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Contributions of Plant Litter Decomposition to Soil Nutrients in Ecological Tea Gardens

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Abstract: Plant litter decomposition and its effect on soil nutrients are important parts of the ecosystem material cycle, and understanding these processes is key for species selection and allocation to promote the effective use of litter in ecological tea gardens. In this study, the in situ litter decomposition method was used to examine the decomposition characteristics of leaf litter of *Cinnamomum glanduliferum*, *Betula luminifera*, *Cunninghamia lanceolata*, *Pinus massoniana*, and *Camellia sinensis* prunings in the Jiu'an ecological tea garden in Guizhou and their effects on soil nutrients. The results showed that the litter decomposition rate of broad-leaved tree species was higher than that of coniferous tree species, with a half-life of 1.11–1.75a and a turnover period of 4.79–7.57a. There are two release modes of nutrient release from litter: direct release and leaching–enrichment–release. Different litters make different contributions to soil nutrients; *Betula luminifera* and *Cinnamomum glanduliferum* litter increased the contents of soil organic carbon, soil total nitrogen, and soil hydrolyzed nitrogen. *Betula luminifera* litter increased the content of soil total phosphorus, soil available phosphorus, and soil available potassium, and *Pinus massoniana* litter increased the content of soil total potassium and soil available potassium; therefore, it is concluded that the decomposition of *Betula luminifera* litter had a positive effect on soil nutrient content. Thus, *Betula luminifera* is a good choice for inclusion in ecological tea gardens to increase their nutrient return capacity, maintain fertility, and generally promote the ecological development of tea gardens.

Keywords: ecological tea garden; litter decomposition; soil nutrients; dynamic change

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1. Introduction

The production and decomposition of plant litter, the product of metabolism during plant growth and development, is the main mechanism of material circulation in forest ecosystems [1,2] and represents a "link" between plants and soil in nutrient cycling [3]. This process is an important factor affecting soil nutrients [4,5]. Through the decomposition of litter, the nutrients absorbed by plants return to the soil, enriching the organic matter and mineral nutrients in the soil, while litter that has not been completely decomposed accumulates on the surface of the soil and becomes an important nutrient reserve in the ecosystem. Studies have shown that approximately 90% of the nitrogen (N) and phosphorus (P) absorbed by plants, as well as approximately 60% of other mineral elements, comes from the recycling of nutrients returned to the soil during the decomposition of plant litter [6]. To a certain extent, plant litter decomposition determines the availability of soil nutrients [7]. Therefore, it is of great significance to study the effect of litter decomposition on soil nutrients.

Camellia sinensis is a small perennial shrub with shallow roots that is mostly distributed in mountainous areas [8]. Tea has become one of the three major nonalcoholic beverages worldwide and its consumption is increasing. There is a substantial consumer market for tea, and the prominent tea industry has become the main choice for eco-economic development in karst plateaus and other areas. In recent years, the area of tea gardens has increased annually; the tea gardens constructed in most tea-growing areas are primarily pure tea gardens. Currently, tea-growing areas face some challenges: serious soil erosion, a decline in soil fertility, the frequent occurrence of diseases and insect pests, low yield and quality, and high agricultural residue levels. Therefore, increasing attention has been given to the construction of ecological tea gardens with tea as the main crop, following ecological principles and ecological laws. At present, some achievements have been made in studies on the hydrological effects of forest litter [9,10], nutrient cycling [11–13], and decomposition characteristics [14,15]. However, there are few reports on the characteristics of litter decomposition and the response of soil nutrients to litter decomposition in ecological tea gardens and there are few reports on the construction of ecological tea gardens according to the characteristics of the nutrient return of litter decomposition.

In this study, an in situ experiment was performed using pruned leaf litter of the common tree species *Cunninghamia lanceolata*, *Pinus massoniana*, *Cinnamomum glanduliferum*, *Betula luminifera*, and *Camellia sinensis* in an ecological tea garden ecosystem of Jiu'an, Guizhou Province, China. The decomposition rate and dynamic changes in litter nutrients and soil nutrients during the process of decomposition were analyzed to further understand the decomposition characteristics of pruning materials from *Camellia sinensis* and associated tree species in tea gardens, to enhance the understanding of the material cycles and energy flows of tea gardens, to recommend reasonable management and utilization of various plant residues in the ecological tea garden in the mountain area, and to provide a theoretical basis for maintaining the fertility of the tea garden and constructing a good tea-forest ecological model for tea gardens. We hypothesized that the litter decomposition of associated tree species in the tea garden could improve the soil nutrients of the tea garden.

2. Materials and Methods

2.1. Study Area

The experimental area is located in Jiu'an Township, Huaxi District, Guiyang City, Guizhou Province (26°31′8′′ N–26°31′12′′ N, 106°36′47′′ E–106°36′50′′ E). The average annual temperature is 13.6 °C, the average temperature of the coldest month (January) is 3–4 °C, the average temperature of the hottest month (July) is 22 °C, the frost-free period is 260 days, the average annual rainfall is 1000–1150 mm, the elevation range is 1100–1446 m, the climate is a subtropical plateau monsoon climate, and the soil type is mainly yellow soil. The main vegetation includes *Pinus massoniana*, *Cunninghamia lanceolata*, *Cinnamomum glanduliferum*, and *Betula luminifera*. The experimental study area is shown in Figure 1.

2.2. Experimental Design and Arrangement

Litter collection and treatment: In July 2019, *Camellia sinensis* pruning material (including branches and leaves) was collected in the Jiu'an ecological tea garden in Huaxi, Guizhou Province. At the same time, materials from *Pinus massoniana*, *Cunninghamia lanceolata*, *Cinnamomum glanduliferum*, and *Betula luminifera*, which are common tree species in the tea garden, were selected for the collection of old leaves. To ensure the consistency of the initial chemical quality of plant leaves, the leaves of the same associated tree species were collected from the same tree. The litter of the same tree species was evenly mixed and brought back to the laboratory to dry at 65 °C to a constant weight.

