality to the difference between long-term N release and long-term P release

**FIGURE S9** Linear regression of the main contributors of the initial root quality structural carbohydrates (SC) to the difference between short-term N release and short-term P release

**FIGURE S10** Linear regression of short-term and long-term N release rate (%) against short-term and long-term P release rate (%) for the three species.

**FIGURE S11** Comparison of initial decomposable carbon fractions in roots with different diameters for the three species

**FIGURE S12** Comparison of initial resistant carbon fractions in roots with different diameters for the three species

**FIGURE S13** Comparison of initial element concentrations in roots with different diameters for the

three species

**FIGURE S14** The ratio of initial elements and carbon quality to phenolics

**FIGURE S15** The ratio between initial carbon, nitrogen, phosphorus, and NSC

**FIGURE S16** The ratio of initial nitrogen, phosphorus, and carbon quality to carbon quality among

root diameters for the three species

**FIGURE S17** Comparison of carbon concentration in roots with different diameters for the three

species at different periods

**Table S1** Decomposition parameters obtained from fitting double exponential, single exponential, and asymptotic model and its Akaike Information Criterion (AIC) for roots with various diameter of three species. C, the fraction of the initial mass that decomposes with decomposition rate  $k_1$ ;  $k_1$ ,  $k_2$ , double exponential model decomposition rate;  $k$ , single exponential model decomposition rate; A, asymptote;  $k_a$ , asymptotic model decomposition rate.

Species	Diameter	double exponential				single exponential		asymptotic		
		C	$k_1$	$k_2$	AIC	$k$	AIC	A	$k_a$	AIC
BP	<1	0.154	4.556	0.067	-47.417	0.123	-22.445	0.582	0.707	-36.385
BP	1-2	0.148	4.845	0.068	-52.681	0.122	-23.376	0.579	0.669	-36.901
BP	2-5	0.186	3.016	0.057	-50.010	0.123	-21.356	0.596	0.803	-39.273
BP	5-10	0.158	7.019	0.089	-27.587	0.138	-10.639	0.483	0.596	-14.338
BP	10-20	0.123	5.872	0.119	-22.296	0.161	-14.319	0.391	0.453	-21.483
UJ	<1	0.290	14.000	0.068	-48.504	0.228	-4.046	0.595	5.027	-26.035

UJ	1-2	0.269	5.718	0.047	-47.522	0.164	-8.789	0.625	2.690	-33.880
UJ	2-5	0.238	6.401	0.076	-54.968	0.187	-11.987	0.559	1.477	-28.519
UJ	5-10	0.220	6.115	0.080	-32.140	0.152	-6.776	0.504	0.939	-14.285
UJ	10-20	0.243	5.776	0.083	-23.326	0.169	-5.560	0.482	1.007	-13.340
FM	<1	0.219	10.210	0.073	-36.667	0.172	-10.582	0.588	1.655	-23.158
FM	1-2	0.256	7.336	0.090	-47.602	0.228	-10.133	0.522	1.585	-24.227
FM	2-5	0.310	4.668	0.125	-41.146	0.350	-11.602	0.394	1.201	-27.486
FM	5-10	0.347	5.635	0.140	-22.642	0.396	-3.514	0.317	1.175	-12.299
FM	10-20	0.716	0.734	0.030	-19.192	0.355	-10.697	0.233	0.680	-21.144

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**Table S2** Repeated measurements analysis of variance for root carbon, nitrogen, phosphorous concentrations for the three tree species

Sources of variation	C concentration		N concentration		P concentration	
	<i>F</i> -value	<i>P</i> -value	<i>F</i> -value	<i>P</i> -value	<i>F</i> -value	<i>P</i> -value
Time (T)	131.672	< 0.001	88.338	< 0.001	5.372	< 0.001
Diameter (D)	23.186	< 0.001	1031.806	< 0.001	212.726	< 0.001
Species (S)	335.384	< 0.001	654.597	< 0.001	692.23	< 0.001
D×S	4.023	0.010	199.577	< 0.001	19.985	< 0.001
D×T	10.807	< 0.001	12.569	< 0.001	4.312	< 0.001
S×T	12.042	< 0.001	3.290	< 0.001	9.113	< 0.001
D×S×T	0.946	0.500	4.126	< 0.001	3.066	< 0.001

**Table S3** Repeated measurements analysis of variance for root carbon, nitrogen, phosphorous remaining for the three tree species

Sources of variation	C remaining		N remaining		P remaining	
	<i>F</i> -value	<i>P</i> -value	<i>F</i> -value	<i>P</i> -value	<i>F</i> -value	<i>P</i> -value
Time (T)	3521.558	< 0.001	24.504	< 0.001	45.287	< 0.001
Diameter (D)	37.739	< 0.001	143.014	< 0.001	101.501	< 0.001
Species (S)	661.988	< 0.001	87.048	< 0.001	158.783	< 0.001
D×S	284.199	< 0.001	1.523	0.227	32.597	< 0.001
D×T	10.812	< 0.001	6.986	< 0.001	4.445	< 0.001
S×T	22.930	< 0.001	7.135	< 0.001	14.649	< 0.001
D×S×T	10.294	< 0.001	1.714	0.038	4.929	< 0.001

**Table S4** Results of two-way analysis of variance for initial root quality for the three species. SS, Soluble sugars; Sta, Starch; NSC, Non-structural carbohydrates; Hemi, Hemicellulose; DC, Decomposable carbohydrates; Cell, Cellulose; Lign, Lignin; SC, Structural carbohydrates; Phe, Phenolics; RC, Resistant carbohydrates; C, Carbon; N, Nitrogen; P, Phosphorus; Ca, Calcium; Mg, Magnesium; Si, Silicon.

