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Predicting Fine Root Decomposition from Functional Traits in 10 Temperate Tree Species

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Abstract: Decomposition of plant roots and their related fungal mutualists is a fundamental process of ecosystem material cycles. Despite the fact that fine roots are the dominant source of soil organic carbon (SOC) storage, our understanding of the functional traits controlling fine root decomposition is still far from clear. In the present study, the decomposition of fine roots among four arbuscular mycorrhizal (AM) and six ectomycorrhizal (EM) species was studied in a temperate forest after 570 days of exposure. Our results showed that fine roots among AM species decomposed faster than EM species. Our findings further suggested that initial aluminum (Al) and manganese (Mn) concentrations were the best predictors for decomposition of fine roots among the traits that we measured. Initial cellulose concentration, carbon:nitrogen ratio (C:N), and lignin:N ratio were closely related to decomposition among AM species. In contrast, among EM species, initial phosphorus (P), calcium (Ca), and non–structural carbohydrate (NSC) concentrations were the best predictors of fine root decomposition. The initial concentrations of Na, Fe, NSC, cellulose, and hemicellulose were useful predictors of fine root decomposition across the 10 studied tree species.

Keywords: fine roots; mycorrhizal; litter decomposition; functional traits; temperate forest

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1. Introduction

Litter decomposition in terrestrial ecosystems is an important part of material cycling and nutrient balance [1]. Up to present, more than 5000 articles have been published on plant litter decomposition (Institute of Scientific Information Network) [2]. However, the vast majority of research focuses on the decomposition of leaf litter in the aboveground parts, and there are few studies on the decomposition of fine roots (generally refers to the fine roots of diameter $\leq$ 2 mm) in the underground part [3,4]. Compared with seasonal litter that occurs on the ground, the death and decomposition of fine roots occurs at any time throughout the year, and thus it most probably represents the function of continuously inputting nutrients to the soil. The carbon (C) transported to the soil through fine root decomposition is probably 4–5 times that of aboveground litter decomposition each year in temperate forests [5]. The organic compounds imported from root exudates into rhizosphere soil accounted for 5%–21% of photosynthates [6]. In temperate forests, organic carbon input to the soil from below-ground litter formed by fine root turnover accounted for 14%–87% of the total input, which was 18%–58% greater than the contribution from above–ground litter decomposition [7]. The direct carbon input from fine root decomposition accounted for 30%–60% of the total carbon input to soil [8]. More and more studies have shown that the decomposition of fine roots was the main way for C and nutrients returnning from plant tissues to the soil [9]. In addition, through the decomposition of fine roots, part of the carbon is released into the atmosphere, and a large amount of organic carbon is converted into stable humus and stored in the soil, becoming the main source of soil organic carbon

pool [10]. Fine root decomposition is of great significance for improving the accuracy of global C dynamic models, promoting soil carbon sink function, and predicting future climate change [11]. Therefore, it is extremely important to study the factors that regulate the decomposition of fine roots.

Root substrate, environmental factors, and decomposers triangularly regulated the process of fine root decomposition [12]. Some studies reported that root substrate was the dominant factor regulating fine root decomposition [13,14], which includes N, P, cellulose, and lignin concentrations, and lignin:N ratios. Other studies showed that non–structural carbohydrate and lignin concentrations were the dominant factors controlling fine root decomposition [15,16]. Thus, there is still large uncertainty concerning the functional traits predicting fine root decomposition.

In addition, the mycorrhizal type of tree species is mostly expected to be an important factor regulating root quality and thus decomposition rates. Ninety percent of tree roots in forest ecosystems can form mycorrhiza, which can be classified as arbuscular mycorrhiza (AM) or ectomycorrhizal (EM) [17,18]. The fungal mycelium of the endophytic mycorrhiza penetrates into the root cells and propagates within the cells. Two typical structures of vesicule and arbuscule are generated in plant root cells. Ectomycorrhiza is a fungal mycelium that penetrates between cortical cells to form a mycelium network (Hartig's net). At the same time, mycelial sheath is formed on the root surface. The external morphology and histological structure of the AM are obviously different from that of the EM. These differences can change the chemical composition of the root system. Decomposition of plant roots and their associated fungal symbionts is a major process in ecosystem carbon and nutrient cycling [19–23]. Some studies had reported that arbuscular mycorrhizal and ectomycorrhizal fungi could promote the decomposition of litter or organic matter [24,25], but other studies had obtained the opposite results [26,27]. It has also been shown that EM fungal infection largely inhibited litter decomposition, and AM fungal infection promoted litter decomposition [28–30]. The litter of ectomycorrhizal species usually had higher C:N ratio and higher concentration of secondary compounds that inhibited decomposition than that of endophytic species [31,32]. Therefore, there was insufficient research on the different of mycorrhizal types and root decomposition, and also the respective factors regulating root decomposition of AM species and EM species. More experimental evidence is clearly needed for verifying these patterns between AM and EM species.

