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Original Research

Effects of Plant and Tree Roots Decomposition on Soil Nutrients in an Abandoned Pyrite Mining Area in China

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Abstract

The study aims to explore the effect of fine root decomposition on soil nutrients in pyrite mining areas and provide a basis for plant selection in the vegetation restoration process in mines. With the decomposition bag method, the root decomposition characteristics of three typical plants (*Castanea mollissima* (*C. mollissima*), *Betula luminifera* (*B. luminifera*) and *Symplocos tetragona* (*S. tetragona*)) in Guizhou Dafang Pyrite Mining Area and their effects on soil nutrients. The loss rates of fine root decomposition of the three plants decreased according to the following order: *S. tetragona*> *B. luminifera*>*C. mollissima*. After a year of decomposition, the mass loss rates of the three plants were respectively 76.00%, 66.28% and 59.36%. Among the three plants, *S. tetragona* had the faster rate of fine root decomposition. Organic carbon presented a significant positive correlation with total nitrogen and nitrate nitrogen ($P<0.05$). Root activities of *S. tetragona* and *C. mollissima* could increase nitrate nitrogen content. Therefore, in abandoned mining areas with a single nutrient source, the plant configuration of *S. tetragona* and *C. mollissima* as well as some native herbaceous plants (such as *Lolium perenne* L., *Cynodondactylon* (Linn.) Pers. and *Agrostisstolonifera* Roth.) are more conducive to the accumulation of nutrients and ecological restoration. At the same time, heavy metal elements in soil may affect nutrient changes during fine root decomposition.

Keywords: fine root decomposition, soil nutrients, mining recovery, abandoned mine-nutrients

Introduction

As an important nutrient organ of plants, the root system can absorb water and nutrients and enter the environment of plant decomposition after its apoptosis. Therefore, the root system plays an important role in plant functions and nutrient cycling. The death and decomposition of roots occur at any time throughout a year, so it can continuously input nutrients into soils and constitute an important part of the biogeochemical cycle [1-3]. Root exudation, death, and shedding are also important sources for replenishing the soil carbon pool [4]. Root decomposition becomes the main source of underground nutrients and organic matters. After root decomposition, a large amounts of organic matter and nutrients enter soils and play an important role in restoring and increasing soil fertility, improving forest productivity and maintaining the sustainable

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development of forest ecosystems. Plant roots are of great significance to the accumulation of soil organic carbon and global carbon cycle [5]. Roots can effectively improve soil structures and stabilize organic carbon in soils through interpenetration, entanglement, and cementation [6]. Root decomposition rate is mainly affected by rhizosphere environment and chemical composition of roots [7-8]. Root nutrient return is also an important source of the soil nutrient pool and can reveal the relationship between fine root decomposition and soil environment.

Roots interact with soils and promotes the formation of soil organic carbon. Existing studies on root decomposition mainly focus on root decomposition rate and nutrient release. The relationship between root decomposition and soil nutrients was seldom explored. In particular, the relationship between nutrient release in root decomposition and soil nutrients in mines was not reported. Due to serious heavy metal pollution, low fertility, poor substrate structure, low vegetation coverage, difficulty in vegetation restoration, and degradation of ecosystem functions, the ecological environment in mines is seriously threatened. The heavy metals in fine vegetative roots were bioaccumulation. At the same time, heavy metals can adversely affect the growth of fine roots. There were significant differences in nutrient contents of soils polluted by heavy metals [9]. The quantity of root decomposition in the ecological restoration in mines directly affects the formation of organic carbon, soil nutrient accumulation, soil fertility and productivity.

Therefore, in order to more accurately estimate the influence of plant root decomposition on soil nutrients in mines, with Guizhou Pyrite Mine Area as the study area, root decomposition of dominant plants in Dongguan Mining Area, Yingjiao Mining Area, and Qingsong Mining Area was explored to discuss the characteristics of root decomposition and its influence on soil nutrients in the mine. The study is of great significance to the accumulation of soil nutrients in mines and provides the basis for developing mine ecosystem management measures and species restoration.

Materials and Methods

Study Area

The study area is located in the central part of Dafang County of Bijie City, Guizhou Province, China (E105°15′47″-106°08′04″, N26°50′02″-27°36′04″). Land resources in the study area are mainly mountains, slopes and hills. It is located in a high-altitude and low-latitude area with a humid monsoon climate in northern subtropics. The climate parameters in the study area are provided as follows: altitude of 1,400 m, annual average temperature of 11.8ºC, annual average rainfall of 1150.4 mm, and annual sunshine hours of 1335.5 h. Dafang County is characterized by mild climate, sufficient rainfall, and abundant mineral resources in a wide area.

Fig. 1. Study area habitat.

The pyrite mine in the study area has been abandoned for a long time, so most of pyrite residues has entered soils and the surrounding plant habitat has been seriously damaged. In this study, the dominant plants in Dongguan, Yingjiao and Qingsong in the study area, and different soil characteristics are shown in Table 1; *Castanea mollissima* (*C. mollissima*), *Betula luminifera* (*B. luminifera*) and *Symplocos tetragona* (*S. tetragona*), were selected to explore the influences of fine root decomposition on soil nutrients (Table 2).

Materials

From May 2018 to April 2019, the dominant species (*C. mollissima*, *B. luminifera*, and *S. tetragona*) were selected. For each species, 3 plants with the similar growth status was selected and then four sampling points were randomly arranged below the canopy width of each plant. Then, soil samples were drilled to acquire the fine roots around each plant according to the following method. At each sampling point, in the depth of 0 to 15 cm, fine roots were obtained, soaked in water for 12 h, and cleaned with a sieve with a pore diameter of 0.4 mm in water. The obtained fine roots (diameter≤2 mm) were selected according to the characteristics of the shape, color, and smell, rinsed with clean water, and finally dried at 85ºC to constant weight.