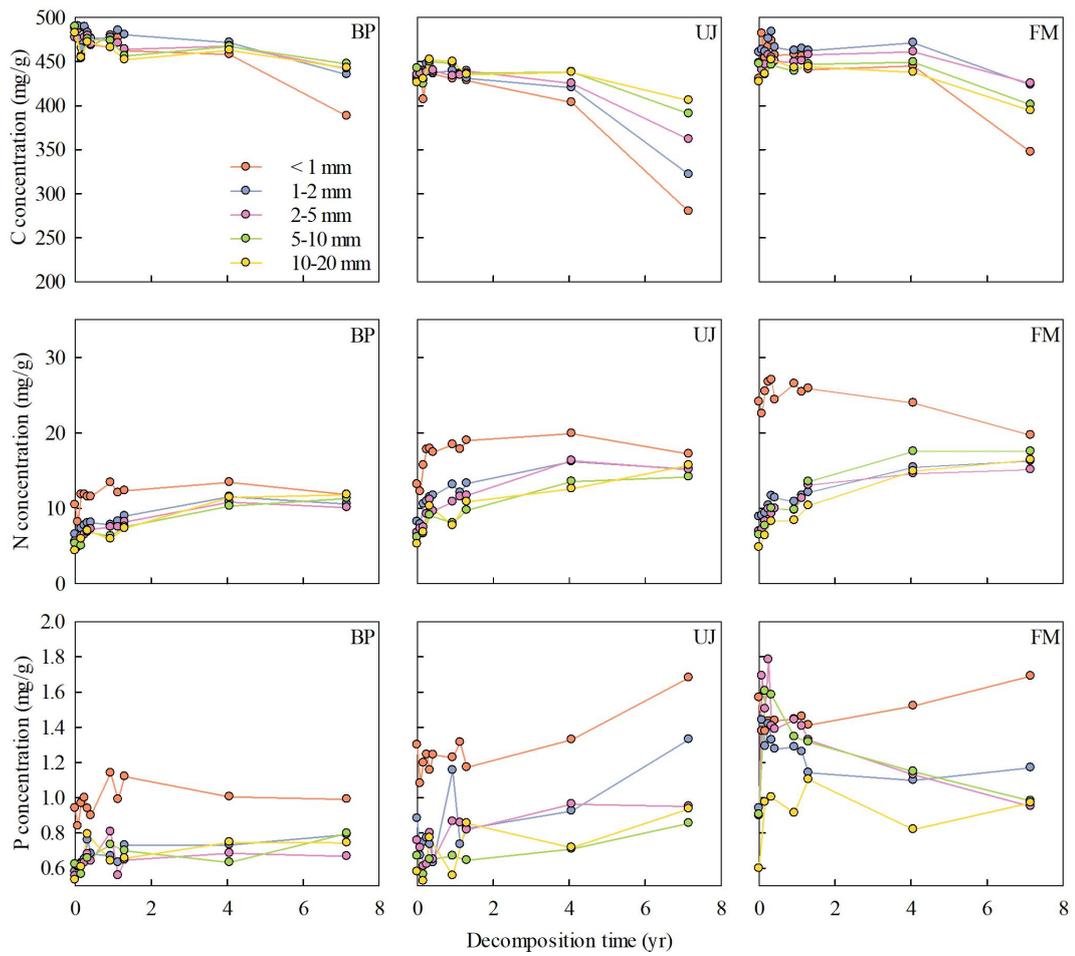
Initial quality	root	Species (S)		Diameter (D)		S×D	
		<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
Soluble sugars		45.382	< 0.001	1.409	0.242	11.053	< 0.001
Starch		42.629	< 0.001	1.358	0.260	3.806	0.001
NSC		39.210	< 0.001	1.952	0.114	11.569	< 0.001
Hemicellulose		40.796	< 0.001	21.435	< 0.001	14.989	< 0.001
DC		24.251	< 0.001	12.206	< 0.001	13.044	< 0.001
Cellulose		18.236	< 0.001	21.552	< 0.001	2.726	0.015
Lignin		6.964	0.002	10.829	< 0.001	2.837	0.012
SC		18.490	< 0.001	4.776	0.003	4.481	< 0.001
Phenolics		272.000	< 0.001	47.663	< 0.001	10.059	< 0.001
RC		21.297	< 0.001	4.322	0.005	4.801	< 0.001
C		148.640	< 0.001	3.636	0.011	2.362	0.029
N		125.931	< 0.001	416.969	< 0.001	65.449	< 0.001
P		60.383	< 0.001	85.396	< 0.001	5.159	< 0.001
Ca		285.398	< 0.001	19.489	< 0.001	26.449	< 0.001
Mg		251.585	< 0.001	72.458	< 0.001	3.736	0.001

Initial quality	root	Species (S)		Diameter (D)		S×D	
		<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
Si		67.200	< 0.001	40.591	< 0.001	4.076	0.002
SS:Phe		1185.90 2	< 0.001	102.828	< 0.001	37.666	< 0.001
NSC:Phe		528.961	< 0.001	83.790	< 0.001	5.769	< 0.001
N:Phe		420.043	< 0.001	132.292	< 0.001	74.668	< 0.001
C:Phe		412.422	< 0.001	65.547	< 0.001	3.488	0.002
Cell:Phe		210.614	< 0.001	74.574	< 0.001	10.261	< 0.001
C:N		72.875	< 0.001	128.209	< 0.001	1.618	0.140
N:P		3.697	0.031	52.208	< 0.001	17.983	< 0.001
C:P		70.244	< 0.001	37.785	< 0.001	1.762	0.104
NSC:N		9.487	< 0.001	76.905	< 0.001	15.512	< 0.001
NSC:P		7.062	0.002	24.677	< 0.001	9.418	< 0.001
C:NSC		69.286	< 0.001	4.514	0.003	12.993	< 0.001
Cell:N		23.760	< 0.001	69.393	< 0.001	2.915	0.010
Lign:N		34.077	< 0.001	57.879	< 0.001	3.118	0.007
Lign:P		32.836	< 0.001	14.686	< 0.001	2.767	0.014
SS:Lign		44.612	< 0.001	5.107	0.002	5.433	< 0.001
SC:NSC		36.911	< 0.001	3.351	0.017	5.215	< 0.001
RC:DC		19.311	< 0.001	14.555	< 0.001	9.778	< 0.001

**Table S5** Forward multiple linear regressions between the initial root quality and root decomposition rate ( $k$ ), nutrient release.  $Lk$ , Long-term decomposition rate; LCR, Long-term C release; LNR, Long-term N release; LPR, Long-term P release;  $Sk$ , Short-term decomposition rate; SCR, Short-term C release; SNR, Short-term N release; SPR, Short-term P release. SS, Soluble sugars; NSC, Non-structural carbohydrates; Hemi, Hemicellulose; DC, Decomposable carbohydrates; Cell, Cellulose; Lign, Lignin; SC, Structural carbohydrates; Phe, Phenolics; RC, Resistant carbohydrates; C, Carbon; N, Nitrogen; P, Phosphorus; Ca, Calcium; Mg, Magnesium; Si, Silicon.

Variable	$R^2$	Regression
$Lk$	0.796	$1.333 \times \text{SS:Lign} - 0.008 \times \text{Phe} + 0.006$
LCR	0.558	$1.474 \times \text{Cell:Phe} + 0.451 \times \text{Si} - 209.751 \times \text{NSC:Phe} + 503.878$
LNR	0.770	$52.789 \times \text{P} - 5.775 \times \text{Ca} - 0.767 \times \text{Hemi} + 0.602 \times \text{SS} - 28.939 \times \text{Mg} + 37.163$
LPR	0.492	$347.430 \times \text{SS:Lign} + 6.996 \times \text{C:NSC} - 61.705$
$Sk$	0.563	$2.328 \times \text{SS:Lign} - 0.003 \times \text{C} - 0.004 \times \text{NSC} + 1.478$
SCR	0.474	$0.331 \times \text{Cell:Phe} - 2.082 \times \text{N:P} - 0.170 \times \text{Lign:N} + 58.095$
SNR	0.698	$1.360 \times \text{N} + 0.476 \times \text{C} + 33.255 \times \text{Mg} - 270.928$
SPR	0.756	$1.132 \times \text{Si} - 0.254 \times \text{SC} + 0.237 \times \text{C} - 6.096 \times \text{RC:DC} + 25.107$





**FIGURE S1** Carbon, nitrogen and phosphorous concentrations dynamic in different root diameter classes of three species during the seven years' decomposition. BP, *Betula platyphylla*; UJ, *Ulmus davidiana* var. *japonica*; FM, *Fraxinus mandshurica*.