Experimental design: Using the in situ decomposition method, a 35 cm × 25 cm decomposition bag with a pore diameter of 1 mm was selected, and the dried litter was put into a decomposition bag at 40 g per bag. In this study, five single treatments were set up: *Camellia sinensis* (CS), *Cunninghamia lanceolata* (CL), *Pinus massoniana* (PM), *Cinnamomum glanduliferum* (CG), and *Betula luminifera* (BL). In the experiment, the samples were recovered every 2 months for a total of 6 times; 3 bags were recovered in the same treatment each time, and a total of 18 bags were recovered in the same treatment. There were five kinds of treatments in the experimental design, and a total of ninety bags of samples were recovered. The initial nutrient content (including contents of litter total carbon (LTC), litter total nitrogen (LTN), litter total phosphorus (LTP), litter total potassium (LTK), litter lignin (LL), and litter cellulose (LC)) of the plant litter was determined (Table 1).

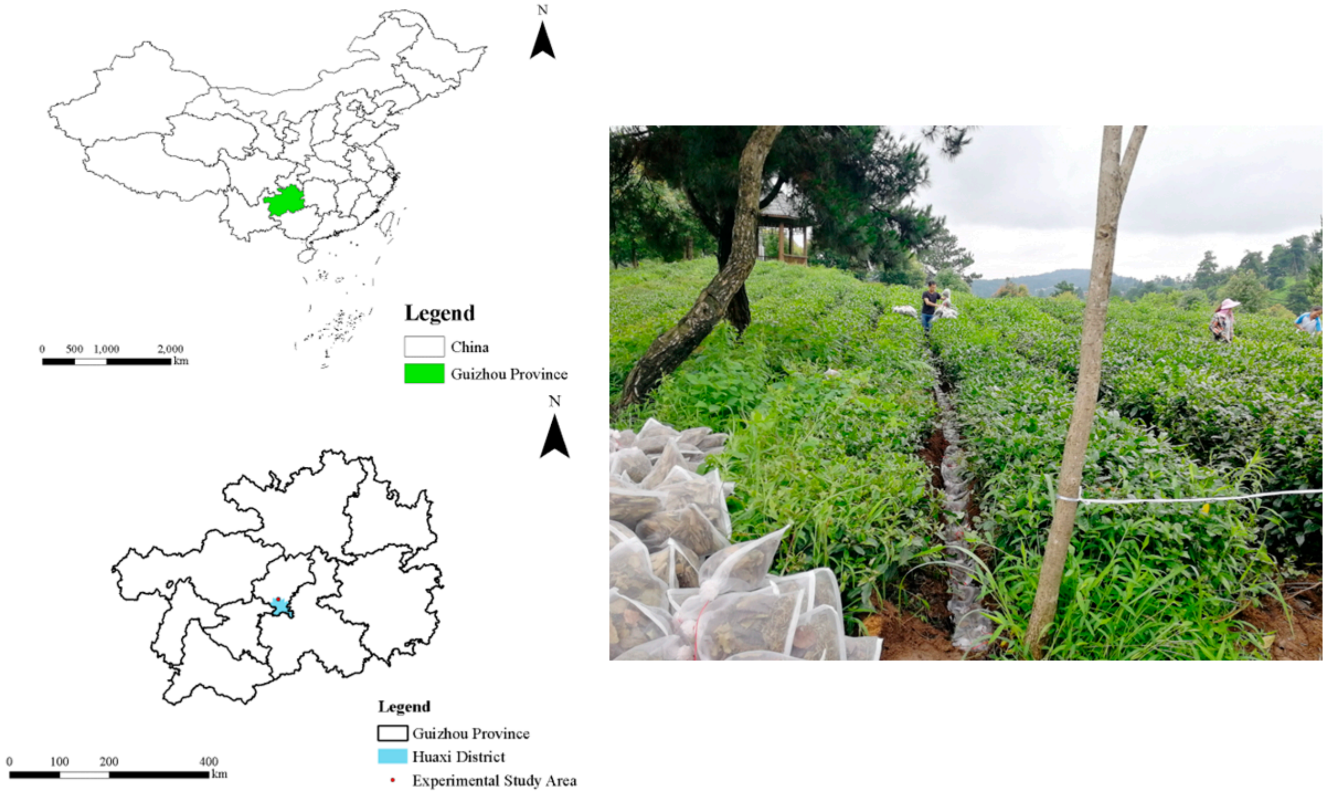

Figure 1. Experimental study area.

Table 1. Basic nutrient properties of the tested litter.

Litter Type	LTC /g·kg^{-1}	LTN /g·kg^{-1}	LTP /g·kg^{-1}	LTK /g·kg^{-1}	LL /mg·g^{-1}	LC /mg·g^{-1}	C/N Ratio	LL/N Ratio
Camellia sinensis	450.01 ± 19.24 ^{b}	17.85 ± 1.40 ^{ab}	1.88 ± 0.10 ^{a}	1.26 ± 0.04 ^{c}	171.40 ± 34.70 ^{a}	16.37 ± 0.54 ^{a}	25.35 ± 2.86 ^{bc}	10.49 ± 1.41 ^{b}
Cunninghamia lanceolata	452.12 ± 14.05 ^{b}	15.28 ± 1.07 ^{c}	1.27 ± 0.09 ^{b}	0.72 ± 0.01 ^{d}	184.74 ± 11.31 ^{a}	12.64 ± 0.95 ^{c}	29.7 ± 2.74 ^{b}	12.16 ± 1.50 ^{b}
Pinus massoniana	530.34 ± 16.94 ^{a}	11.78 ± 1.62 ^{d}	0.87 ± 0.05 ^{c}	0.26 ± 0.01 ^{e}	195.06 ± 25.34 ^{a}	14.79 ± 0.49 ^{b}	45.49 ± 5.48 ^{a}	18.01 ± 2.40 ^{a}
Cinnamomum glanduliferum	509.17 ± 8.5 ^{a}	16.38 ± 0.74 ^{bc}	0.91 ± 0.03 ^{c}	2.14 ± 0.01 ^{a}	117.20 ± 15.57 ^{b}	16.51 ± 0.55 ^{a}	31.11 ± 0.96 ^{b}	7.19 ± 1.30 ^{c}
Betula luminifera	432.22 ± 13.73 ^{b}	19.37 ± 0.70 ^{a}	1.82 ± 0.12 $_{a}$	1.49 ± 0.01 ^{b}	159.05 ± 25.38 ^{ab}	10.31 ± 0.14 ^{d}	22.33 ± 0.62 ^{d}	7.46 ± 0.47 ^{c}