To sum up, the existing studies lacked sufficient understanding of the factors regulating fine root decomposition in forests. In this study, we used four AM species and six EM species in a temperate forest in Northeast China. These ten tree species were selected for our experment design, not only based on the criteria of relative abundance, but also of distinct root substrate in C:N ratio, lignin, and other initial chemical composition characteristics. Therefore, we made hypothesis 1 that different mycorrhizal types could regulate the decomposition of fine roots. Hypothesis 2 was that the initial chemical composition was the dominant factor regulating the decomposition of fine roots. Our overall objective for this research is to study the factors regulating fine root decomposition in temperate forests.

2. Materials and Methods

2.1. Site Description

The experimental site was located in Laoshan Artificial Forest Experimental Station (127°29′–127°44′ E, 45°14′–45°29′ N) of Maoershan Experimental Forest Farm of Northeast Forestry University. Maoershan area belongs to the temperate zone, with hot and humid summers and cold and dry winters. Annual precipitation was approximately 723 mm, and mean annual temperature was 2.8 °C. During the experiment, the average monthly temperatures during the day and night were 20.6 °C and 8.7 °C in May 2021, 29.8 °C and 21.2 °C in July 2021, 12.5 °C and–0.5 °C in October 2021, and 19.9 °C and 7.3 °C in May 2022. The zonal soil was mainly dark brown soil. The average forest cover was 95%. The main forest types were *Populus* L., *Betula platyphylla*, *Acer mono*, *Quercus mongolica*, *Ulmus pumila* L., and coniferous plantation dominated by *Pinus koraiensis*, *Larix gmelinii*, and *Pinus sylvestris* var. *mongolica*. The

10 tree species in our experiment are all from Laoshan Artificial Forest Experimental Station of Maoershan Experimental Forest Farm of Northeast Forestry University.

2.2. Experimental Design

In this experiment, the litterbags method was used to study the decomposition of fine roots of 10 common tree species in a temperate forest in Northeast China. The selected tree species included 4 AM tree species (*Acer mono, Juglans mandshurica*, *Fraxinus mandshurica*, *Phellodendron amurense*) and 6 EM species (*Pinus koraiensis*, *Larix gmelinii*, *Betula platyphylla*, *Quercus mongolica*, *Tilia amurensis*, *Ulmus davidiana* var. *Japonica*). The average height of the plantation was 13.40 ± 0.55 m and diameter at breast height was 9.94 ± 0.86 cm at the time of root sampling. Our fine root decomposition experiment was carried out in secondary forest plots.

In September 2020, the invidual sampling tree of each species was first determined. The morphological and structural characteristics of fine roots vary among species. To ensure species identity, we harvested only roots that could be traced back to the stems of each target individual. In the experimental plots, we randomly selected 10 target tree species. Following the trunk to the taproot, we next used a shovel to excavate the soil between the litter layer and the soil depth of 15 cm within a range of 2 m from the main root of the targeted trees. After identifying the fine roots of the target species, we carefully separated the roots from the clods, keeping the fine roots as intact as possible. After removing the soil on the surface of the root system, it was transported back to the laboratory. Separation of fine roots from the soil could damage the original rhizosphere environment, including rhizosphere microorganisms, which might not truly reflect the decomposition of fine roots. We used a vernier caliper to indentify the fine root samples which were less than 2 mm in diameter. All fine root samples were dried in a constant temperature oven at 60 °C to a constant mass. We weighed 3 g of fine root samples and placed them in a nylon mesh bag with a length and width of 15 cm (aperture of 0.2 mm), yielding a total of 10 bags × 4 harvests × 4 plots (n = 4) = 160 bags. Four 20 m × 20 m plots of secondary forest were randomly selected in October 2020. Four repetitive quadrats were arranged in each plot, and each root litterbag for each species was buried in a 10–centimeter–deep soil layer in each quadrate. The distance between each plot was more than 200 m. We marked the exact spot where the bags were buried so we could take root samples. We retrieved litterbags in May, July, and October 2021 and May 2022.

2.3. Data Collection and Root Quality Determination

Fine root samples were milled for chemical composition analysis. The concentrations of NSC in initial samples of fine roots were measured by the high–temperature concentrated sulfuric acid–anthracene method, The contents of copper (Cu), zinc (Zn), sodium (Na), potassium (K), magnesium (Mg), iron (Fe), phosphorus (P), S, Al, Ca, Mn, and other nutrient elements in the initial fine root samples were determined by the iterative closest point (ICP) method. Concentrations of lignin, cellulose, and hemicellulose were measured using Filter Bag Technology (ANKOM 2000i). The total C and N contents of the initial samples of fine roots were determined by elemental analyzer (MACRO cube). Root samples were regularly returned to the laboratory, cleaned, and packed in envelopes. We first dried samples in an oven at 60 °C to a constant mass, and then weighed them in order to obtain the weight of the decomposed dry matter.