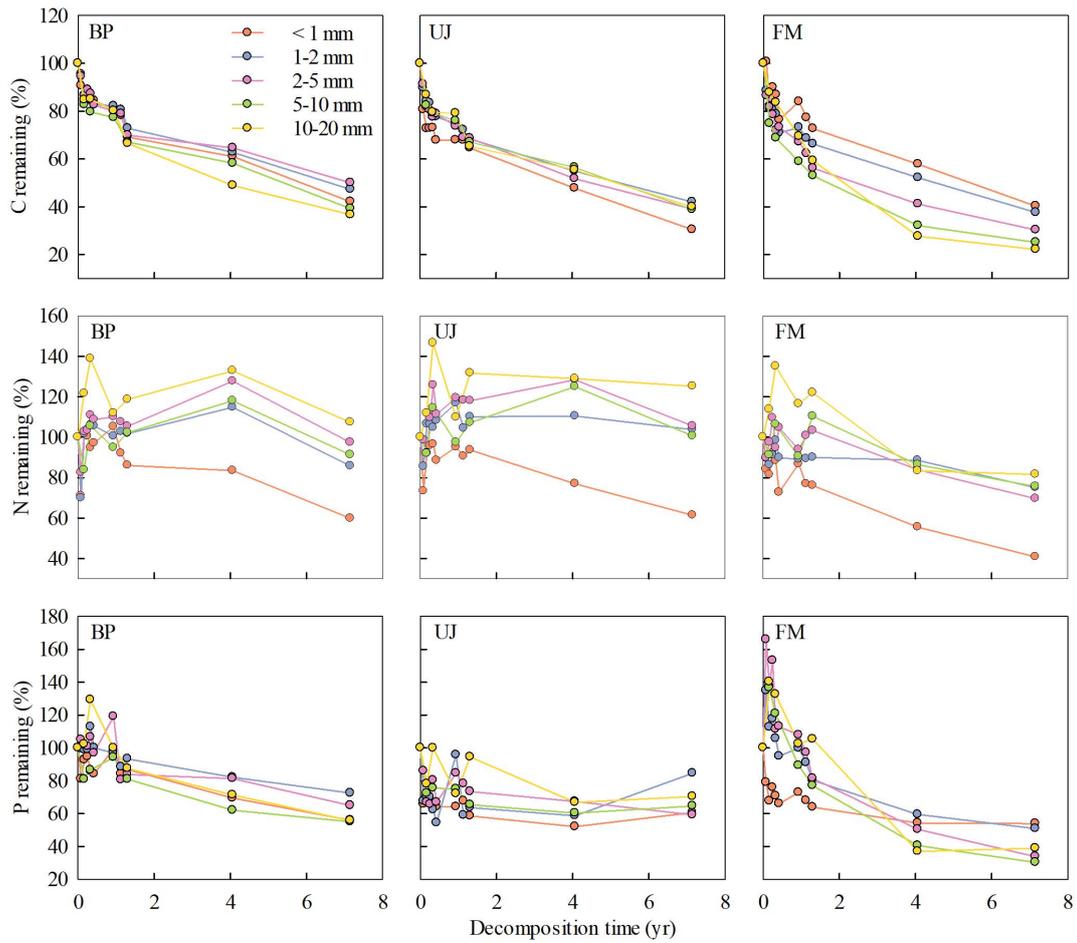
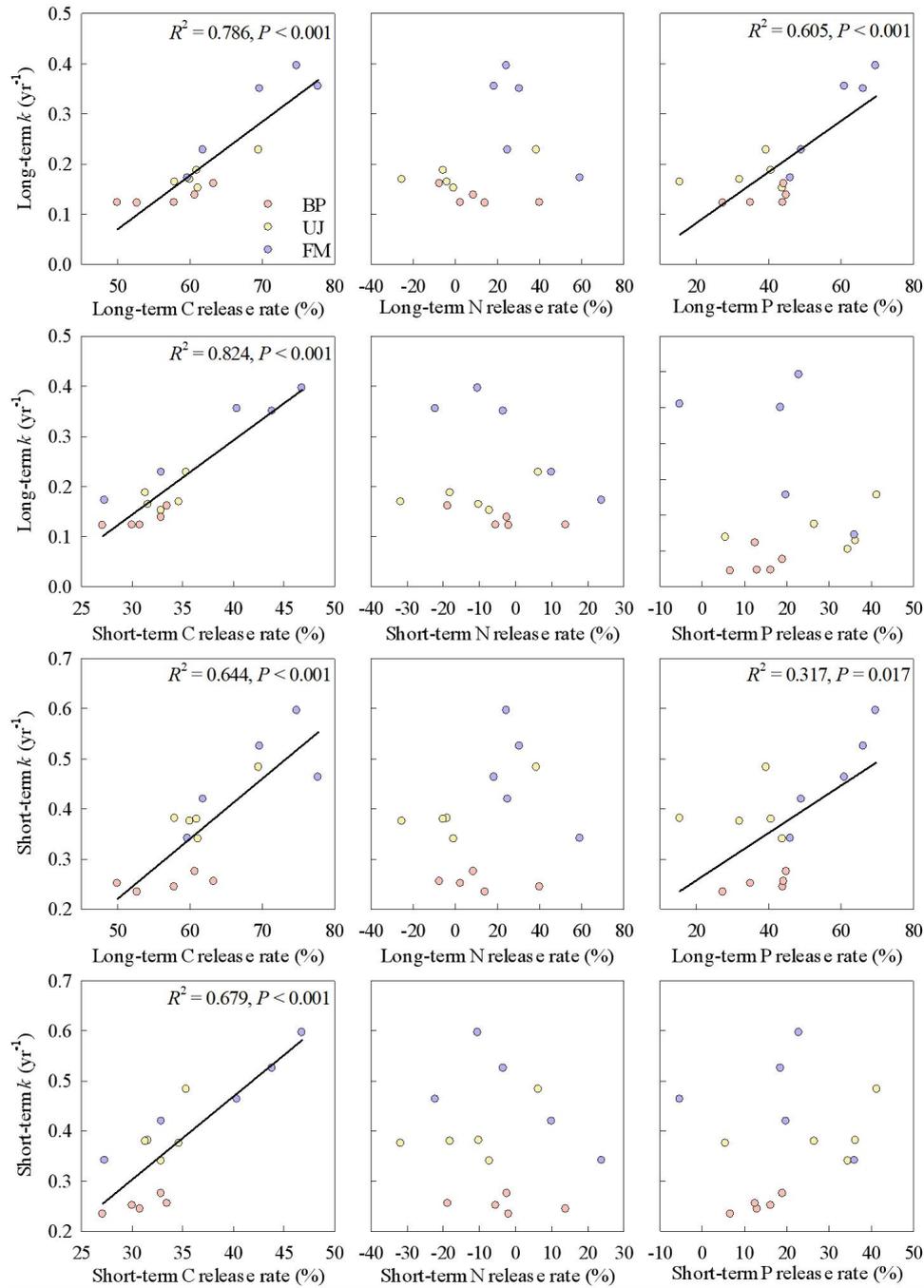


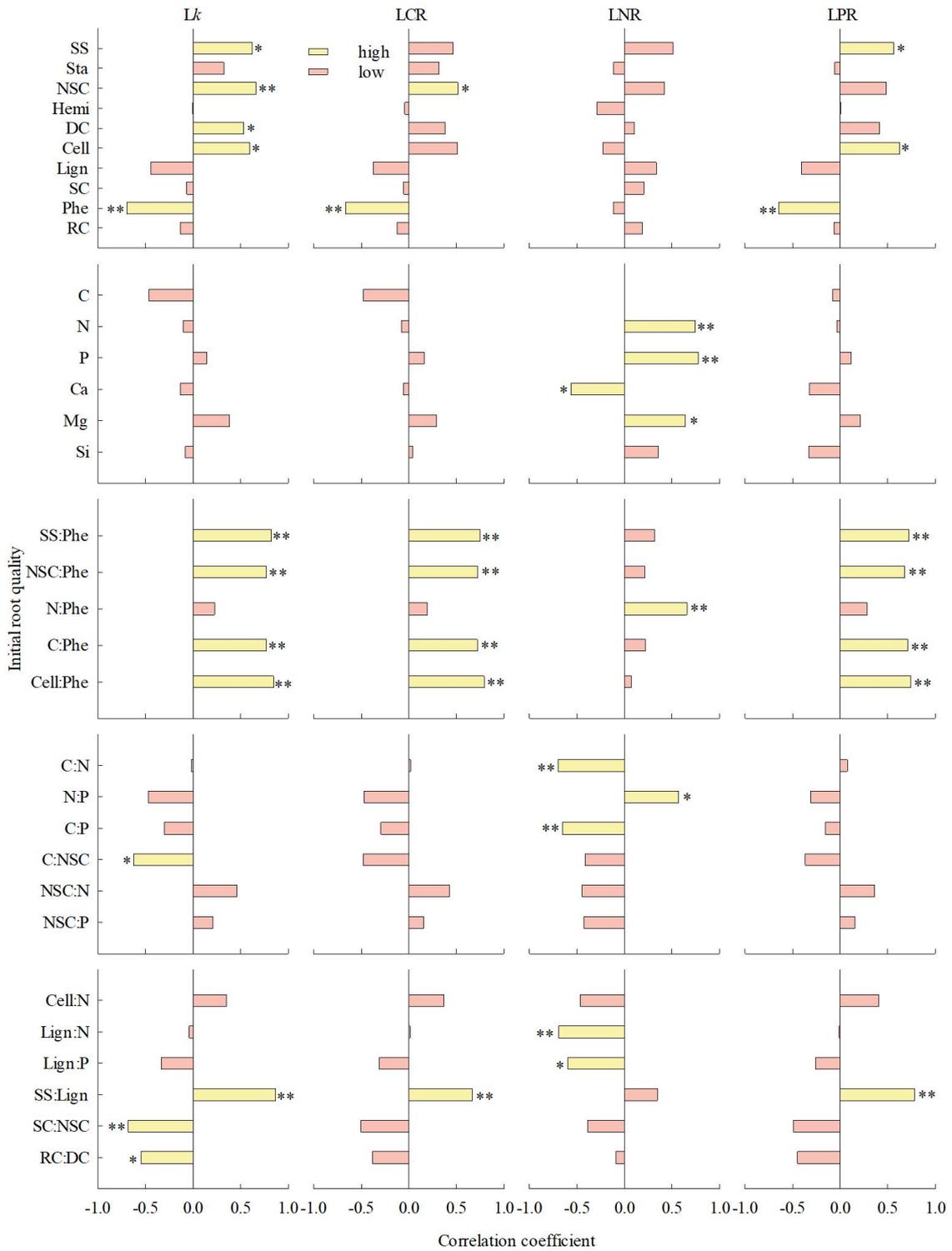
FIGURE S2 Carbon, nitrogen and phosphorous dynamics in different root diameter classes of three species during the seven years' decomposition. BP, *Betula platyphylla*; UJ, *Ulmus davidiana* var. *japonica*; FM, *Fraxinus mandshurica*.