LTC—litter total carbon, LTN—litter total nitrogen, LTP—litter total phosphorus, LTK—litter total potassium, LL—litter lignin, LC—litter cellulose; different letters in the same column indicate significant differences in the data ($p < 0.05$); $^{a, b, c, d, e}$—differences between treatments in the same index. The same applies below.

Test arrangement: In a flat region of the experimental area, a 5 m × 10 m decomposition field was set up, and decomposition bags containing samples were laid in the original habitat where the litter was collected and buried in the soil between rows of the tea forest in the ecological tea garden (Figure 2). The soil thickness was 10 cm. A row without landfill litter was selected as a control treatment. Each row contained a single treatment, placed at intervals of 10 cm. The decomposition bags were arranged in parallel with no overlap to simulate the natural state.

2.3. Sample Collection and Testing

Litter recovery: From July 2019 to September 2020, samples were taken every 2 months (the fourth sampling should have been carried out in March 2020, but due to epidemic control, sampling was limited, and the fourth decomposition stage was 4 months, i.e., 184–305 days). Three bags were randomly removed from each treatment. After removing the roots and residues of other plants from the samples, the samples were dried to a constant mass in an oven at 65 °C; the dry mass data was recorded and then the litter was crushed based on the requirements for measuring its chemical properties (contents of litter total carbon (LTC), litter total nitrogen (LTN), litter total phosphorus (LTP), litter total potassium (LTK), litter lignin (LL), and litter cellulose (LC)).

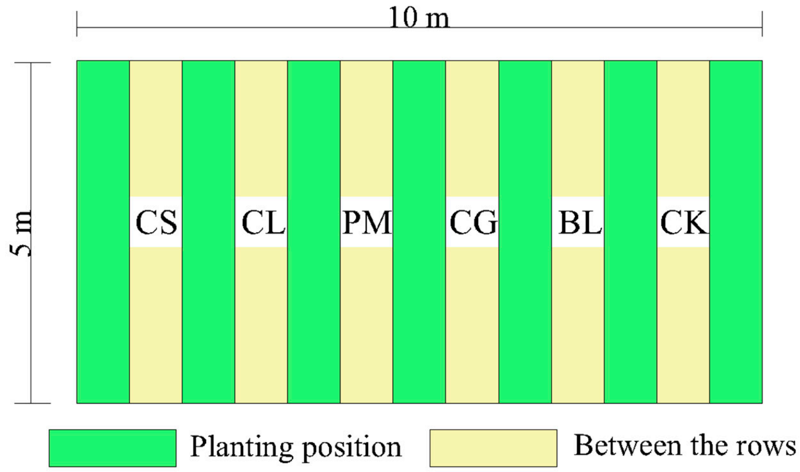

Figure 2. Schematic diagram of the experimental layout. CS—*Camellia sinensis*, CL—*Cunninghamia lanceolata*, PM—*Pinus massoniana*, CG—*Cinnamomum glanduliferum*, BL—*Betula luminifera*, CK—control; the same below.

Soil sample collection: The soil samples were collected a total of 7 times. Soil was collected under the decomposition bag, that is, from the 20–30 cm layer, according to the 5-point sampling method, with 3 bags collected at a time for each treatment. A total of 21 bags were collected for each treatment, and a total of 126 bags were collected from 6 treatments (including 5 kinds of litter treatment and control treatment). The roots and residues of plants were removed from the soil, and the soil was air-dried and sifted at 2 mm and 0.25 mm to determine its chemical properties (contents of soil organic carbon (SOC), soil total nitrogen (STN), soil total phosphorus (STP), soil total potassium (STK), soil hydrolyzed nitrogen (SAN), soil available phosphorus (SAP), and soil available potassium (SAK)).

Test methods: The concentrated sulfuric acid-potassium dichromate method was used to measure carbon (C), the semi-trace Kjeldahl method was used to measure N, molybdenum-antimony anticolorimetry was used to measure P, and flame spectrophotometry was used to measure potassium (K) [16]. The contents of litter lignin and litter cellulose were determined by biochemical kit of Beijing Solarbio Science & Technology Co., Ltd. (Beijing, China).

2.4. Data Analysis

(1) Litter decomposition rate:

$$L = (1 - M_t/M_0) \times 100\% \quad (1)$$

where L represents the decomposition rate of litter, %; M_t represents the dry mass of the remaining sample of litter in the bag during sampling at time t, g; and M_0 represents the initial dry mass of the litter without decomposition, g.

(2) Litter residue rate:

$$R = (M_t/M_0) \times 100\% \quad (2)$$

where R represents the litter residue rate, %.

(3) The decomposition coefficient in the Olson exponential model $y = ae^{-kt}$ [17,18] is often used to describe the litter decomposition rate, where y represents the litter residue

rate, %; k represents the decomposition coefficient; α is a fit parameter; and t represents the decomposition time of the litter, d.