2.4. Data Processing and Analysis

Root decomposition was calculated by root mass residue rate, that is, the proportion of root dry mass in the initial dry mass at each harvest time. Root decomposition rate constant (k) was calculated by a negative exponential decay model:

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

where X is the mass residue rate (%) at the decomposition time t (unit: annual), and k is the annual decomposition rate constant. The relationship between k and initial chemical components was analyzed by linear regression with Origin 2021 software. Figures were drawn with Origin 2021 software. All statistical analyses were conducted using SPSS 22 software. An independent–sample t-test was used to analyze significant difference between AM and EM. Differences in initial composition between species were obtained by one–way ANOVA. Pearson's correlation coefficients were used to examine the bivariate correlations between functional traits. We examined species and mycorrhizal interactions using two–way ANOVA. A mixed linear model was used to explain the effects of initial chemical elements on the decay constants of 10 species at different plots.

3. Results

3.1. Initial Chemical Composition of Fine Roots

There were large differences in initial chemical characteristics in fine roots of the studied 10 tree species. There were significant effects among different litter species on almost all initial root chemical composition ($p < 0.001$, Table 1). *Quercus mongolica* had the highest initial C:N ratio and the lowest initial P concentration. The initial Al concentration and initial C:N ratio of the *Phellodendron amurense* were the lowest. The initial P concentration and NSC concentration of *Pinus koraiensis* were the highest, and initial Ca concentration was the lowest. We found that the initial Ca concentration was the highest in *Juglans mandshurica*. In addition, there were significant differences in initial C:N ratio, cellulose, lignin, and lignin:N ratio among different mycorrhizal types, but with no significant differences in other initial chemical components (Table 1). The initial concentrations of Ca, P, K, NSC, and hemicellulose in AM species were generally higher than those in EM species. In contrast, the initial Al concentration, lignin, and cellulose in fine roots of EM species were higher than that of AM species. The C:N ratio and lignin:N ratio of EM species were almost twice that of AM species ($p < 0.05$).

3.2. Decomposition Rate of Fine Roots on Different Mycorrhizal Species

Among the 10 studied temperate tree species, the percentage of mass remaining showed a decreasing trend in 570 days. During the whole experimental period, we found significant difference in the percentage of remaining fine roots between AM and EM species ($p < 0.01$). Decomposition rates of EM species were significantly slower than those of AM species. The average decomposition constants of AM species and EM species were 0.70 and 0.37, respectively (Figure 1). Our results proved that there were significant differences between AM and EM species in decomposition rates of fine roots ($p < 0.05$). AM species decomposed faster than EM species. During the period of decomposition, the fastest decomposing species was *Phellodendron amurense*, which decomposed 73% by the end of the experiment. The slowest decomposing tree species was the *Larix gmelinii*, which decomposed by 31% in the end of the experiment (Figure 1). The interaction between species and mycorrhizal types had a significant effect on the decomposition rate of fine roots ($p = 0.002$) (Table 2).

Table 1. Differences in initial chemical elements under the same mycorrhizal type and significance of differences in initial chemical elements between AM and EM species. (4 arbuscular mycorrhizal (AM) species represent the means of 4 AM species, and 6 ectomycorrhizal (EM) species represent the means of ectomycorrhizal species (means with SE, $n = 3$). We used independent–sample *t*-tests, Duncan's test, homogeneity tests, and descriptive statistics to compose the table. Lowercase letters represent the significance of mycorrhizal types and uppercase letters represent significant differences between species.