Experimental Design

The experiments of fine root decomposition were performed in a plot of 10 m×10 m in each mining area. In the plot, root decomposition ditches (5 m×10 cm ×20 cm) were dug with the interval of 1 m. Three decomposition ditches were arranged for each species and an additional decomposition ditch without fine root decomposition bag was arranged as a control. Fine roots with a diameter ≤2 mm were into 2-cm long root segments with scissors. Then, 30 g of root segments

Table 1. Different soil characteristics (n = 5).

Sample name	pH	Soil bulk density (g/cm^3)	Soil organic- atter (g/kg)	Total S (mg/kg)	Total Fe (mg/kg)	Total Pb (mg/kg)	Total Zn (mg/kg)
DG	4.32	1.94	22.3	575.3	90.4	108.3	3854.6
YJ	4.24	1.98	27.4	581.7	117.3	236.1	4315.7
QS	4.43	2.04	20.7	517.4	96.7	216.3	4132.6

Data are provided in the form of mean±standard deviation (SD). DG is the abbreviation for the sample site Dongguan, YJ is the abbreviation for the sample site Yingjiao, QS is the abbreviation for the sample site Qingsong.

Table 2. Basic condition of the sample (n = 10).

Sample name	Typical plant	Planting age (years)	Tree height (m)	DBH (cm)	Altitude (m)
DG	*Castanea mollissima*	20	7.3±0.63a	11.5±1.53a	1641
YJ	*Betula luminifera*	16	5.2±0.42a	5.5±0.37c	1742
QS	*Symplocos tetragona*	15	2.5±0.06b	8.7±0.65b	1736

Data are provided in the form of mean±standard deviation (SD). DG is the abbreviation for the sample site Dongguan, YJ is the abbreviation for the sample site Yingjiao, QS is the abbreviation for the sample site Qingsong; DBH, diameter at breast height or basal. Different small letters in each column indicate the significant difference among height and DBH of the tree (Duncan's post-ANOVA, p<0.05).

were added into a decomposition bag. For each species, 180 decomposition bags were arranged. Firstly, 30 g of roots were mixed with soil thoroughly, put into a nylon decomposition bag with a size of 15 cm×15 cm (the hole diameter of the bag is about 200-mesh) and sealed. Then, the bags containing mixed samples were randomly buried in ditches in such a way that roots in decomposition bags were evenly spread. Root samples were acquired after certain decomposition time and used to measure the decomposition rate and the amount of plant residues. In the middle of each month of the period from May 2018 to April 2019, 5 root samples of each species were taken back to the laboratory. Then the collected fine root samples were cleaned indoors with distilled water and dried to constant weight. One part of each dried sample was used to calculate the dry matter loss of fine roots after decomposition. The other part was crushed and passed through a sieve with the mesh size of 2 mm. The soil layer (0~15 cm deep) covering fine roots was drilled to obtain 150 g of soil samples. One part of each soil sample was immediately stored in a refrigerator at -20ºC and the other part was air-dried and passed a sieve with the mesh size of 0.15 mm.

Determination of Chemical Indicators

Organic carbon, total nitrogen, total phosphorus and other indicators in soils and plants were determined according to the methods in Soil Agrochemical Analysis. Organic carbon of roots was determined with $K_2Cr_2O_7$ method. Total nitrogen of roots was determined with H_2SO_4-H_2O_2 digestion method. Total phosphorus of roots was determined with vanadium-molybdenum-yellow colorimetric method. Soil organic carbon was determined with $K_2Cr_2O_7$ external heating method, and the use of elemental absorption spectroscopy to determine iron, lead and zinc in soils.

Data Processing

The mass loss rate and residual rate of fine roots are respectively calculated as follows [10]:

$$R = (X_0 - X_t)/X_0, \tag{1}$$

$$Y = X_t/X_0, \tag{2}$$

where R is the mass loss rate; Y is the residual rate; X_0 is the initial mass of fine roots; X_t is the mass of fine roots after a period of decomposition.

The change in the residual rate of dry matters during the decomposition process is described with an exponential decay model:

$$\ln(X_t/X_0) = -kt, \tag{3}$$

where k is the decomposition rate constant; t is decomposition time. According to the half-life and turnover period, we get:

$$t_{0.5} = \ln 0.5/(-k), \tag{4}$$

$$t_{0.95} = \ln 0.05/(-k), \tag{5}$$

where $t_{0.5}$ is the time required to decompose 50% of fine roots; $t_{0.95}$ is the time required to decompose 95% of fine roots. All data were sorted in Microsoft Excel 2010 and Origin Pro 9.0 was used for plotting. With the One-way

Table 3. Initial chemical properties of roots (n = 10).

Typical plant	Initial mass /g	C /(g /kg)	N/(g/kg)	P /(g /kg)	C /N	C /P	N /P
Castanea mollissima	30	681.59±6.24b	14.33±1.35b	1.03±0.25b	47.56b	661.73b	13.91b
Betula luminifera	30	771.06±5.49a	13.11±1.58b	1.88±0.41a	58.81a	410.14c	6.97c
Symplocos tetragon	30	810.81±8.38a	18.37±1.87a	1.09±0.53b	44.13b	743.86a	16.85a

Values suffixed with different letters meant significant difference in each column, while the same letters in the same column showed less difference (Duncan's post-ANOVA, $p<0.05$).

Table 4. Olson nonlinear exponential equation regression analysis.

Typical plant	Fitting equation	Correlation coefficient (R^2)	$t_{0.5}$/ month	$t_{0.95}$/ month
Castanea mollissima	$y = 3.7006e^{-0.05x}$	0.97	13.86	59.91
Symplocos tetragon	$y = 3.2315e^{-0.098x}$	0.90	7.07	30.57
Betula luminifera	$y = 3.4356e^{-0.06x}$	0.97	11.55.	49.93

ANOVA method, the statistical analysis was performed to test the differences in the initial properties, nutrient loss rate and residual rate during root decomposition. Pearson correlation test was performed to analyze the correlation between nutrient release from fine roots and soil nutrient changes.