(4) Decomposition half-life (50% decomposition):

$$t_{0.5} = ln0.5/(-k)$$

Decomposition turnover period (95% decomposition):

$$t_{0.95} = ln0.05/(-k)$$

(5) Nutrient release rate of litter:

$$E = [(C_0 \times M_0 - C_t \times M_t)/C_0 \times M_0] \times 100\%$$

where E represents the nutrient release rate of litter, %; C_0 represents the initial nutrient content of the litter when it is not decomposed, g·kg^{-1}; C_t represents the nutrient content of the remaining sample of litter in the bag during sampling at time t, g·kg^{-1}; M_0 represents the initial dry mass of the litter without decomposition, g; and M_t represents the dry mass of the remaining sample of litter in the bag during sampling at time t, g. When E is positive, net release occurs, and when E is negative, net enrichment occurs.

2.5. Data Processing

Data management and analysis were completed in SPSS 22.0 software, graphs were created in Origin 2018 software and in the R environment, the litter decomposition curve was fitted by nonlinear regression analysis, redundancy analysis was carried out in the R environment, and the contribution of the release rate of each element in the litter to the litter–soil nutrient cycle was analyzed.

3. Results

3.1. Decomposition Characteristics of Different Litters

3.1.1. Decomposition Rate

The decomposition rates of different litters in ecological tea gardens varied with the duration of decomposition time (Figure 3). The litter decomposition rates of *Cinnamomum glanduliferum* and *Betula luminifera* were higher, followed by *Camellia sinensis*, and *Cunninghamia lanceolata* and *Pinus massoniana* were lower, indicating that broad-leaved tree species decompose more easily than coniferous tree species. The decomposition rates of *Camellia sinensis*, *Cinnamomum glanduliferum*, and *Betula luminifera* increased rapidly in the early stage (62 d, 123 d, 184 d) and showed a gentle increasing trend in the later stage (305 d, 366 d, 428 d). On the other hand, *Cunninghamia lanceolata* and *Pinus massoniana* showed a gentle trend at 366 days, indicating that the litter decomposition process of broad-leaved tree species was different from that of coniferous tree species; the decomposition of broad-leaved tree species was faster in the early stage and slower in the later stage, and the decomposition of coniferous tree species lagged behind that of broad-leaved tree species in general.

3.1.2. Decomposition Rate (k)

The correlation coefficients of the five litters were all significant (Table 2). The decomposition coefficient (k) of *Cinnamomum glanduliferum*, *Camellia sinensis*, and *Betula luminifera* was greater than that of *Cunninghamia lanceolata* and *Pinus massoniana*. The half-lives and turnover periods of *Cinnamomum glanduliferum*, *Camellia sinensis*, and *Betula luminifera* were lower, and those of *Cunninghamia lanceolata* and *Pinus massoniana* were higher, which further indicates that the decomposition rates and processes of broad-leaved tree species and coniferous tree species are different. The half-life of the five kinds of plant litter was between 1 and 2 years and the turnover period was more than 4.5 years. This has important implications for the soil nutrient management of ecological tea gardens; that is, the contribution of litter to soil nutrients occurs mostly in the first two years, and the contribution rates of various species differ. This is of great importance for the plant allocation in tea gardens.

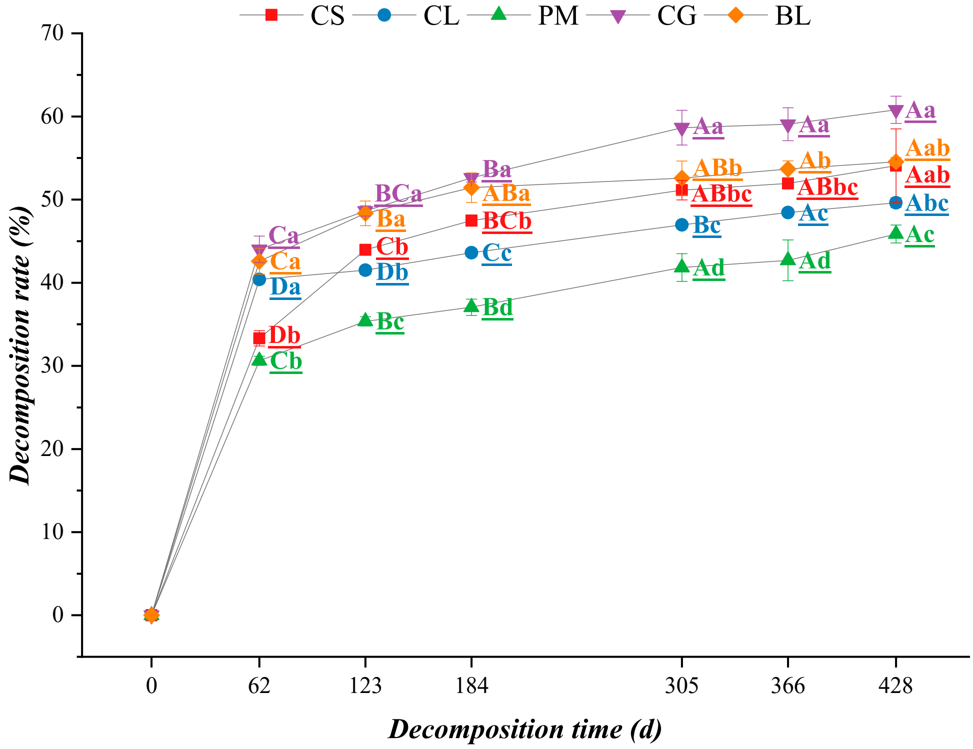

Figure 3. Variation characteristics of the decomposition rates of different litters with decomposition time. CS—*Camellia sinensis*, CL—*Cunninghamia lanceolata*, PM—*Pinus massoniana*, CG—*Cinnamomum glanduliferum*, BL—*Betula luminifera*; A, B, C—differences between decomposition stages of the same treatment; a, b, c—differences between treatments in the same decomposition period; the same applies below.

Table 2. Regression model of the loss of dry matter mass for different litters.