Mycorrhiza Type	**AM Specie**	**AM Specie**	**AM Specie**	**AM Specie**	**EM Specie**	**EM Specie**	**EM Specie**	**EM Specie**	**EM Specie**	**EM Specie**	**AM Species**	**EM Species**
Root type	*Phellodendron amurense*	*Juglans mandshurica*	*Fraxinus mandshurica*	*Acer mono*	*Pinus koraiensis*	*Larix gmelinii*	*Betula platyphylla*	*Ulmus davidiana* var. *japonica*	*Tilia amurensis*	*Quercus mongolica*	4 AM specles	6 EM specles
P	1.23(0.06)aC	1.00(0.05)bD	1.25(0.06)aC	0.88(0.04)cE	1.79(0.09)aA	0.75(0.04)cF	0.83(0.04)cEF	1.48(0.07)bB	0.60(0.03)dG	0.50(0.03)dG	1.09(0.05)	0.99(0.05)
K	1.13(0.06)aA	0.48(0.02)cD	1.18(0.06)aA	0.69(0.03)bC	0.64(0.03)bC	0.31(0.02)deEF	0.27(0.01)eF	1.07(0.05)aB	0.44(0.02)cD	0.36(0.02)dE	0.87(0.04)	0.52(0.03)
Ca	9.06(0.45)cC	12.53(0.63)aA	7.54(0.38)dD	10.58(0.53)bB	4.83(0.24)dE	7.52(0.38)cD	9.12(0.46)abC	8.84(0.44)bC	9.30(0.47)abC	9.67(0.48)aC	9.93(0.50)	8.21(0.41)
Al	1.16(0.06)dF	1.47(0.07)cE	1.72(0.09)bD	2.17(0.11)aC	1.35(0.07) dE	2.53(0.13)bB	1.66(0.08)cD	1.72(0.09)cD	3.56(0.18)aA	1.31(0.07)dEF	1.63(0.08)	2.02(0.10)
Fe	0.95(0.05)cG	1.32(0.07)bDE	1.24(0.06)bEF	1.75(0.09)aC	1.15(0.06)dF	2.06(0.10)bB	1.43(0.07)cD	1.44(0.07)cD	2.72(0.14)aA	0.82(0.04)eG	1.32(0.07)	1.60(0.08)
Mg	1.33(0.07)bcCDE	1.23(0.06)cE	1.85(0.09)aA	1.45(0.07)bC	1.25(0.06)dDE	0.98(0.05)eF	0.99(0.05)eF	1.65(0.08)bB	1.96(0.10)aA	1.37(0.07)cCD	1.47(0.07)	1.37(0.07)
Mn	0.10(0.01)dF	0.12(0.01)cDE	0.17(0.01)aA	0.15(0.01)bB	0.10(0.01)cF	0.09(0.00)dG	0.12(0.01)bE	0.14(0.01)aBC	0.13(0.01)aCD	0.10(0.00)cdFG	0.14(0.01)	0.11(0.01)
Na	0.48(0.02)cDE	0.64(0.03)bB	0.70(0.04)aA	0.49(0.02)cD	0.41(0.02)dF	0.43(0.02)cdEF	0.47(0.02)bcDE	0.50(0.02)bD	0.54(0.03)aC	0.42(0.02)dF	0.58(0.03)	0.46(0.02)
S	0.14(0.01)aA	0.09(0.00)cC	0.13(0.01)aB	0.09(0.00)cC	0.09(0.00)aC	0.07(0.00)bD	0.08(0.00)bD	0.07(0.00)bD	0.07(0.00)bD	0.06(0.00)cE	0.11(0.01)a	0.07(0.00)b
Zn	0.07(0.00)cE	0.08(0.00)bC	0.10(0.00)aB	0.04(0.00)dFG	0.04(0.00)cF	0.03(0.00)eH	0.12(0.01)aA	0.08(0.00)bD	0.03(0.00)dG	0.02(0.00)eH	0.07(0.00)	0.05(0.00)
NSC (mg/g)	58.56(1.70)bD	81.33(0.99)aB	63.65(1.88)bC	42.56(1.03)cG	86.70(0.11)aA	51.26(0.69)bEF	49.71(1.46)bcEF	47.62(0.66)cF	52.28(0.20)bE	48.97(1.37)bcEF	61.53(1.40)	56.09(0.75)
Lignin (%)	23.27(0.30)bE	15.05(0.96)cF	22.83(0.11)bE	27.11(0.11)aCD	25.25(0.24)cDE	31.62(0.87)bB	26.15(1.56)cCD	28.14(0.44)cC	35.26(0.79)aA	27.89(0.72)cC	22.07(0.37)b	29.05(0.77)a
Cellulose (%)	16.67(1.12)bcC	14.85(0.00)cC	17.22(0.24)bC	21.08(0.04)aB	21.62(0.12)abAB	23.37(0.04)abAB	20.64(0.52)bB	22.53(0.67)abAB	22.17(0.22)abAB	24.31(2.04)aA	17.46(0.35)b	22.44(0.60)a
Hemicellulose (%)	18.94(2.02)aB	10.6(0.56)cE	14.92(0.24)abC	11.67(0.20)bcDE	6.95(0.04)eF	6.51(0.05)eF	11.35(0.00)cE	25.68(0.27)aA	10.02(0.06)dE	13.76(0.56)bCD	14.03(0.76)	12.38(0.16)
C:N	21.60(1.08)bG	26.28(1.31)bFG	26.91(1.35)bFG	38.06(1.90)aDE	52.36(2.62)cdC	59.26(2.96)bcBC	43.65(2.18)dD	31.83(1.59)eEF	65.53(3.28)abAB	71.29(3.56)aA	28.21(1.41)b	53.99(2.70)a
Lignin:N	10.53(0.53)bcE	8.50(0.43)cE	13.12(0.66)bE	22.4(1.12)aD	27.45(1.37)cC	39.53(1.98)bB	24.21(1.21)cdCD	20.84(1.04)dD	49.66(2.48)aA	39.84(1.99)bB	13.64(0.69)b	33.59(1.68)a