Results and Analysis

The main components of fine roots determine the potential of roots to release nutrients into soils and are also the main limitation factors affecting its decomposition. The initial carbon contents of the roots of three typical plants decreased according to the following order: *C. mollissima* (810.81 g/kg)>*B. luminifera* (771.06 g/kg)>*S. tetragona* (681.59 g/kg) (Table 3). The initial carbon contents of the roots of three typical plants were respectively 81%, 77%, and 68% of their initial root mass. The results indicated that fine roots of the three plants had sufficient carbon nutrients and great potential in the nutrient cycle of root decomposition. The initial nitrogen content of roots of *S. tetragona* and the initial phosphorus content of roots of *B. luminifera* were significantly higher than those of the other two plants ($P<0.05$). The initial C/N of roots of *B. luminifera* was significantly different from that of *C. mollissima* and *S. tetragona* ($P<0.05$). The initial C/P and N/P showed significant differences between the three plants ($P<0.05$).

Fine Root Decomposition Rate and Nutrient Release Characteristics

Decomposition Rate Characteristics of Fine Roots

The calculation results of decomposition rates are shown in Table 4. The decomposition coefficients of fine roots of the three plants were respectively 0.05, 0.098 and 0.06. Among the three plants, *S. tetragona* showed the fastest decomposition rate. According to fitting results, the correlation coefficient of each fitting equation was above 0.90, indicating that the models fit well. The half-lives of fine roots of the three plants were respectively 13.86, 7.07 and 11.55 months and it took about one year to decompose 50% of fine roots. The turnover periods of fine roots of the three plants were respectively 59.91, 49.93 and 30.57 months. It took 2.5 to 4.9 years to decompose 95% of fine roots. The decomposition rates of fine roots of the three plants decreased according to the following order: *S. tetragona* >*B. luminifera*>*C. mollissima*.

Mass Loss Rate of Fine Roots

According to the change of fine root decomposition rate and its mass loss rate, the mass loss rate of fine roots was obtained (Fig. 2). The mass loss rate of fine roots increased exponentially, indicating that the mass loss of fine roots gradually increased with the increase in decomposition time. In the mass loss rate curves, the changes of the mass loss rates of the three plants decreased according to the following order: *S. tetragona*>*B. luminifera*>*C. mollissima*. After a year of decomposition, the mass loss rates of the three plants were respectively 76%, 66.28% and 59.36%. Among the three plants, *B. luminifera* showed a faster rate of decomposition.

Residual Rate of Fine Root Decomposition

The decomposition of fine roots is a dynamic process. The residual rate of fine roots per month gradually decreased. Fig. 3 shows the decomposition process of fine roots. During the fine root decomposition process, the mass of roots gradually decreased and the

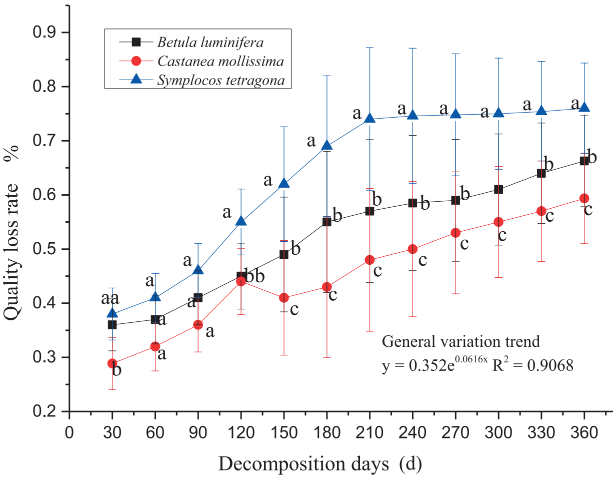

Fig. 2. Comparison of foot root loss rate of three plants. Different letters meant significant difference at 0.05 level, The same below.

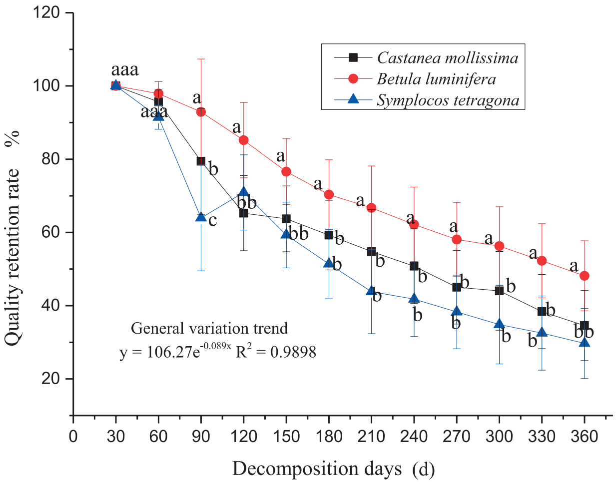

Fig. 3. Changes in the residual rate of fine roots of different plant types.

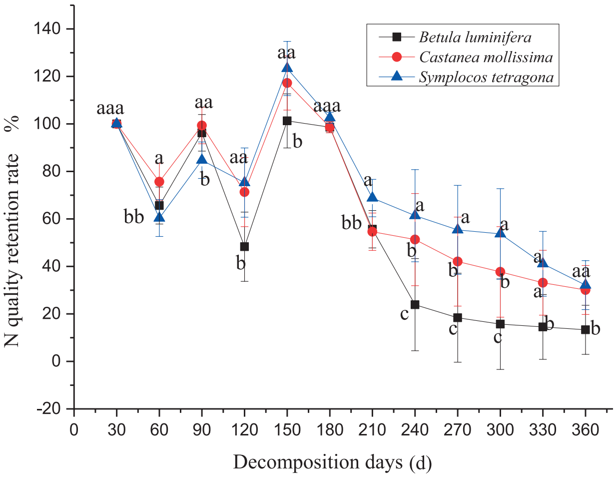

Fig. 4. Change of N residual rate in the process of fine root decomposition of different plant species.