**FIGURE S3** Linear regression of long-term and short-term decomposition rates ( $k$ ) against long-term and short-term nutrient release for the three species. Each point within a species represents a different diameter class. Linear regression showed that long-term C and P release but not N release were significantly positively correlated with long-term decomposition rate ( $P < 0.05$ ), short-term C release but not N and P release was significantly positively correlated with decomposition rate ( $P < 0.05$ ).

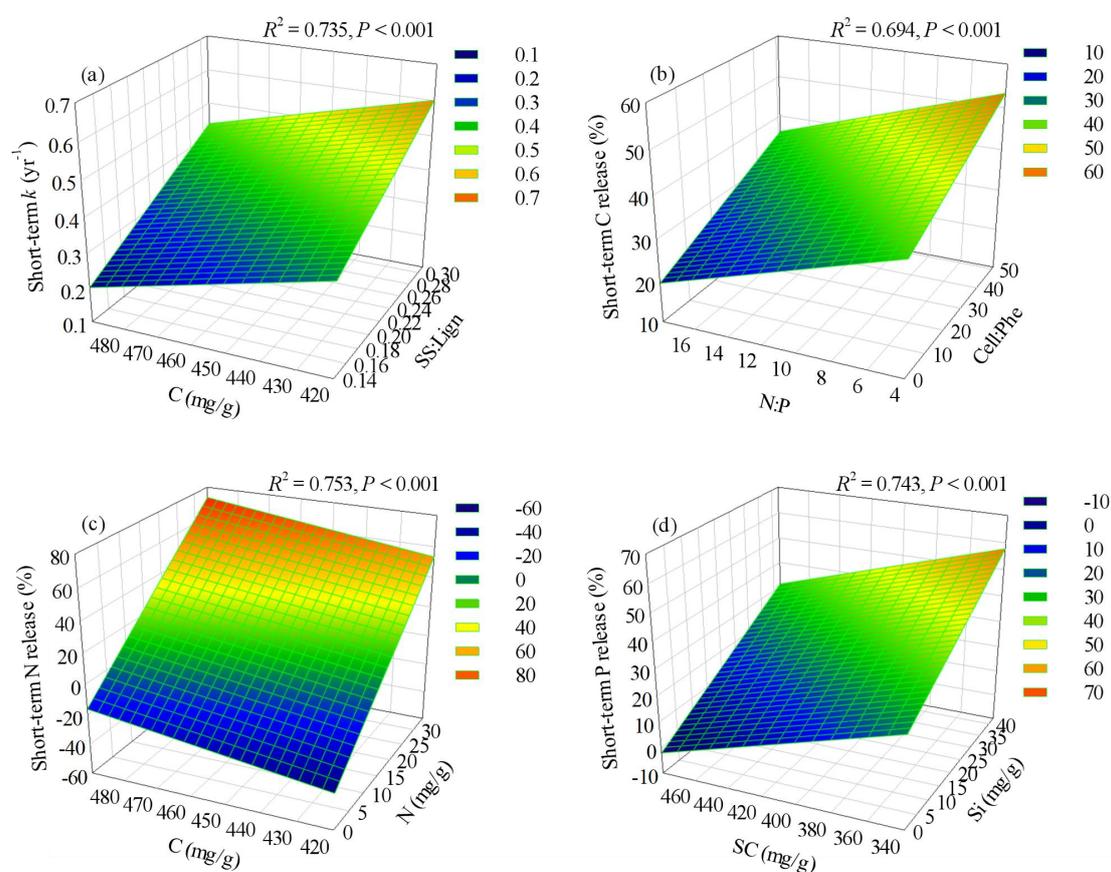


**FIGURE S4** Correlations between initial root quality and short-term decomposition rate ( $k$ ), nutrient release for the three species.  $Sk$ , Short-term decomposition rate; SCR, Short-term C release; SNR, Short-term N release; SPR, Short-term P release. SS, Soluble sugars; Sta, Starch; NSC, Non-structural carbohydrates; Hemi, Hemicellulose; DC, Decomposable carbohydrates (NSC, Hemi); Cell, Cellulose; Lign, Lignin; SC, Structural carbohydrates (Cell, Lign); Phe, Phenolics; RC, Resistant carbohydrates (Cell, Lign, Phe); C, Carbon; N, Nitrogen; P, Phosphorus; Ca, Calcium; Mg, Magnesium; Si, Silicon. \* represents  $P < 0.05$ , and \*\* represents  $P < 0.001$ . The same below.