Litter Type	Regression Equation	*k*	R^2	Half-Life/a	Turnover Period/a
Camellia sinensis	$y = 78.305 \times 10^{-0.045t}$	0.045 [b]	0.8697 **	1.31 ± 0.20 [b]	5.68 ± 0.88 [b]
Cunninghamia lanceolata	$y = 75.665 \times 10^{-0.035t}$	0.035 [c]	0.9963 **	1.67 ± 0.03 [a]	7.20 ± 0.12 [a]
Pinus massoniana	$y = 82.056 \times 10^{-0.033t}$	0.033 [c]	0.9791 **	1.75 ± 0.05 [a]	7.57 ± 0.23 [a]
Cinnamomum glanduliferum	$y = 73.000 \times 10^{-0.052t}$	0.052 [a]	0.9658 **	1.11 ± 0.09 [c]	4.79 ± 0.38 [c]
Betula luminifera	$y = 71.900 \times 10^{-0.040t}$	0.040 [bc]	0.8425 *	1.44 ± 0.04 [b]	6.24 ± 0.16 [b]

[a, b, c]—differences between treatments in the same index; ** indicates that the significant level is 0.01 ($p < 0.01$); * indicates that the significant level is 0.05 ($p < 0.05$).

3.2. Nutrient Dynamics of Different Litter Decompositions

3.2.1. Dynamic Changes in the Nutrient Content of Litter

The change trend of the total carbon content of the five kinds of litter was essentially the same, decreasing at first and then increasing (Figure 4a). The LTC content of the five kinds of litter increased to varying degrees in the later stage of decomposition. After 428 days of decomposition, the LTC content of *Cunninghamia lanceolata*, *Cinnamomum glanduliferum*, and *Betula luminifera* litter was higher than that in the period before decomposition. The LTC content of *Camellia sinensis* and *Pinus massoniana* was lower than that in the period before decomposition.

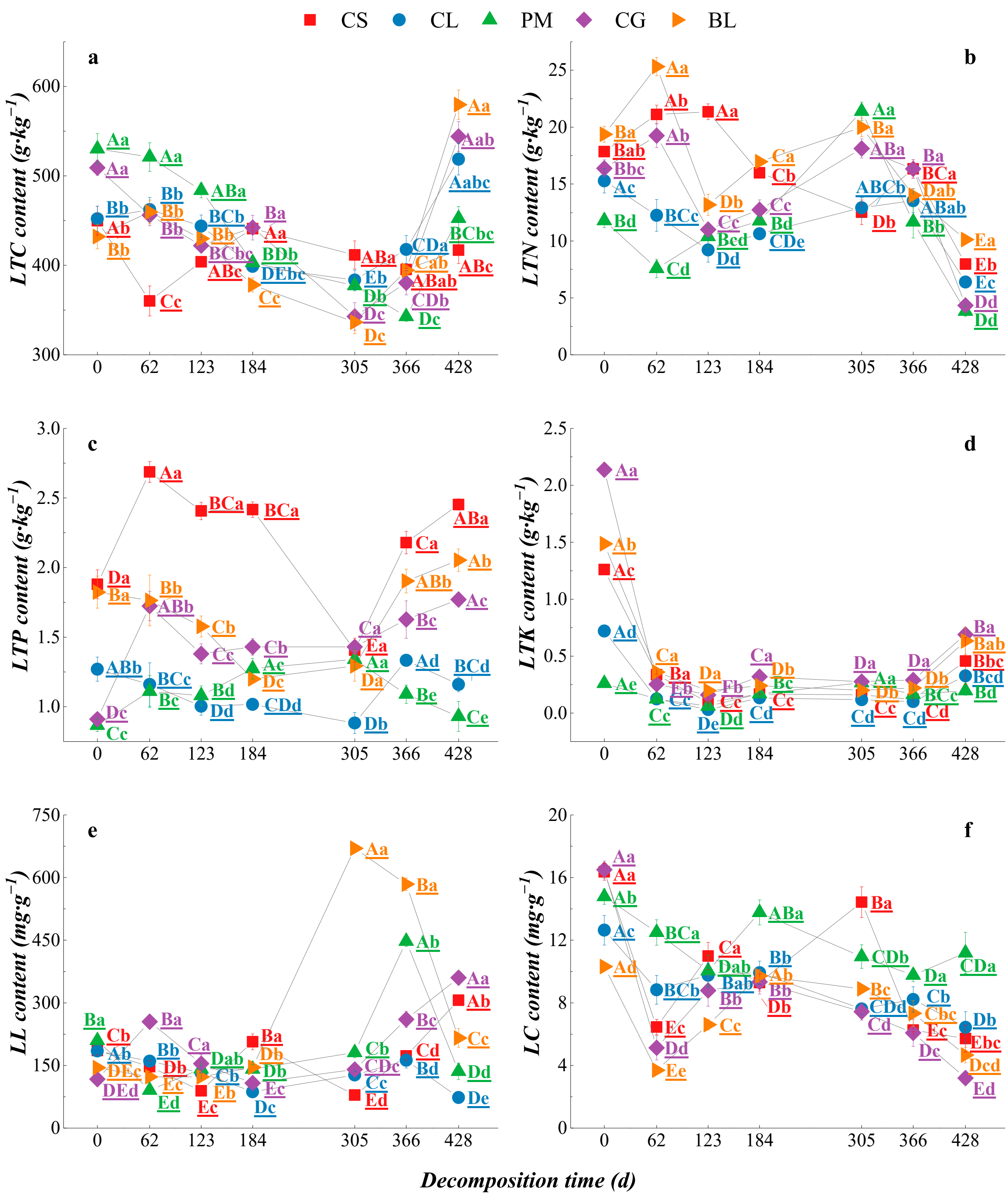

Figure 4. Dynamics of nutrient content in different litters during the litter decomposition process. CS—*Camellia sinensis*, CL—*Cunninghamia lanceolata*, PM—*Pinus massoniana*, CG—*Cinnamomum glanduliferum*, BL—*Betula luminifera*; LTC—litter total carbon, LTN—litter total nitrogen, LTP—litter total phosphorus, LTK—litter total potassium, LL—litter lignin, LC—litter cellulose; A, B, C—differences between decomposition stages of the same treatment; a, b, c—differences between treatments in the same decomposition period; (**a**–**f**) represents the LTC content, LTN content, LTP content, LTK content, LL content and LC content, respectively.