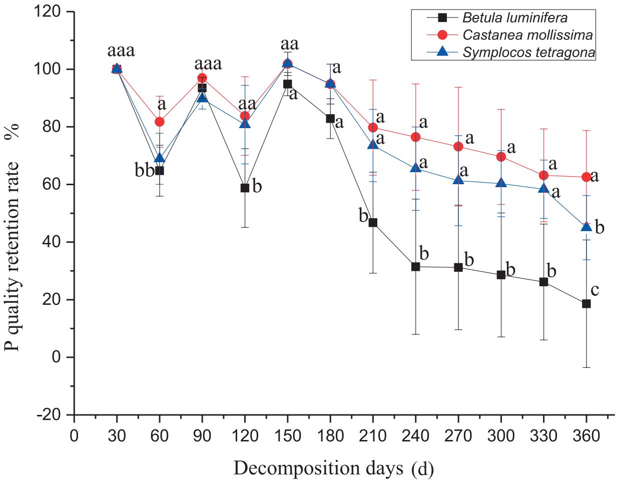

Fig. 5. Change of P residual rate in the process of fine root decomposition of different plant species.

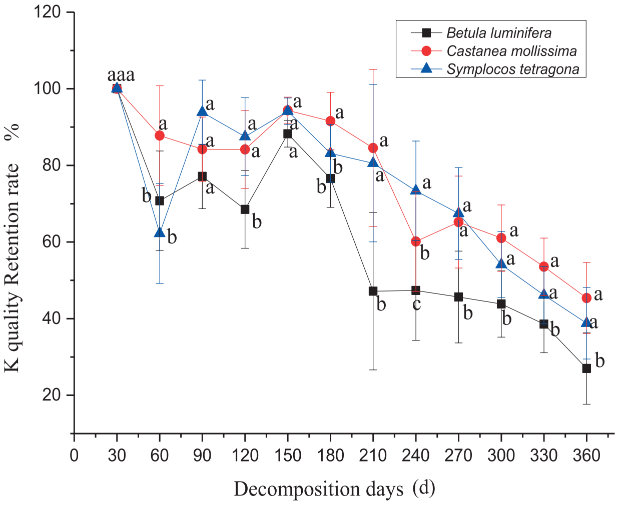

Fig. 6. Change of K residual rate in the process of fine root decomposition of different plant species.

residual rates of fine roots exponentially decreased. The residual rates of fine roots of the three plants increased according to the following order: *C. mollissima* <*B. luminifera*<*S. tetragona*. The mass residue rates of the three plants were 48.16%, 34.57% and 29.70%, respectively.

Residual Rates of Fine Root Nutrients

The nutrient changes of fine roots of different plants in the mining area are shown in Figs 4-6. The residual rates of N, P, and K in fine roots were basically the same in the first 150 days, displaying fluctuations. The residual rates of N, P, and K in fine roots peaked after 150 days of decomposition and then gradually decreased. The residual rates of N and P of different fine roots showed a downward trend except the 90th and 150th days, whereas the residual rate of K element was enriched in the 150th day and remained stable in other days (Fig. 6). In general, the residual rates of N, P, and K in fine roots showed significant difference among different plant species ($P<0.05$).

Influences of Fine Root Decomposition on Soil Organic Carbon

Soil organic carbon is an important indicator of soil nutrients. The soil organic carbon content firstly increased and then decreased (Fig. 7). Compared with the blank treatment, fine root decomposition significantly increased soil organic carbon in the first 90 days. The soil organic carbon content decreased in the 120th day and peaked in the 150th day. Within 150 days of decomposition, the increased organic carbon contents in the soil layer of 0-15 cm with the fine roots of the three plants increased according to the following order: *C. mollissima* (0.19 g/kg)< *B. luminifera* (0.83 g/kg)<*S. tetragona* (1.17 g/kg). After 150 days, the soil organic carbon contents showed a downward trend. In 360 days of decomposition, the organic carbon contents in the soil layer with the fine roots of *C. mollissima*, *B. luminifera*, and *S. tetragona* were respectively in the ranges of 12.37~17.64 g/kg, 12.57~17.46 g/kg, and 13.11~19.29 g/kg. After 360 days of decomposition, the organic carbon contents in the soil layer with the fine roots of *C. mollissima*, *B. luminifera*, and *S. tetragona* were respectively 12.95 g/kg, 13.11 g/kg and 13.23 g/kg. The organic carbon contents in the soil layer of 0-15 cm were lower than the initial soil organic carbon content. The organic carbon content in the soil layer of 0-15 cm covered by fine roots was higher than that in the control treatment. The increased organic carbon contents in the soil layer of 0-15 cm in Dongguan Mining Area, Yingjiao Mining Area, and Qingsong Mining Area were respectively 0.10 g/kg, 0.96 g/kg, and 0.59 g/kg. At the end of the experiment, the soil organic carbon contents were lower than its initial values in the soil layer of 0-15 cm.

Influences of Fine Root Decomposition on Total Nitrogen in Soils

The total nitrogen content in soil during 360 days of fine root decomposition fluctuated (Fig. 8). The total nitrogen contents in the soil layer with the fine roots of *C. mollissima*, *B. luminifera*, and *S. tetragona* were respectively in the ranges of 0.36-0.75 g/kg, 0.28-0.71 g/kg, and 0.49-0.77 g/kg. In the soil layer of 0-15 cm, the total nitrogen content in the control treatment varied between 0.42 and 0.71 g/kg. The total nitrogen content in the soil layer covered by fine roots was different from that in the control soil layer. The total nitrogen content in the soil layer peaked in the 150th day. After 360 days of fine root decomposition, the total nitrogen contents in the soil layer covered by fine roots of *S. tetragona* and *C. mollissima* were respectively 0.041 g/kg and 0.003 g/kg higher than that of the control treatment. The total nitrogen content in the soil layer covered by fine roots of *B. luminifera* was not higher than that of the control treatment. Although root decomposition had a certain effect on soil total nitrogen, the difference in soil total nitrogen between the soil layer covered by fine roots and the control treatment was not significant. The influences of root decomposition of three plants on soil total nitrogen showed no significant difference. In general, soil total nitrogen firstly increased and then decreased and was in line with the enrichment-release model.