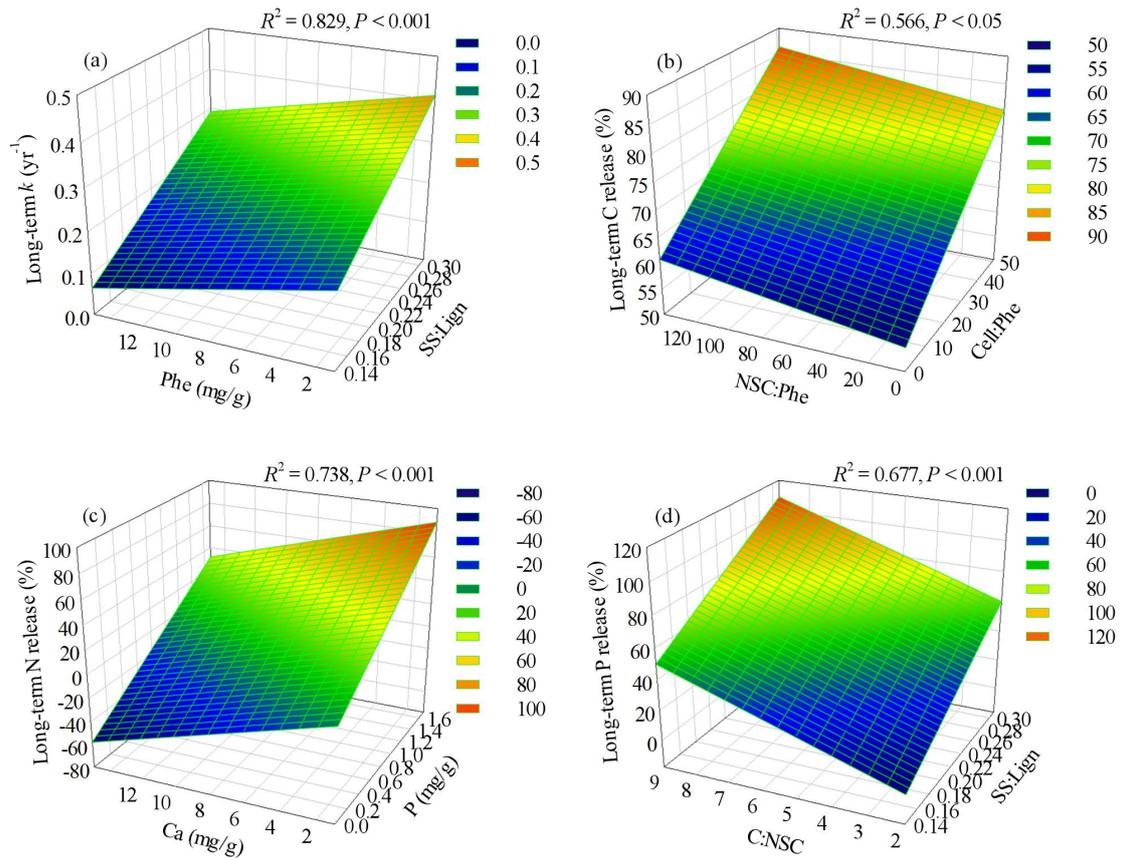


**FIGURE S5** Correlations between initial root quality and long-term decomposition rate ( $k$ ), nutrient release of the three tree species.  $Lk$ , Long-term decomposition rate; LCR, Long-term C release; LNR, Long-term N release; LPR, Long-term P release. SS,

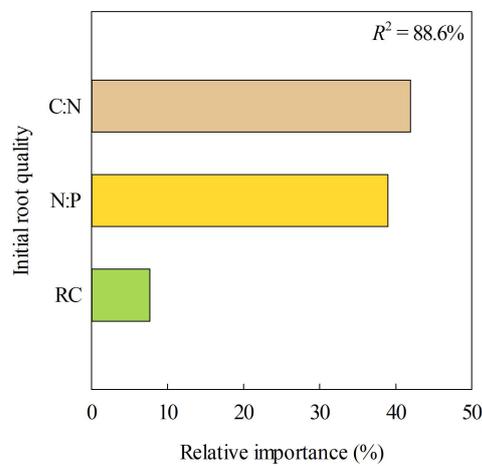
Soluble sugars; Sta, Starch; NSC, Non-structural carbohydrates; Hemi, Hemicellulose; DC, Decomposable carbohydrates (NSC, Hemi); Cell, Cellulose; Lign, Lignin; SC, Structural carbohydrates (Cell, Lign); Phe, Phenolics; RC, Resistant carbohydrates (Cell, Lign, Phe); C, Carbon; N, Nitrogen; P, Phosphorus; Ca, Calcium; Mg, Magnesium; Si, Silicon.



**FIGURE S6** Sensitivities of short-term decomposition rate ( $k$ ) and nutrient release to their two major contribution factors. The other significant factors were not considered. SS, Soluble sugars; Cell, Cellulose; Lign, Lignin; SC, Structural carbohydrates (Cell, Lign); Phe, Phenolics; C, Carbon; N, Nitrogen; P, Phosphorus; Si, Silicon.

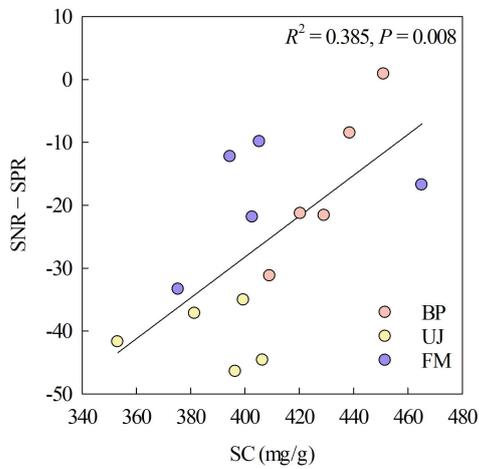


**FIGURE S7** Sensitivities of long-term decomposition rate ( $k$ ) and nutrient release to their two major contribution factors. The other significant factors were not considered. SS, Soluble sugars; NSC, Non-structural carbohydrates; Cell, Cellulose; Lign, Lignin; Phe, Phenolics; C, Carbon; P, Phosphorus; Ca, Calcium.

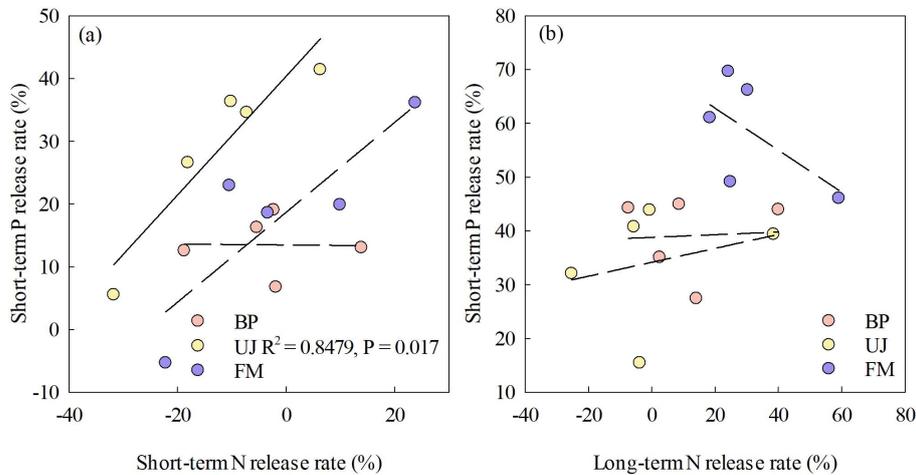


**FIGURE S8** The relative importance (%) of the main contributors of the initial root

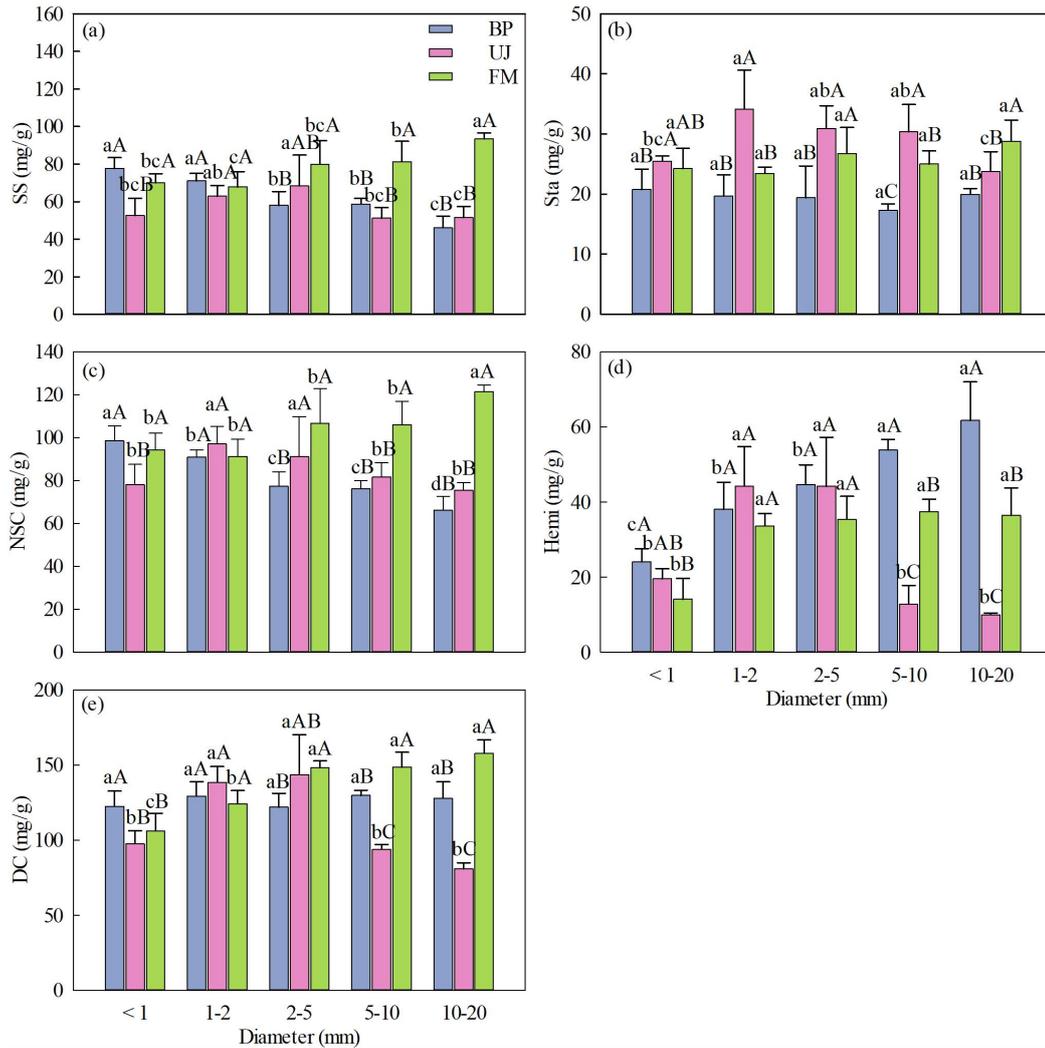
quality to the difference between long-term N and P release from the same species and diameter class. C: Carbon, n: nitrogen, P: phosphorous; RC: Resistant carbohydrates.