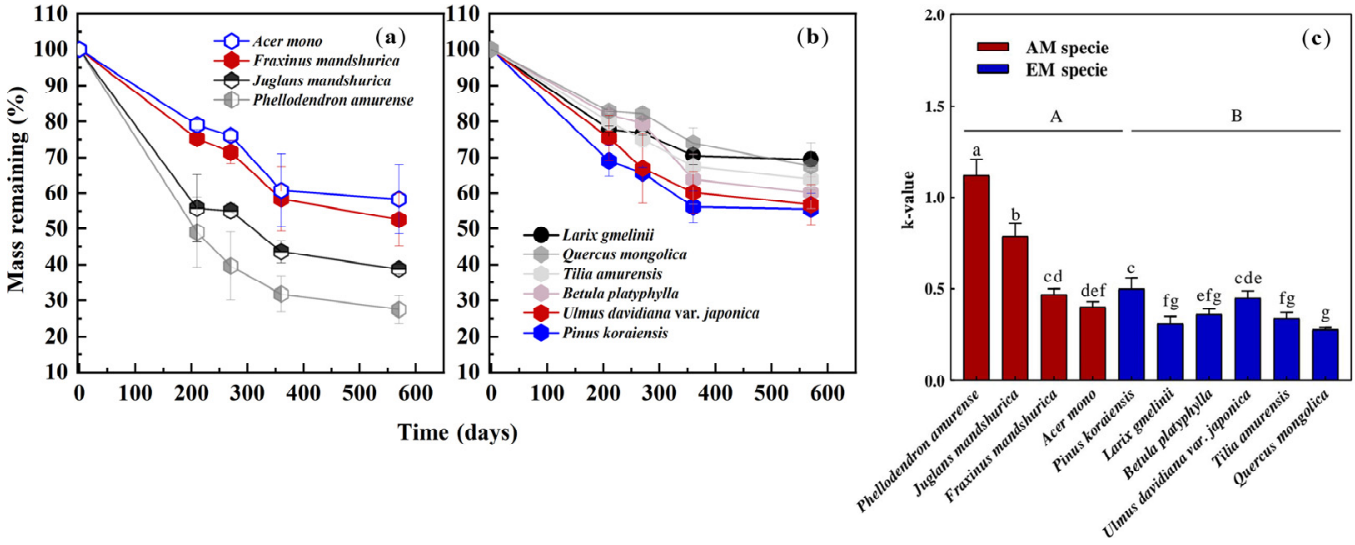

Figure 1. Initial mass remaining in different mycorrhiza types of 4 arbuscular mycorrhizal (AM) species (**a**) and 6 ectomycorrhizal (EM) species (**b**) within litterbags, during 570 days of decomposition. Error bars represent mean ± SE. Decay constants (*k*-value, means with SE) between AM and EM species are shown in (**c**).

Table 2. Results of two–way ANOVAs on the effects of tree species, mycorrhiza types, and their interactions on decay rates of fine roots in 570 days. D.f., degrees of freedom.

Source of Variation	Decay Period (Days)			
	210	**270**	**360**	**570**
Species	<0.001	<0.001	<0.001	<0.001
Mycorrhiza	0.072	0.093	0.029	0.020
Species × Mycorrhiza	0.002	0.002	0.002	0.002

3.3. Relationship between Fine Roots Decomposition Rates and Initial Chemical Composition

k–values were significantly and negatively correlated with initial concentrations of Al (r^2 = 0.871), Mn (r^2 = 0.862), Fe (r^2 = 0.659), Mg (r^2 = 0.361), cellulose (r^2 = 0.379), C:N ratio (r^2 = 0.657), and lignin:N ratio (r^2 = 0.494) in AM species (Figure 2). *k*–values were positively correlated with initial hemicellulose (r^2 = 0.369).

Initial P (r^2 = 0.949), S (r^2 = 0.580), and NSC (r^2 = 0.476) concentrations were significantly and positively correlated with the *k*–values of EM species (Figure 2). The experimental results showed that the *k*–values were consistent with the trend of the initial concentrations of P, S, and NSC. That is, the higher initial concentrations of P, S, and NSC, the faster decomposition of EM species. In contrast, the initial Ca concentration (r^2 = 0.459), C:N ratio (r^2 = 0.441), and lignin:N ratio (r^2 = 0.438) were significantly and negatively correlated with the *k*–values. As shown by data, initial P concentration showed the tightest (positive) correlation with EM species decomposition rates among all of the traits measured (Figure 2). The decomposition rate among all studied species has a very significant correlation with the initial concentrations of Na, Fe, NSC, cellulose, and hemicellulose (Table 3).