Influences of Fine Root Decomposition on Available Nitrogen in Soils

The ammonium nitrogen contents in the soil layer of 0~15 cm during 360 days of fine root decomposition fluctuated (Fig. 9). The ammonium nitrogen contents in the soil layer with the fine roots of *C. mollissima*, *B. luminifera*, and *S. tetragona* were respectively in the ranges of 3.61-12.01 mg/kg, 2.31-12.49 mg/kg,

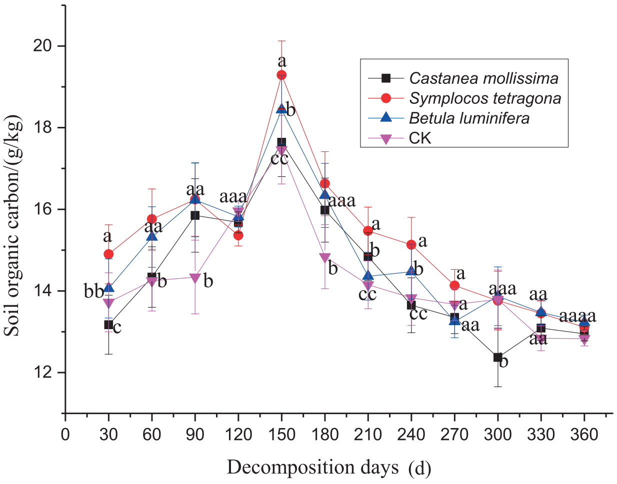

Fig. 7. Changes of soil organic carbon at different decomposition time of roots CK stands for contrast.

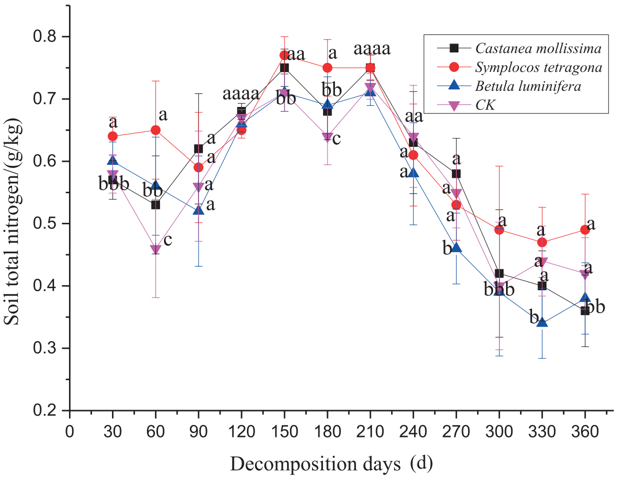

Fig. 8. Changes of soil total nitrogen at different decomposition time of roots CK stands for contrast.

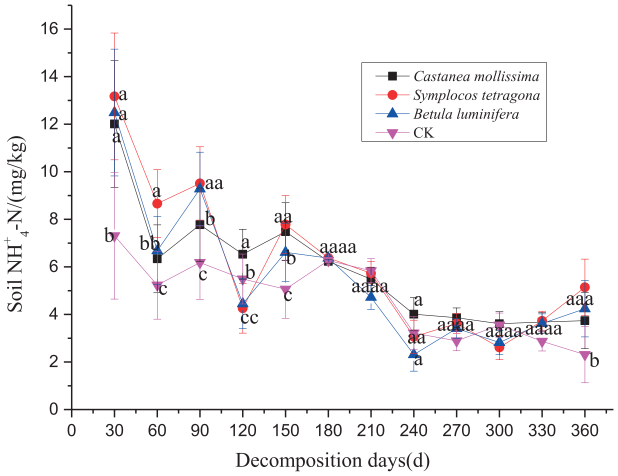

Fig. 9. Changes of soil ammonium nitrogen at different decomposition time of roots CK stands for contrast.

and 2.61-13.17 mg/kg. The ammonium nitrogen content in the control treatment ranged from 2.31 to 7.31 mg/kg. In the late decomposition period, the soil ammonium nitrogen content showed a downward trend, indicating that it was more difficult to decompose fine roots under the influence of lignin in the late stage.

The nitrate nitrogen contents in the soil layer of 0~15 cm increased firstly, peaked in the 60th day and then decreased (Fig. 10). The highest nitrate nitrogen contents in the soil layer with the fine roots of *C. mollissima*, *S. tetragona*, and *B. luminifera* were 8.48 mg/kg, 9.56 mg/kg, and 9.16 mg/kg. In the 60th day, the nitrate nitrogen content in the control treatment was 9.06 mg/kg. The nitrate nitrogen contents in the soil layer with the fine roots of *C. mollissima*, *B. luminifera*, and *S. tetragona* were respectively in the ranges of 1.17-8.48 mg/kg, 0.86-9.16 mg/kg, and 1.45-9.56 mg/kg. The nitrate nitrogen content range in the control treatment was 1.01-9.06 mg/kg. The above data indicated that the relatively high soil temperature in the initial decomposition stage might promote the accumulation of nitrate nitrogen. During the decomposition period, the average nitrate nitrogen contents in the soil layer with the fine roots of *S. tetragona* and *C. mollissima* were respectively 0.60 mg/kg and 0.02 mg/kg higher than that in the control treatment, indicating that root activities could increase the nitrate nitrogen content in the soil layer of 0~15 cm.