The LTN content of the five kinds of litter showed two dynamic trends during the process of decomposition (Figure 4b). Specifically, the LTN content of *Camellia sinensis*, *Cinnamomum glanduliferum*, and *Betula luminifera* showed an "M" pattern, that is, increasing–

decreasing–increasing–decreasing. In contrast, the pattern of change in the LTN content from *Cunninghamia lanceolata* and *Pinus massoniana* was an inverted "N" pattern, that is, decreasing–increasing–decreasing. The results showed that the change law of LTN content during the litter decomposition of broad-leaved tree species was different from that of coniferous tree species. At the end of the experiment, the LTN content of the five kinds of litter was lower than that of undecomposed litter ($p < 0.05$).

In the process of decomposition, the LTP content fluctuated (Figure 4c). The dynamic change in the LTP content of *Camellia sinensis* and *Cinnamomum glanduliferum* exhibited an "N" pattern, i.e., increasing at first, decreasing, and then increasing again. *Cunninghamia lanceolata* litter exhibited an inverted "N" pattern; that is, the content decreased at first, then increased, and then decreased. *Pinus massoniana* litter exhibited an inverted "V" pattern, and *Betula luminifera* litter showed a "V" pattern. At the end of the experiment, the LTP content of *Camellia sinensis*, *Cinnamomum glanduliferum*, and *Betula luminifera* litter was significantly higher than that of undecomposed litter ($p < 0.05$).

The dynamic changes in LTK content of the five kinds of litter were basically the same (Figure 4d), exhibiting a "V" pattern of first decreasing and then increasing. After 428 days of decomposition, the LTK content of each litter was lower than that of undecomposed litter ($p < 0.05$).

The dynamic changes in LL content during decomposition exhibited three patterns (Figure 4e): *Cinnamomum glanduliferum* showed an "N" pattern, *Camellia sinensis* showed a "W" pattern, and *Pinus massoniana*, *Cunninghamia lanceolata* and *Betula luminifera* showed an inverted "N" pattern. At the end of the decomposition period, i.e., after 428 days of decomposition, the LL content of the coniferous tree species *Pinus massoniana* and *Cunninghamia lanceolata* was lower than the initial value, with the LL content showing a downward trend over the entire period. On the other hand, the LL content of the broad-leaved tree species *Camellia sinensis*, *Cinnamomum glanduliferum*, and *Betula luminifera* was higher than the initial value and showed an increasing trend overall.

The dynamics of the LC content of the five kinds of litter were similar (Figure 4f); it first decreased, then increased, and finally decreased again. After 428 days of decomposition, the LC content of the five kinds of litter was significantly lower than the initial value ($p < 0.05$).

3.2.2. Dynamic Changes in Nutrient Release from Litter

In the process of decomposition, there were some differences in nutrient release rates among the litter types (Figure 5). The release patterns of LTC, LTN, LTP, LTK, and LC in the five kinds of litter were all direct release (Figure 5a–d,f). The LL release patterns of the five kinds of litter during decomposition can be divided into three types: direct release, leaching–enrichment–release and enrichment–release–enrichment. During the whole experiment, the LL release rate of *Camellia sinensis* and *Cunninghamia lanceolata* litter was positive, lignin was released, and *Camellia sinensis* and *Cunninghamia lanceolata* exhibited direct release. After 366 days of decomposition, the LL release rate of *Pinus massoniana* litter was negative, which belonged to enrichment state, while the LL release rate of other decomposition stages was positive, which belonged to release state, and its LL release pattern exhibited leaching–enrichment–release. During 305–366 days of decomposition, the lignin of *Betula luminifera* litter was enriched, and the rest of the decomposition stage was released, and the LL release pattern also exhibited leaching–enrichment–release. When decomposing 62 days and 428 days, the lignin of *Cinnamomum glanduliferum* litter was enriched, and released at other decomposition stages. The LL release pattern of *Cinnamomum glanduliferum* exhibited enrichment–release–enrichment (Figure 5e).

3.3. Soil Nutrient Characteristics of Different Litters during the Process of Decomposition

During the process of decomposition, the SOC content in the five litter treatments was somewhat higher than that without decomposition (Figure 6). The SOC content of *Betula luminifera*, *Cinnamomum glanduliferum*, and *Camellia sinensis* increased rapidly in the early stage of decomposition (184 days before decomposition), and the SOC content of

Pinus massoniana litter increased slowly before 62 days of decomposition. During the decomposition of *Cunninghamia lanceolata* litter, the SOC content increased slowly, indicating that the trend of increasing SOC content during litter decomposition of broad-leaved tree species was better than that of conifer tree species.