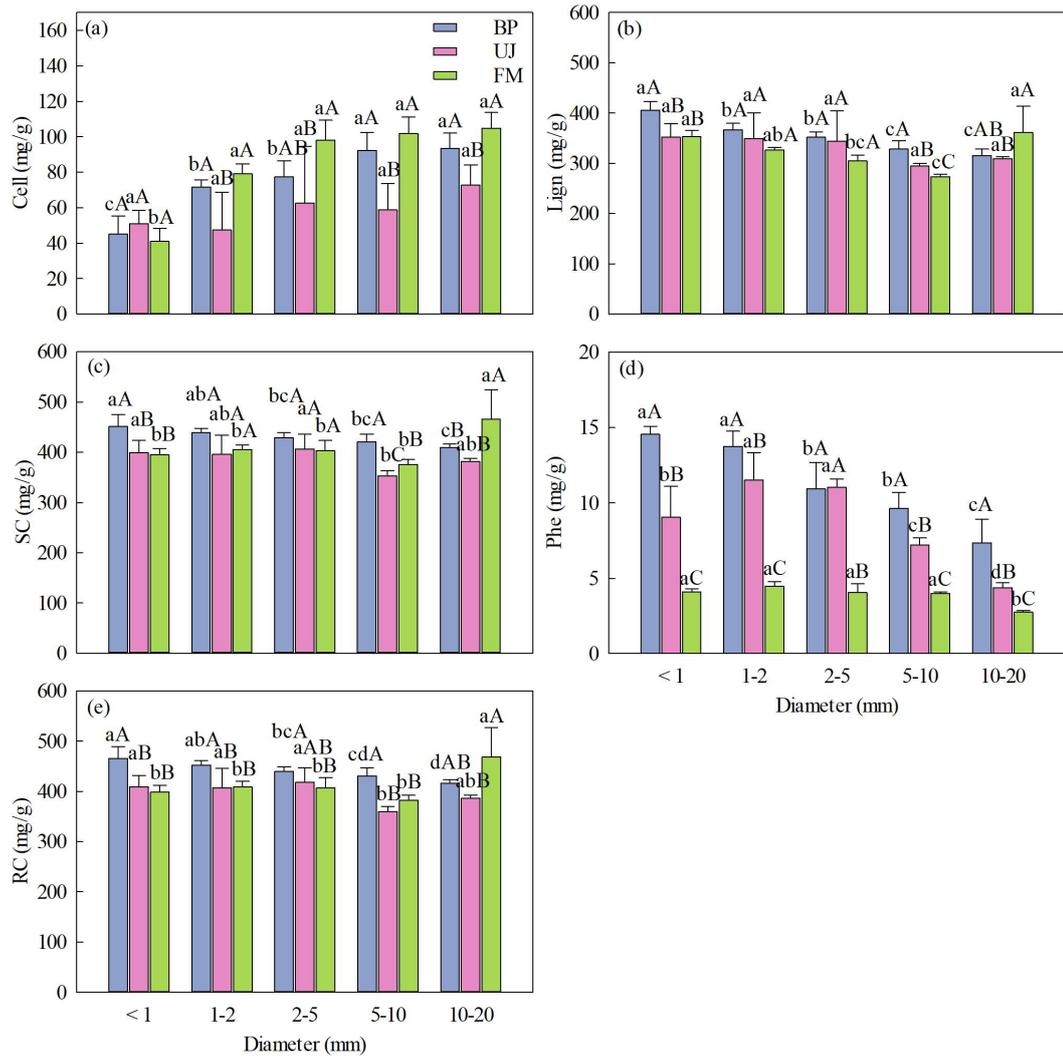
**FIGURE S9** Linear regression of the main contributor of the initial root quality structural carbohydrates (SC) to the difference between short-term N release and short-term P release.



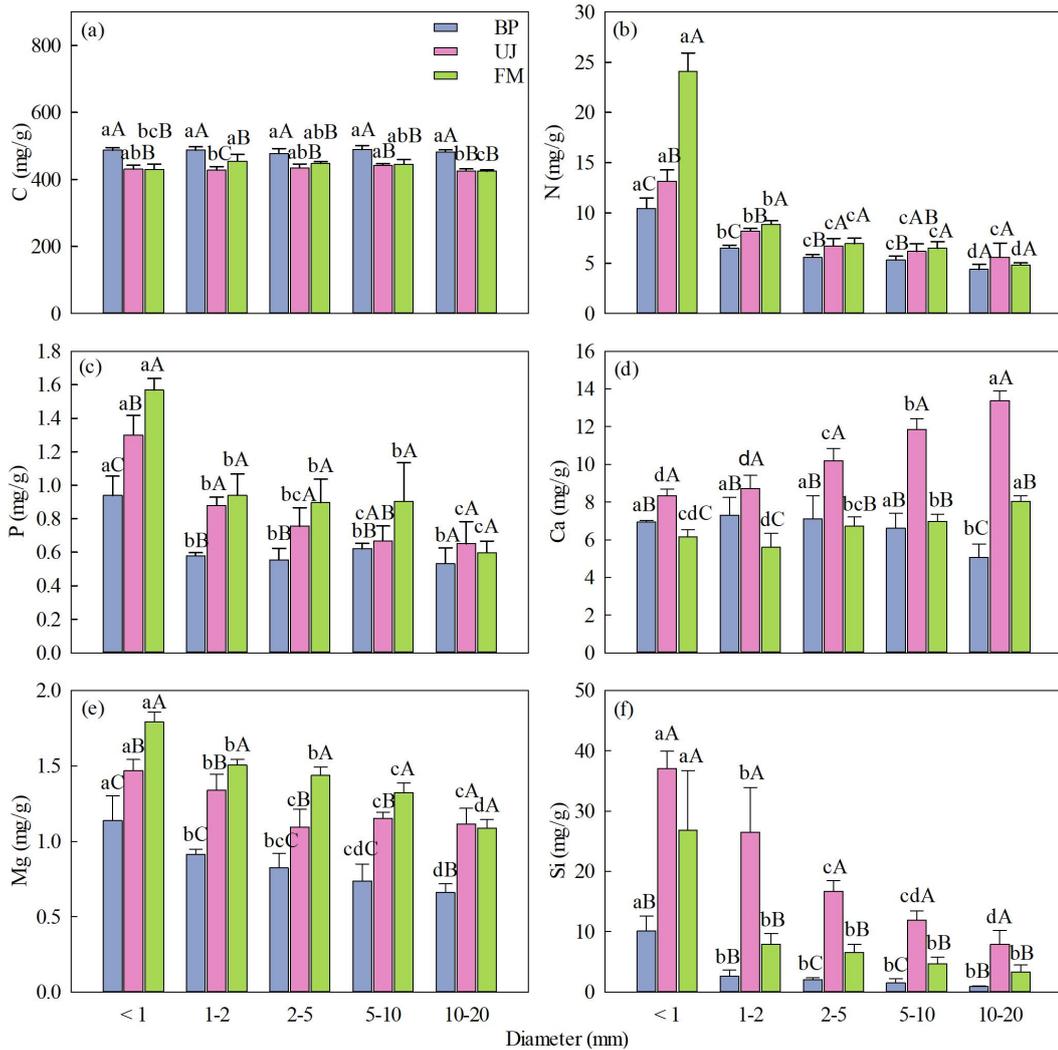
**FIGURE S10** Linear regression of short-term and long-term N release rate (%) against short-term and long-term P release rate (%) for the three species.