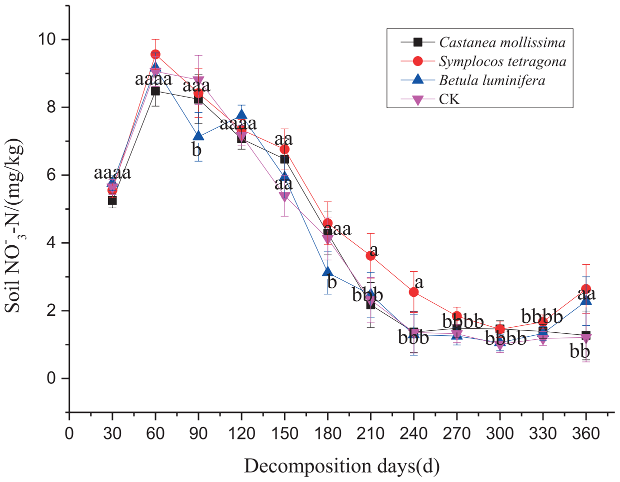

Fig. 10. Changes of soil nitrate nitrogen at different decomposition time of roots CK stands for contrast.

Correlation Analysis of Various Indexes of Soil Nutrients

In order to further illustrate the influences of fine root decomposition on soil nutrients, the correlation analysis between soil organic carbon, soil total nitrogen, soil ammonium nitrogen, and soil nitrate nitrogen after nutrients release in fine root decomposition was carried out. The quantity of fine root nutrient release was correlated with the changes of soil nutrients ($P<0.05$, Table 5). In the three experimental areas, soil organic carbon showed the significant positive correlation with soil total nitrogen in the soil layer of 0-15 cm after fine root decomposition ($P<0.01$) and the correlation coefficients were respectively 0.789, 0.812 and 0.705. Soil organic carbon showed a significant positive correlation with soil nitrate nitrogen ($P<0.05$).

Discussion

Decomposition Characteristics of Fine Roots in the Pyrite Mining Area

The mass loss rates of fine root decomposition of the three plants in this study decreased according to the following order: *S. tetragona*>*B. luminifera* >*C. mollissima*. After decomposition for one year, the mass loss rates of the three were 76.0%, 66.28% and 59.36%, respectively. Among the three plants, *S. tetragona* showed the fastest mass loss rate after decomposition. The decomposition rate of fine roots was relatively fast in the initial stage because the high content of soluble carbohydrates in the roots were easily lost through leaching and soil microorganisms utilized released nutrients and further promoted root decomposition [11]. The accumulation of lignin and other substances which were difficult to be decomposed in fine roots in the late decomposition stage led to the decreased root decomposition rate, as reported by previous scholars [12-13] . In addition, soil pH inhibited the activities of enzymes in plants [14-15]. Soil acidity reduced the number of soil microorganisms, slowed down the decomposition rate of organic matters, and inhibited the decomposition of litters [16]. This study area belongs to an acid mining area, so the inhibitory effect of soil acidity on root decomposition was more significant.

Table 5. Correlation analysis between roots nutrient release and soil nutrient change.

Experimental area		Soil organic carbon	Soil total nitrogen	Soil ammonium nitrogen	Soil nitrate nitrogen
CM	Soil organic carbon	1	0.789**	0.363	0.649*
	Soil total nitrogen		1	0.401	0.409
	Soil ammonium nitrogen			1	0.659*
	Soil nitrate nitrogen				1
BL	Soil organic carbon	1	0.812**	0.409	0.620*
	Soil total nitrogen		1	0.471	0.560
	Soil ammonium nitrogen			1	0.659*
	Soil nitrate nitrogen				1
ST	Soil organic carbon	1	0.705**	0.328	0.595*
	Soil total nitrogen		1	0.407	0.503
	Soil ammonium nitrogen			1	0.616*
	Soil nitrate nitrogen				1

Castanea mollissima is abbreviated to CM, *Betula luminifera* is abbreviated to BL, *Symplocos tetragon* is abbreviated to ST;
* Correlation is significant at the level of $p<0.05$. ** Correlation is significant at the level of $p<0.01$.

Influences of Fine Root Decomposition on Soil Organic Carbon in the Pyrite Mining Area

Plant roots are an important carbon pool and nutrient pool in the forest ecosystem and play an important role in the material cycle, nutrient balance, and energy flow in the ecosystem [16]. After fine root decomposition, a large amounts of organic matters and nutrients are generated and enter soils [17]. Fine roots of different plants have significant differences in the physiological functions, which affect their histochemical composition as well as its decomposition rate [17-18]. The decomposition of fine roots is closely related to their own characteristics and the decomposition environment [19]. The decomposition of fine roots is the main way for C and nutrients to return to soils. In this study, the soil organic carbon content increased when fine roots began to decompose, decreased in the 120th day, and peaked in the 150th day (September) (Fig. 7). In September, the water and heat conditions were good, indicating the climatic factors affected the dynamic changes of root decomposition by changing the activities of microorganisms. After 150 days of decomposition, the soil organic carbon content decreased until the 360th day. The soil organic carbon contents in the soil layer of 0-15 cm with the fine roots of three plants were respectively 12.95 g/kg, 13.11 g/kg, and 13.23 g/kg, which were higher than that in the control treatment. The soil organic contents in in Dongguan Mining Area, Yingjiao Mining Area, and Qingsong Mining Area were respectively 0.10 g/kg, 0.96 g/kg, and 0.59 g/kg higher than that in the control treatment, indicating that fine root decomposition increased the soil organic carbon content [20-22].