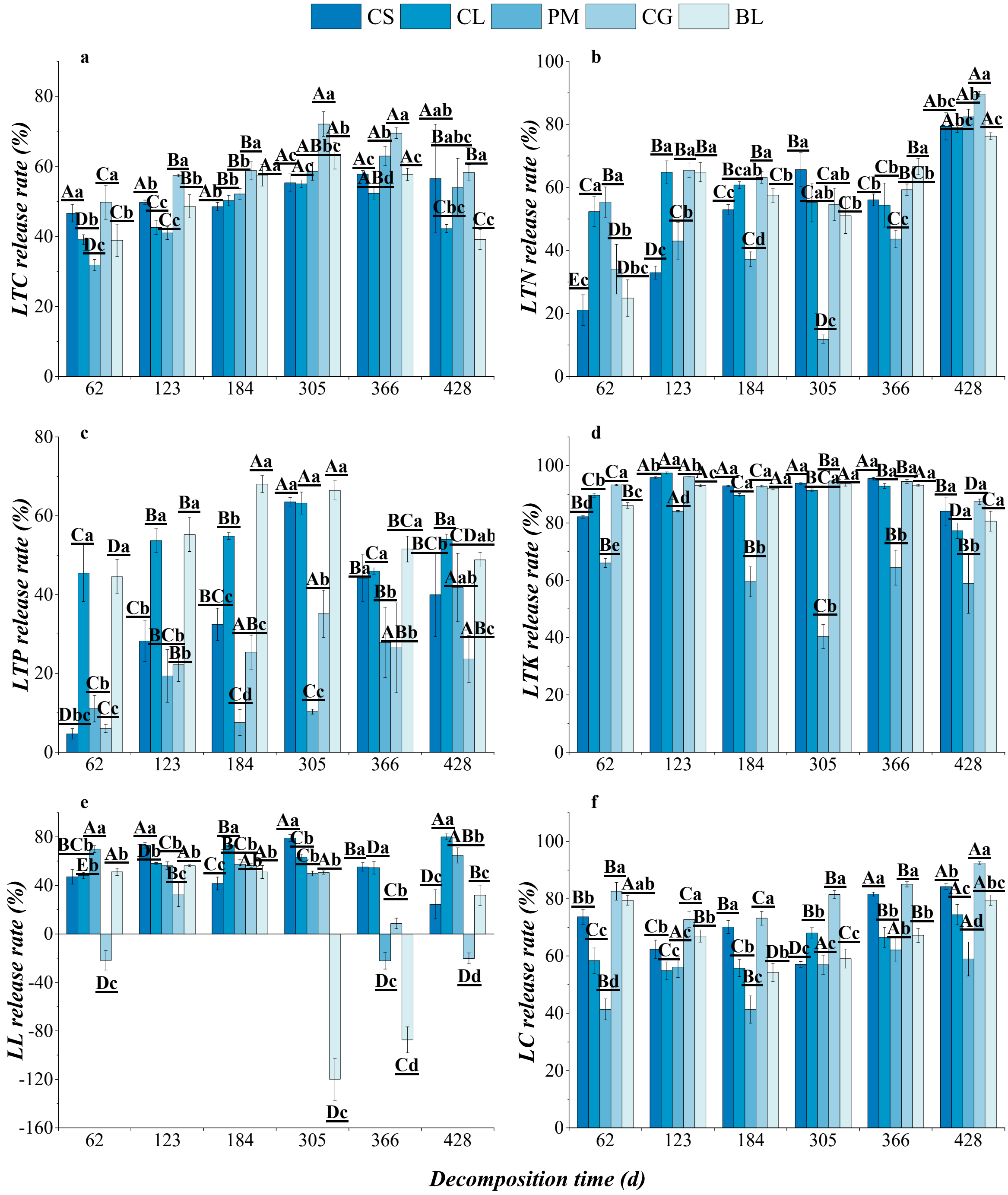

Figure 5. Nutrient release rate of different litters during the litter decomposition process. CS—*Camellia sinensis*, CL—*Cunninghamia lanceolata*, PM—*Pinus massoniana*, CG—*Cinnamomum glanduliferum*, BL—*Betula luminifera*; LTC—litter total carbon, LTN—litter total nitrogen, LTP—litter total phosphorus, LTK—litter total potassium, LL—litter lignin, LC—litter cellulose; A, B, C—differences between decomposition stages of the same treatment; a, b, c—differences between treatments in the same decomposition period; (**a**–**f**) represents the LTC release rate, LTN release rate, LTP release rate, LTK release rate, LL release rate and LC release rate, respectively.

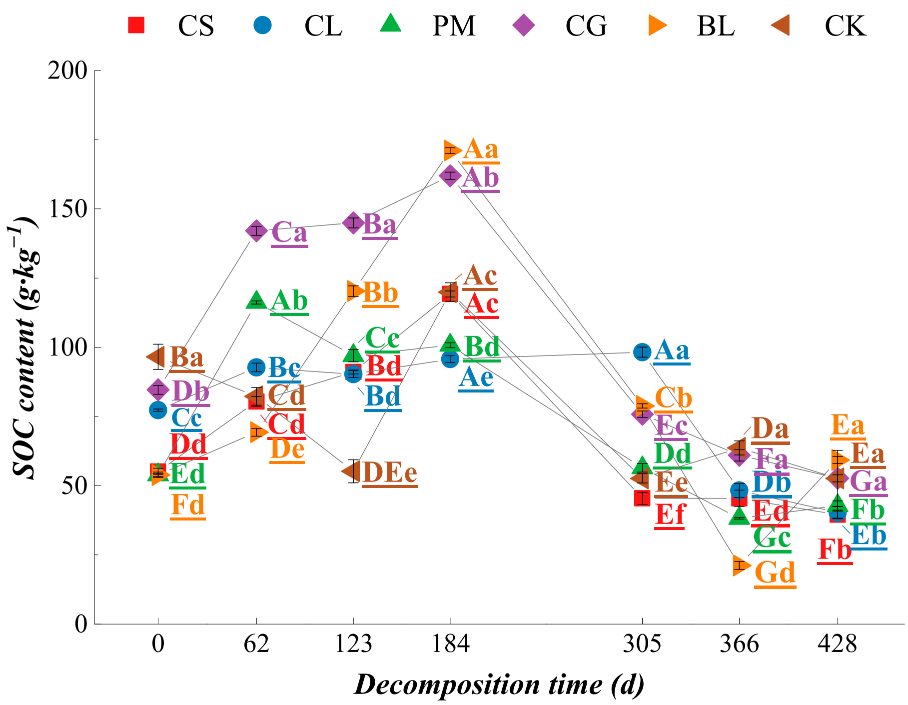

Figure 6. Dynamic changes in SOC content in different litter decomposition processes. CS—*Camellia sinensis*, CL—*Cunninghamia lanceolata*, PM—*Pinus massoniana*, CG—*Cinnamomum glanduliferum*, BL—*Betula luminifera*, CK—control; SOC—soil organic carbon; A, B, C—differences between decomposition stages of the same treatment; a, b, c—differences between treatments in the same decomposition period.