Table 3. Linear mixed models (LMMs) used to explain the effects of initial chemical elements on the decay constants of 10 species at different plots.

Initial Chemical Parameters	d.f.	*p*
Ca	32	0.384
Na	32	0.000 ***
Fe	32	0.007 **
NSC	32	0.023 *
C:N	32	0.400
Cellulose	32	0.000 ***
Hemicellulose	32	0.000 ***

Signif. codes: 0 '***', 0.01 '**', 0.05 '*'. R^2 = 0.839 (R^2 represents the correlation of the initial element on the decay constants).

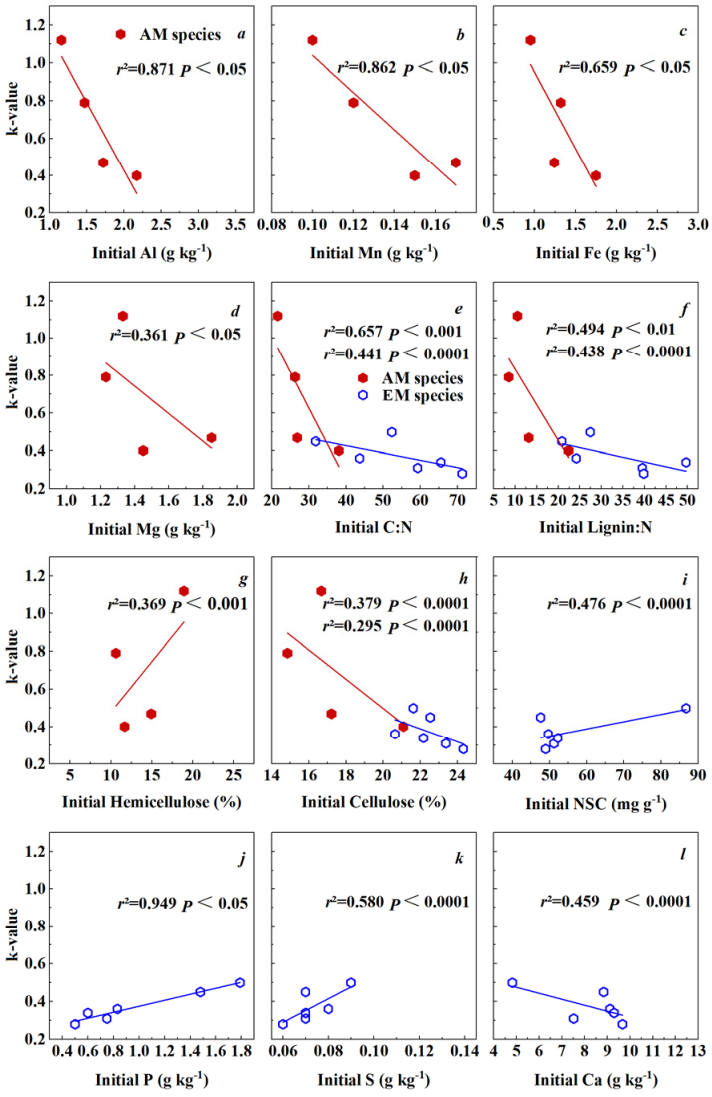

Figure 2. (**a**–**l**) Regression relationship between decay constants (*k*–value) and initial aluminum (Al), manganese (Mn), iron (Fe), magnesium (Mg), carbon:nitrogen ratio (C:N) ratio, phosphorus (P), calcium (Ca), non–structural carbohydrate (NSC), and sulphur (S) concentrations in 4 AM and 6 EM species. The linear relationship between the initial element and AM species is shown by the red line. The linear relationship between the initial element and the EM species is shown by the blue line. The *r* in the subfigures represents the correlation coefficient and *p* stands for correlation significant on layer 0.1, 0.01, 0.001 and 0.0001.

4. Discussion

4.1. Factors Controlling Fine Root Decomposition Rates

Understanding fine root decomposition might improve our predictions of underground processes and terrestrial biosphere models [33,34]. In this study, there were significant differences in the decomposition rate of fine roots between species. C–and nutrient–related traits had substantial contributions to predicting decomposition of fine roots (Table 3), which was consistent with the recent studies in which substrate chemistry was the leading factor of root decomposition [35–37]. Our data showed that the initial concentrations of Na, Fe, NSC, cellulose, and hemicellulose were the main factors regulating decomposition of fine roots. Cellulose and hemicellulose were one of the C components in root which are abundant and difficult to decompose. How fast it degrades controls the whole process of root decomposition [38]. In addition, microorganisms used the energy substance NSC in roots to influence decomposition. Therefore, NSC affected the decomposition rate of fine roots [39].