Influences of Fine Root Decomposition on Soil Nutrients in the Pyrite Mining Area

The N release process of roots is more complicated. In the different periods of root decomposition, N is released or enriched in soils. Some scholars found that after plant decomposition, N content in soils increased to 120%-150% of its initial content [23]. Increasing temperature obviously promoted the decomposition of litters [24]. In the study, the soil total nitrogen content in fine root decomposition period was lower in summer and higher in autumn (Fig. 8) and soil nutrients showed an enrichment-release pattern. The dynamics of N, P and heavy metal elements (such as Fe, Al, Mn, Pn, Cu, and Zn) in plants in the decomposition of litters mostly displayed the enrichment-release modes, as reported by other researchers [24-26] . The previous studies focused on the effects of heavy metals on decomposition in non-mining areas, whereas our study was performed in heavy metal mining areas. Therefore, in the mining area, N, P and other elements often became the limiting nutrients for the growth and development of the microbial community and were fixed by the microbes, thus resulting in obvious enrichment during the decomposition process [27]. In the early stage of root decomposition, the N element was released, so the soil nitrate nitrogen content increased slightly. However, the ammonium nitrogen content increased more slightly due to the increase in rainfall and temperature (Fig. 9). Seasonal factors in different periods including temperature and moisture mainly affected the processes of organic nitrogen mineralization, nitrification and denitrification as well as the content of available nitrogen. In this study, the amount of nitrogen released from the roots of the three plants showed no correlation with the soil nitrate nitrogen content. The average nitrate nitrogen contents in the soil layer with the fine roots of *S. tetragona* and *C. mollissima* were respectively 0.60 mg/kg and 0.02 mg/kg higher than that in the control treatment, indicating that root activities could increase the nitrate nitrogen content in the soil layer. Especially, the contribution of *S. tetragona* to nitrate nitrogen contents in the soil layer was the most obvious.

Correlation analysis showed that heavy metals could affect the decomposition of plant roots. However, there is some correlation between soil nutrients (Table 5). Soil organic carbon showed significant positive correlation with soil total nitrogen, soil nitrate nitrogen, and soil ammonium nitrogen (P<0.05). Root decomposition increased soil organic carbon content and soil nitrogen content, indicating that root decomposition could provide nutrients to the soils. In addition, the correlation between the changes of other elements in soils was not significant, indicating that in the environment in the pyrite mining area where soil nutrients had a single source, soil nutrients mainly came from the decomposition of plant roots or litters. The N element was released, so the soil nitrate nitrogen content increased slightly. The plant configuration of *S. tetragona* and *C. mollissima* as well as some native herbaceous plants (Such as *Lolium perenne* L., *Cynodondactylon* (Linn.) Pers. and *Agrostisstolonifera* Roth.) are more conducive to the accumulation of nutrients and ecological restoration.

Conclusion

In summary, among fine roots of three plants, the fine roots of *S. tetragona* exhibited a faster decomposition rate and different elements showed different enrichment-release patterns. Soil organic carbon decreased after 360 days of decomposition. The soil organic carbon contents in the soil layer of 0-15 cm in Dongguan Mining Area, Yingjiao Mining Area, and Qingsong Mining Area were respectively 0.10 g/kg, 0.96 g/kg, and 0.59 g/kg higher than that in the control treatment, indicating that fine root decomposition increased the soil organic carbon content. The total nitrogen content in soils was lower in summer and higher in autumn, displaying the enrichment-release mode. Therefore, heavy metals affected soil nutrients in the process of fine root decomposition. Soil organic carbon and total nitrogen had a significant positive correlation with soil nitrate nitrogen (P<0.05). The average nitrate nitrogen contents in the soil layer with fine roots of *S. tetragona* and *C. mollissima* were respectively 0.60 mg/kg and 0.02 mg/kg higher than that in the control treatment, indicating that root activities could increase the nitrate nitrogen content in the soil layer. In mining areas with a single nutrient source, the plant configuration of *S. tetragona* and *C. mollissima* as well as some native herbaceous plants (such as *Lolium perenne* L., *Cynodondactylon* (Linn.) Pers. and *Agrostisstolonifera* Roth.) is conducive to nutrient accumulation and ecological restoration.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. YANG F., HUANG M,B., LI C.H., WU X.F., GUO T.Q., ZHU M.Y. Changes in soil moisture and organic carbon under deep-rooted trees of different stand ages on the Chinese Loess Plateau. Agriculture, Ecosystems & Environment, **328**, 107855, **2022**.
2. LIU J.X., LIU S.G., LI Y.Y., LIU S.Z., YIN G.C., HUANG J., XU Y., ZHOU G.Y. Warming effects on the decomposition of two litter species in model subtropical forests. Plant and Soil, **420**, 277, **2017**.
3. HE W.Y., ZHANG M.M., JIN G.Z., SUI X., ZHANG T., SONG FQ. Effects of Nitrogen Deposition on Nitrogen-Mineralizing Enzyme Activity and Soil Microbial Community Structure in a Korean Pine Plantation. Microbial Ecology, **81**, 410, **2021**.
4. LIU C., LIAO W.B. Potassium signaling in plant abiotic responses: Crosstalk with calcium and reactive oxygen species/reactive nitrogen species. Plant Physiology and Biochemistry, **173**, 110, **2022**.
5. SUN T., DONG L.L., ZHANG L.L., WU Z.J., WANG Q.K., LI Y.Y., ZHANG H. G., WSNG, Z.W. Early Stage Fine-Root Decomposition and Its Relationship with Root Order and Soil Depth in a *Larix gmelinii* Plantation. Forests, **7** (10), 234, **2016**.
6. DIJKSTR A., FEIKE A., BIAO Z., CHENG W.X. Root effects on soil organic carbon: a double-edged sword. New Phytologist, **230**, 60, **2021**.
7. DEAAEO N., GRANDEZ-RIOS J., MARTIUS C., HERGOUALC'H K. Degradation-driven changes in fine root carbon stocks, productivity, mortality, and decomposition rates in a palm swamp peat forest of the Peruvian Amazon.Carbon Balance and Management, **16** (1), 33, **2021**.
8. BAI TS., WANG P., HALL S. J., WANG F.W., YE C.L., AHEN L., LI S.J., AHOU L.Y., QIU Y.P., GUO J.X., WANG L., HU S. J. Interactive global change factors mitigate soil aggregation and carbon change in a semi-arid grassland. Global Change Biology, **26**, 5320, **2020**.