**FIGURE S11** Comparison of initial decomposable carbon fractions in roots with different diameters for the three species. BP, *Betula platyphylla*, UJ, *Ulmus davidiana* var. *japonica*, FM, *Fraxinus mandshurica*. SS, Soluble sugars; Sta, Starch; NSC, Non-structural carbohydrates; Hemi, Hemicellulose; DC, Decomposable carbohydrates. Different low-case letters indicate significant differences between root diameter with in species; Different capital letters indicate significant difference between species with in root diameters ( $P < 0.05$ ),  $n = 5$ . The same below.

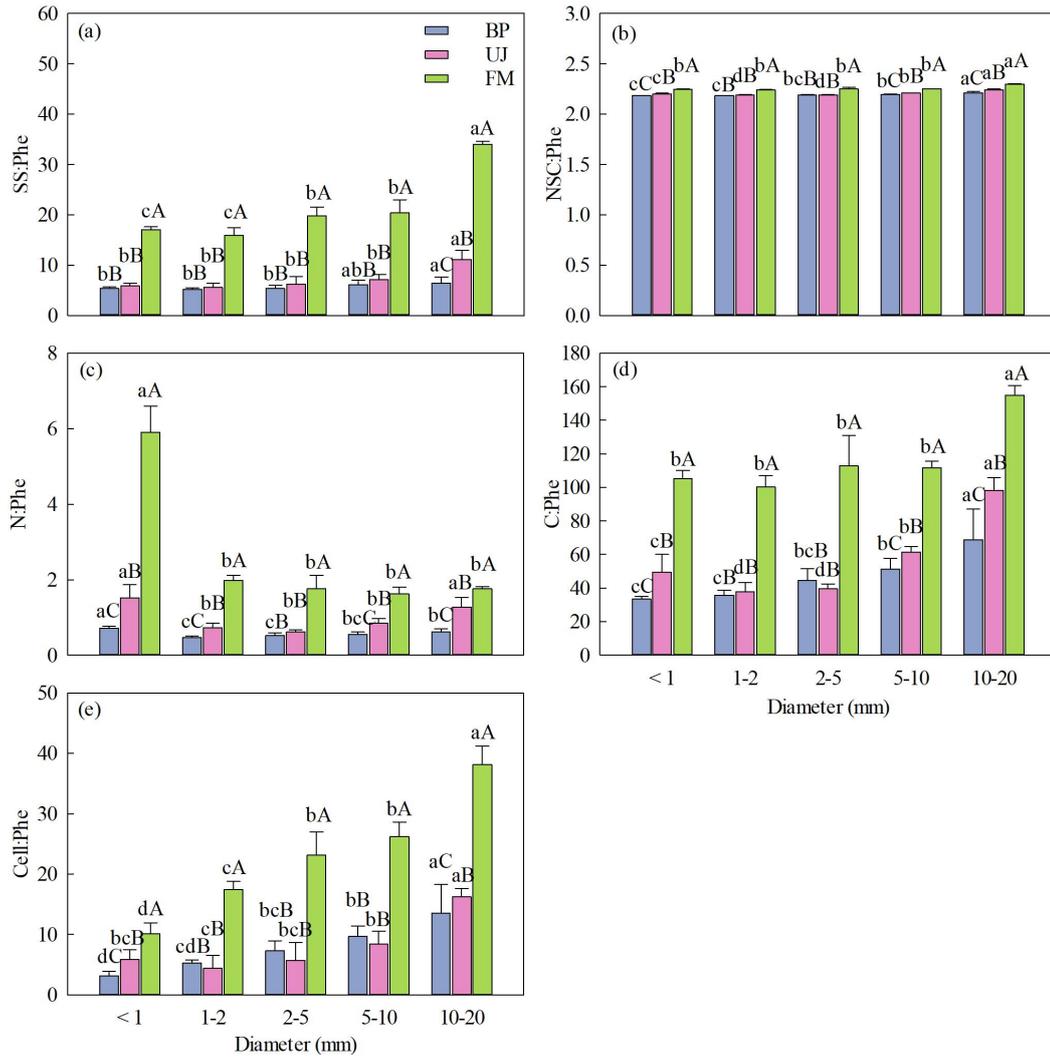


**FIGURE S12** Comparison of initial resistant carbon fractions in roots with different diameters for the three species. BP, *Betula platyphylla*, UJ, *Ulmus davidiana* var. *japonica*, FM, *Fraxinus mandshurica*. Cell, Cellulose; Lign, Lignin; SC, Structural carbohydrates; Phe, Phenolics; RC, Resistant carbohydrates.