4.2. Effects of Different Mycorrhizal Types on Decomposition

Mycorrhizal types were critical factors in predicting litter quality and decomposition. AM and EM fungi inhibited or hindered the decomposition of fine roots by altering their physical structure and chemical properties [40,41]. AM and EM species had huge differences in morphological structure and chemical properties (such as nutrient acquisition methods, mycelial turnover rate, and so on), and differences in the chemical properties of AM and EM litter led to diverse decomposition rates. EM species rely on their own carrion or fast–growing mycelia to release a large number of enzymes or organic acids to affect fine root decomposition [42,43]. Studies have shown that, by competing for the same nutrient resources, mycorrhizal fungi affect the activity of saprophytes and indirectly regulate the decomposition rate of litters [44]. There were significant differences in nutrient utilization characteristics between AM and EM fungi [45]. Our experimental data showed that there were significant differences in the decomposition rates of different mycorrhizal types of roots. Compared with EM litters, many AM litters usually had lower initial C:N ratio, lignin:N ratio, and higher decomposition rates, which is in line with published studies [46,47].

Our experimental data interestingly showed that, when the AM and EM species were not distinguished, initial chemical components had no significant effect on the *k*–values of fine roots (Table 3). However, when they were distinguished, these initial chemical components had a significant effect on the *k*–values (Figure 2), which was further demonstrated in that mycorrhizal types had a significant effect on decomposition of fine roots. In addition, mycorrhizal fungal hyphae could combine with metals to limit their migration to the aboveground plant parts, achieving the purpose of protecting plants from metal poisoning [48], especially the complexation with the element Mn. Variation in Mn concentration played a key role in regulating manganese peroxidase activity, which effected litter decomposition of refractory components [49,50]. There was a negative correlation between Mn concentration and easily extractable glomalin in the rhizosphere soil, which was closely related to the ability of the easily extractable glomalin to adsorb, complex, and chelate Mn ions [51]. Compared with EM species, the cell walls of AM mycelia and spores were rich in chitin, wall acids, and globomycin, which could adsorb, complex, precipitate, and strand a large number of metals [52,53]. There was no correlation between initial Mn concentration and any element in AM species (Table 4). Lignin is one of the components that make up the cell wall of woody plants. Lignin had a complex network structure that allowed a small number of microorganisms to produce the enzymes necessary to decompose it [54,55]. Lignin–degrading compounds are attacked by specific microorganisms. The aromatic structure is opened by multiple degradation [56–58]. Decomposition rate was controlled by lignin through physical method interfered with decay of other cell wall sections, as well as through its resistanced to enzymatic attack. There was a negative linear correlation between decomposition constant (*k*–values) of fine roots and initial C:N ratio (Figure 2), that is, the decomposition of fine roots was slower with increasing initial C:N ratio. In our experiment,

initial C:N ratio was an important indicator reflecting the substrates quality of fine roots. As the initial C:N ratio increases, the quality of the substrates became lower. In addition, C:N ratio was positively correlated with Al and Fe. The *k*–value had a higher correlation with the initial Al concentration. That is to say, initial Fe and Al concentration and C:N ratio affected the decomposition of fine roots. Initial Al concentration is the main regulator of fine root decomposition (Table 4). Our experiment also had shortcomings. Root separation from the soil could disrupt the original soil environment, which could affect the decomposition process. In the present study, initial Ca concentration significantly correlated with *k*–values of EM species, which was consistent with the general conclusion that initial Ca concentration was believed to limit root decomposition at the global scale [43,59]. EM fungi were able to form mycorrhizal sheaths and wrapped around root tips to form mycelium. EM species contained large amounts of organic acids, especially oxalates, which helped to obtain certain nutrients, such as Ca. The secretion of oxalate enabled Ca fixation in calcium oxalate crystals, which could prevent grazing in fungal–eating animals [33,60,61]. Therefore, decomposition of fine root in EM species had a strong relationship with initial Ca concentration. It not only provided the necessary nutrients for microbial growth, but could also be utilized by heterotrophic bacteria and fungi to form oxalate [62,63]. Therefore, initial Ca concentration has an effect on the decomposition rate of fine roots in EM species. In addition, there was a significant negative correlation between Ca and NSC. Ca and NSC may jointly regulate fine root decomposition in EM species (Table 5).

Table 4. Analysis of Pearson correlation coefficient between elements of AM species.