9. GHOSH S., BAKSHI M., MAHANTY S., CHAUDHURI P. Assessment of role of rhizosphere process in bioaccumulation of heavy metals in fine nutritive roots of riparian mangrove species in river Hooghly: Implications to global anthropogenic environmental changes. Marine pollution bulletin, **174**, 113157, **2022**.
10. XU Y., HUANG R., ZHOU B., GE X. Fine-Root Decomposition and Nutrient Return in Moso Bamboo (Phyllostachys pubescens J. Houz.) Plantations in Southeast China. Frontiers in Plant Science, **13**, 735359, **2022**.
11. AHMED M., AALAM M.A., HAYAT R., WAJID N., MUHAMMAD A., MUHAMMAD M., SAJJAD H.,SHAKEEL A. Nutrient Dynamics and the Role of Modeling. Building Climate Resilience in Agriculture, 297-316, **2022**.
12. WAMBSGANSS J., FRESCHET G.T., BEYER F., BAUHUS J., SCHERER-LORENZEN M. Tree Diversity, Initial Litter Quality, and Site Conditions Drive Early-Stage Fine-Root Decomposition in European Forests. Ecosystems, 1, **2021**.
13. LI X.F., ZHENG X.B., ZHOU Q.L., MCNULTY S., KING J.S. Measurements of fine root decomposition rate: Method matters.Soil Biology and Biochemistry, **164**, 108482, **2022**.
14. LI Y., GONG J., ZHANG Z.H., SHI J.Y., ZHANG W.Y., SONG L.Y. Grazing directly or indirectly affect shoot and root litter decomposition in different decomposition stage by changing soil properties. **209** (1), 108482, **2022**.
15. FU X.F., XU C.H., GENG Q.H., MA X.C., ZHANG H.G., CAI B., HU G.Q., XU X. Effects of nitrogen application on the decomposition of fine roots in temperate forests: a meta-analysis, Plant and Soil, **472** (1), 77, **2021**.
16. NICOLAS F., TANIA L., MAXWELL, AADREAS ALTINALMAZIS-KONDYLIS, LUCIE B., CELINE M., HERVE J., MARK R., BAKKER L.A. Effects of mixing tree species and water availability on soil organic carbon stocks are depth dependent in a temperate podzol. European Journal of Soil Science, **73** (1), e13133,**2022**.
17. LIU X.P., LUO Y.Q., CHENG L., HU H.J., WANG Y.H., DU Z. Effect of Root and Mycelia on Fine Root Decomposition and Release of Carbon and Nitrogen Under Artemisia halodendron in a Semi-arid Sandy Grassland in China[J]. Frontiers in Plant Science, **12**, 698054, **2021**.
18. GUO L.L., DENG M.F., YANG S., LIU WX., WANG X., WANG J., LIU L.L. The coordination between leaf and fine root litter decomposition and the difference in their controlling factors[J]. Global Ecology & Biogeography Letters, **30** (11), 2286, **2021**.
19. ARGIROFF W.A., ZAKR D.R., UPCHURCH R.A., UPCHURCH, SALLEY S.O., GRANDY A.S, Anthropogenic N deposition alters soil organic matter biochemistry and microbial communities on decaying fine roots. Global Change Biology, **25**, 4369, **2019**.
20. DONG L., BERG B., SUN T., WANG Z., HAN X. Response of fine root decomposition to different forms of n deposition in a temperate grassland. Soil Biology and Biochemistry, **147**, 107845, **2020**.
21. LUO X.Z.,HOU E.Q.,CHEN J.Q., LI J., ZHANG H., LING L., ZANG X.W.,WEN D.Z. Dynamics of carbon, nitrogen, and phosphorus stocks and stoichiometry resulting from conversion of primary broadleaf forest to plantation and secondary forest in subtropical china. Catena, **193**, 104606, **2020**.
22. ZHU X.M., MEI L., KOU Y.P., LIU D.Y., LIU Q., ZHANG Z.L., JIANG Z., YIN H.J. Differential effects of N addition on the stoichiometry of microbes and extracellular enzymes in the rhizosphere and bulk soils of an alpine shrubland.Plant and Soil, **449**, 285, **2020**.
23. ZHAO M.Y., LUO Y.K., CHEN Y.H., SHEN H.H., ZHAO X., FANG J.Y., HU H.F. Varied nitrogen versus phosphorus scaling exponents among shrub organs across eastern China. Ecological Indicators, **121**, 107024, **2021**.
24. BHATTATAI K.P., MANDAL T.N., GAUTAM T.P. Fine root decomposition and nutrient release in two tropical forests of Central Himalaya: a comparative and factor controlling approach. Tropical Ecology, 1, **2022**.
25. MOSHE A., GUY D., TANIA M., EFRAT S. Soil nitrogen regulates symbiotic nitrogen fixation in a legume shrub but does not accumulate under it. Ecosphere, **12** (12), e03843, **2021**.
26. GONG X.W., GUO J.J., JING D.M., LI X.H., SCHOLZ F.G., BUCCI S.J. GUILLERMO GOLDSTEIN, GUANG-YOU HAO Contrasts in xylem hydraulics and water use underlie the sorting of different sand-fixing shrub species to early and late stages of dune stabilization[J] Forest Ecology and Management, **457** (C), 117705, **2020**.
27. WANG S., LI L., ZHOU D.W. Root morphological responses to population density vary with soil conditions and growth stages: The complexity of density effects. Ecology and Evolution, **11** (15), 10590, **2021**.