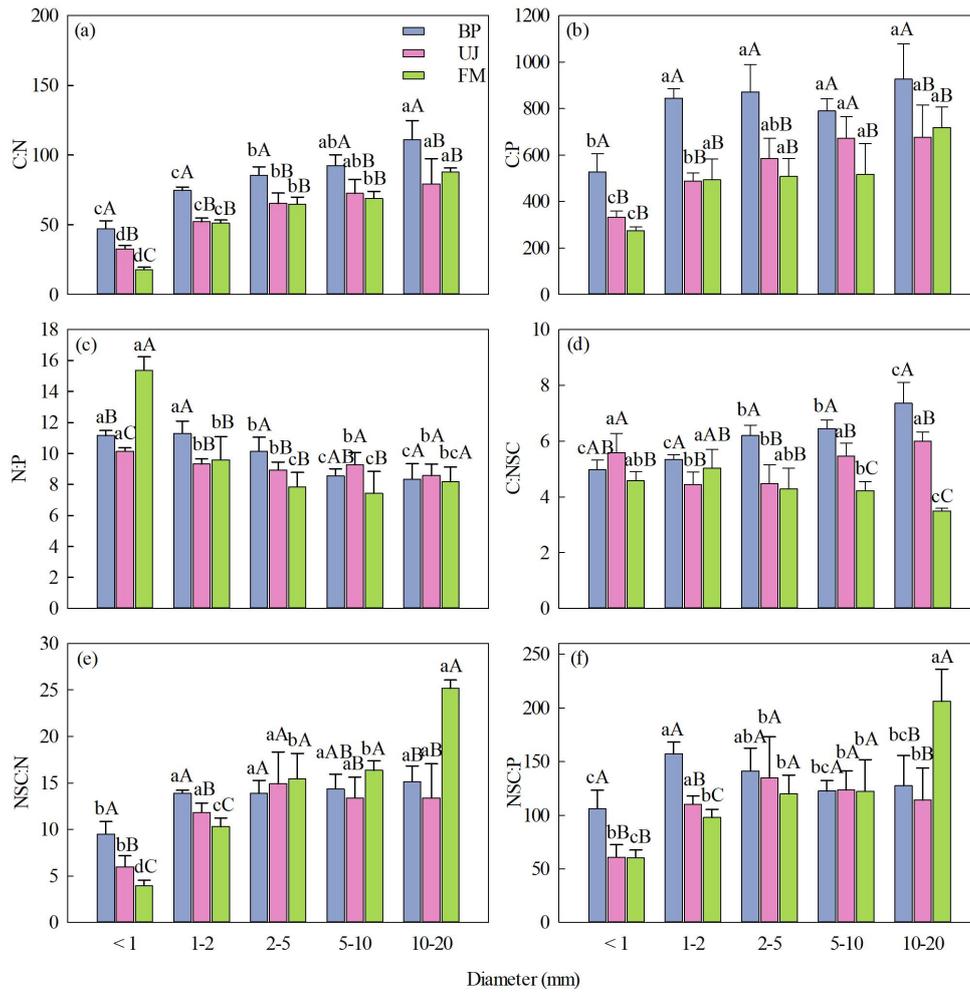


**FIGURE S13** Comparison of initial element concentrations in roots with different diameters for the three species

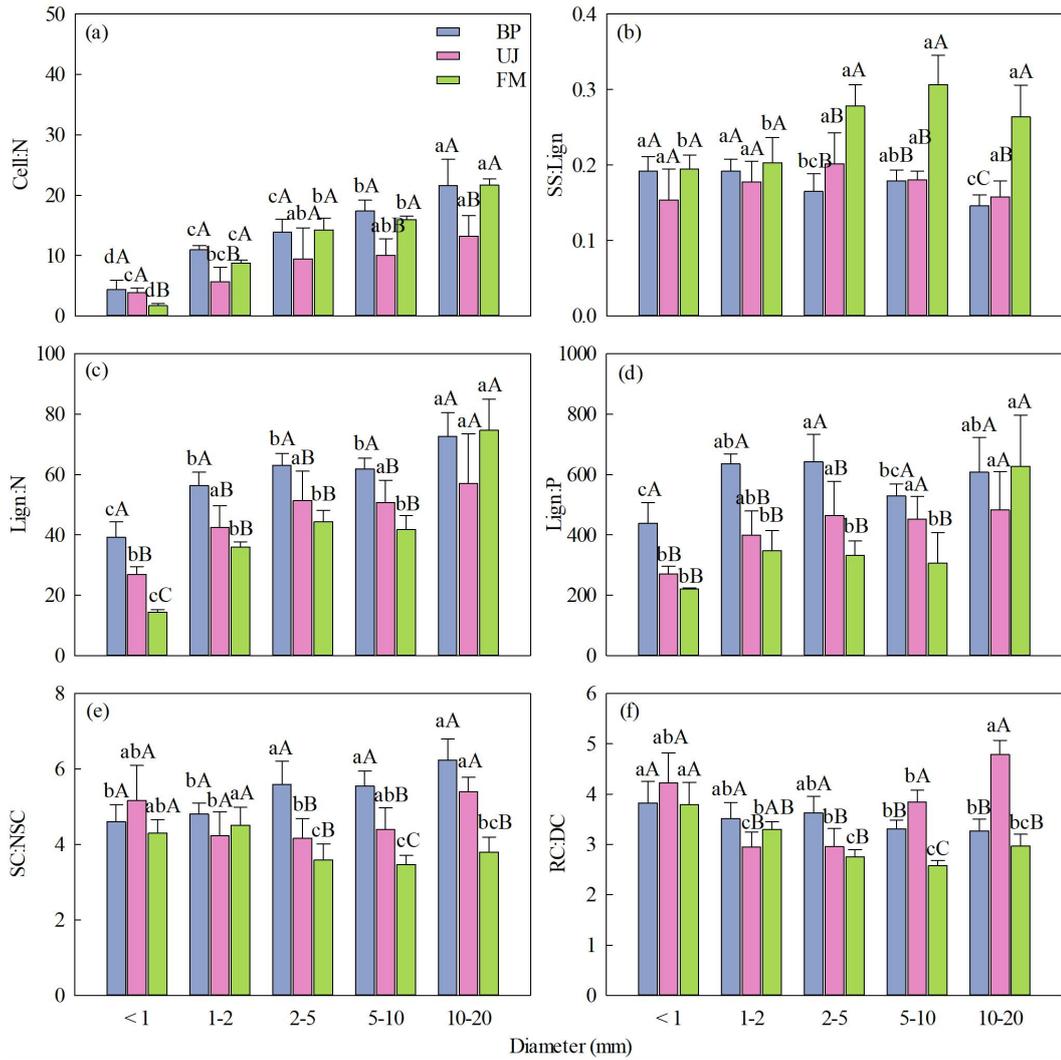
BP, *Betula platyphylla*, UJ, *Ulmus davidiana* var. *japonica*, FM, *Fraxinus mandshurica*. C, Carbon; N, Nitrogen; P, Phosphorus; Ca, Calcium; Mg, Magnesium; Si, Silicon.



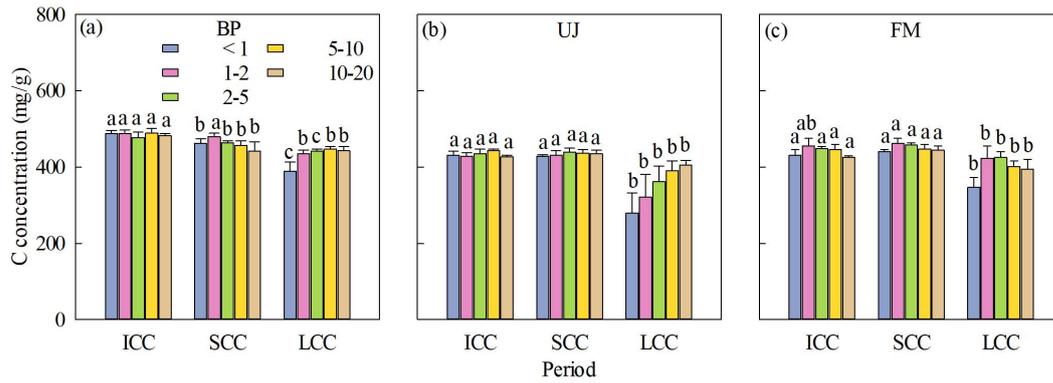
**FIGURE S14** The ratio of initial elements and carbon quality to phenolics. BP, *Betula platyphylla*, UJ, *Ulmus davidiana* var. *japonica*, FM, *Fraxinus mandshurica*. SS, Soluble sugars; NSC, Non-structural carbohydrates; Cell, Cellulose; Phe, Phenolics; C, Carbon; N, Nitrogen.



**FIGURE S15** The ratio between initial carbon, nitrogen, phosphorus, and NSC. BP, *Betula platyphylla*, UJ, *Ulmus davidiana* var. *japonica*, FM, *Fraxinus mandshurica*. NSC, Non-structural carbohydrates; C, Carbon; N, Nitrogen; P, Phosphorus.



**FIGURE S16** The ratio of initial nitrogen, phosphorus, and carbon quality to carbon quality among root diameters of the three species. BP, *Betula platyphylla*, UJ, *Ulmus davidiana* var. *japonica*, FM, *Fraxinus mandshurica*. SS, Soluble sugars; NSC, Non-structural carbohydrates; DC, Decomposable carbohydrates; Cell, Cellulose; Lign, Lignin; SC, Structural carbohydrates; RC, Resistant carbohydrates; N, Nitrogen; P, Phosphorus.



**FIGURE S17** Comparison of carbon concentration in roots with different diameters for the three species at different periods. The change of C concentration in the root decomposition was small, and the change of short-term decomposition C concentration diameter of *Betula platyphylla* and *Fraxinus mandshurica* roots was not significant. BP, *Betula platyphylla*; UJ, *Ulmus davidiana* var. *japonica*; FM, *Fraxinus mandshurica*. ICC, initial carbon concentration; SCC, short-term carbon concentration; LCC, long-term carbon concentration.