Root Traits	*k*–Value	Al	Ca	Fe	K	Mg	Mn	Na	P	S	Zn	Lignin	Hemicellulose	Cellulose	NSC	C:N	Lignin:N
k–value	1																
Al	−0.933	1															
Ca	0.106	0.047	1														
Fe	−0.812	0.942	0.374	1													
K	0.168	−0.296	**−0.962** *	−0.587	1												
Mg	−0.601	0.367	−0.818	0.047	0.643	1											
Mn	−0.928	0.756	−0.414	0.538	0.154	0.848	1										
Na	−0.343	−0.003	−0.146	−0.104	0.036	0.525	0.533	1									
P	0.431	−0.652	−0.759	−0.867	0.863	0.456	−0.065	0.315	1								
S	0.470	−0.591	−0.825	−0.814	0.945	0.403	−0.143	0.003	0.943	1							
Zn	0.123	−0.472	−0.407	−0.615	0.423	0.473	0.193	0.842	0.755	0.494	1						
Lignin	−0.362	0.517	−0.551	0.331	0.460	0.413	0.351	−0.543	−0.050	0.228	−0.524	1					
Hemicellulose	0.607	−0.615	−0.702	−0.780	0.864	0.170	−0.356	−0.306	0.806	0.949	0.224	0.329	1				
Cellulose	−0.615	0.812	−0.189	0.719	0.032	0.268	0.461	−0.501	−0.476	−0.235	−0.722	0.892	−0.125	1			
NSC	0.363	−0.578	0.359	−0.456	−0.271	−0.242	−0.271	0.656	0.246	−0.050	0.694	**−0.976** *	−0.199	−0.944	1		
C:N	−0.811	**0.965** *	0.229	**0.980** *	−0.441	0.123	0.557	−0.216	−0.803	−0.695	−0.676	0.512	−0.640	0.843	−0.622	1	
Lignin:N	−0.703	0.887	−0.095	0.814	−0.086	0.259	0.522	−0.420	−0.571	−0.363	−0.716	0.817	−0.272	**0.988** *	−0.883	0.913	1

* Correlation significant on layer 0.05 (double-tailed). This is shown in bold in the table.

Table 5. Analysis of Pearson correlation coefficient between elements of EM species.

Root Traits	*k*–Value	Al	Ca	Fe	K	Mg	Mn	Na	P	S	Zn	Lignin	Hemicellulose	Cellulose	NSC	C:N	Lignin:N
k–value	1																
Al	−0.326	1															
Ca	−0.678	0.258	1														
Fe	−0.210	**0.982** **	0.166	1													
K	0.716	−0.207	−0.169	−0.156	1												
Mg	0.101	0.503	0.330	0.424	0.465	1											
Mn	0.292	0.254	0.464	0.282	0.576	0.675	1										
Na	−0.020	0.691	0.545	0.695	0.257	0.736	**0.868** *	1									
P	**0.974** **	−0.441	−0.745	−0.324	0.720	−0.034	0.136	−0.198	1								
S	0.761	−0.221	−0.781	−0.084	0.103	−0.309	−0.066	−0.202	0.717	1							
Zn	0.294	−0.279	0.183	−0.154	0.145	−0.281	0.507	0.259	0.225	0.366	1						
Lignin	−0.487	**0.952** **	0.381	**0.890** *	−0.191	0.551	0.179	0.616	−0.563	−0.483	−0.458	1					
Hemicellulose	0.223	−0.246	0.457	−0.246	0.762	0.418	0.719	0.402	0.217	−0.364	0.368	−0.150	1				
Cellulose	−0.543	−0.018	0.255	−0.152	−0.037	0.115	−0.392	−0.295	−0.404	−0.795	−0.735	0.281	0.115	1			
NSC	0.690	−0.288	**−0.920** **	−0.238	0.135	−0.138	−0.359	−0.469	0.700	0.795	−0.212	−0.417	−0.459	−0.320	1		
C:N	−0.664	0.309	0.124	0.159	−0.664	0.096	−0.558	−0.224	−0.653	−0.411	−0.788	0.445	−0.602	0.553	0.010	1	
Lignin:N	−0.662	0.713	0.265	0.585	−0.532	0.369	−0.251	0.197	−0.704	−0.485	−0.742	**0.814** *	−0.485	0.467	−0.184	**0.880** *	1

** Correlation significant on layer 0.01 (double–tailed) and * correlation significant on layer 0.05 (double–tailed) in bold font.

5. Conclusions

Our experimental data suggested that the initial concentrations of Na, Fe, NSC, cellulose, and hemicellulose were the best predictors of fine root decomposition. In addition, our research showed that roots of AM species decompose faster than those of EM species. The initial chemical composition controlling decomposition was also different between AM and EM species. Our findings further suggested that initial Al and Mn concentrations were the best predictors for decomposition of fine roots among the traits that we measured in AM species. Initial cellulose, C:N ratio, and lignin:N ratio were the next–best predictors for decomposition of AM species. In EM species, initial P concentration was the best predictor for decomposition of fine root. Initial concentrations of Ca and NSC were the next–best predictors for decomposition of fine roots in EM species. The novelty of the results of this study is important for both improving predictions of the forest carbon cycle and understanding plant–soil feedback.

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