The content of soil nitrogen fluctuated during the decomposition of the five different types of litter, and it was higher at different decomposition stages than at the beginning of the experiment (Figure 7). Overall, the STN content exhibited an increasing trend during the whole experimental period, and the STN content increased more during the decomposition of *Betula luminifera* litter (0–62 d, 123–305 d, 366–428 d). After decomposition for 428 days, the STN contents of treatments with litter from the broad-leaved tree species *Betula luminifera*, *Cinnamomum glanduliferum*, and *Camellia sinensis* were significantly higher than that in the control ($p < 0.05$). The change in the SAN content under the five kinds of litter decomposition showed a trend of increasing at first and then decreasing, in which the increasing trend of the SAN content was better under the litter decomposition of *Betula luminifera*, followed by *Cinnamomum glanduliferum*, which was consistent with the change in the STN content. After decomposition for 428 days, the soil hydrolyzable nitrogen content in the five litter treatments was significantly higher than that in the control ($p < 0.05$), with that in the *Camellia sinensis* treatment being the highest. The results showed that the litter decomposition of broad-leaved tree species had a good contribution to the soil nitrogen content, and the litter of *Betula luminifera* was the best.

The dynamic changes in soil phosphorus content with decomposition differed among the types of litter (Figure 8). The STP content in the *Camellia sinensis*, *Cunninghamia lanceolata*, *Pinus massoniana*, and *Betula luminifera* treatments at each decomposition stage was higher than the initial content, and the change trend increased at first and then decreased. The increasing rate of STP content was higher in *Betula luminifera* (0–305 days), while the STP content increased slowly during litter decomposition of *Camellia sinensis*, *Cunninghamia lanceolata*, and *Pinus massoniana*. *Cinnamomum glanduliferum* showed a decreasing–increasing–decreasing trend. Consistent with the changes in STP, the SAP content in the *Camellia sinensis*, *Cunninghamia lanceolata*, *Pinus massoniana*, and *Betula luminifera* treatments at each decomposition stage was higher than the initial content. During the decomposition of broadleaf tree species *Betula luminifera* and *Camellia sinensis* litter, the SAP increased rapidly during the initial decomposition period of 0–305 days, followed by *Pinus massoniana*. *Cunninghamia lanceolata* increased slowly in the early stage of decomposition (0–184 days), then increased rapidly, and gradually decreased after 305 days of decomposition. Under the decomposition of *Cinnamomum glanduliferum* litter, the content of SAP first decreased and then increased; that is, the content of SAP increased gradually in the later stage of decomposition (184 days after start of decomposition). The results showed that the contribution of the five kinds of litter to the soil phosphorus content was different depending on the decomposition periods, and the contribution rate also differed; this finding is of great importance to the species allocation of ecological tea gardens.

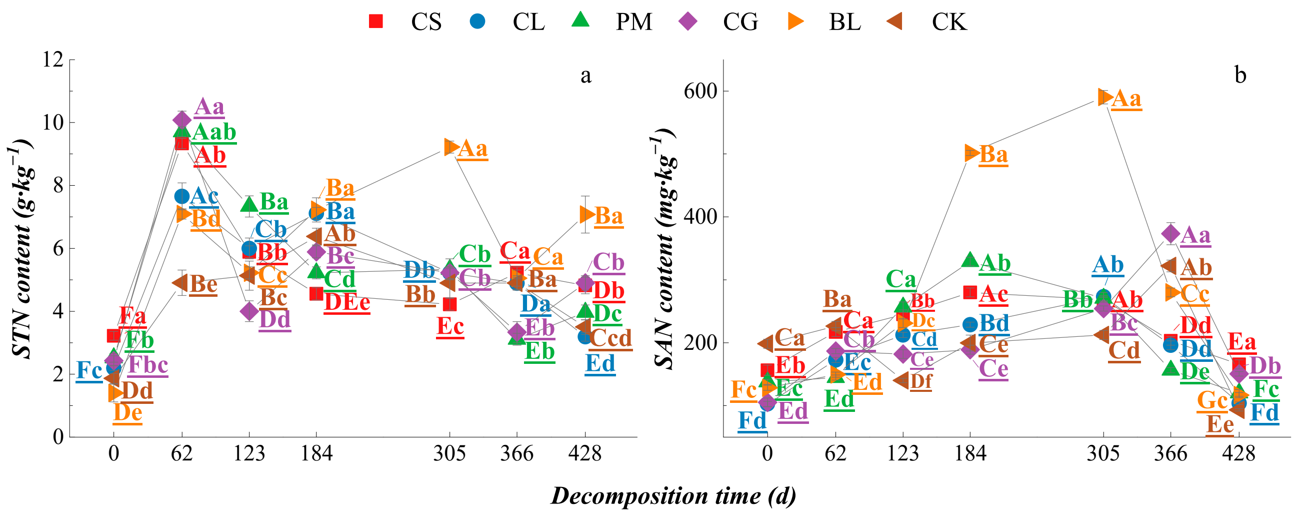

Figure 7. Dynamic changes in soil N content during the litter decomposition process ((**a**)-STN, (**b**)-SAN). CS—*Camellia sinensis*, CL—*Cunninghamia lanceolata*, PM—*Pinus massoniana*, CG—*Cinnamomum glanduliferum*, BL—*Betula luminifera*, CK—control; STN—soil total nitrogen, SAN—soil hydrolyzed nitrogen; A, B, C—differences between decomposition stages of the same treatment; a, b, c—differences between treatments in the same decomposition period.

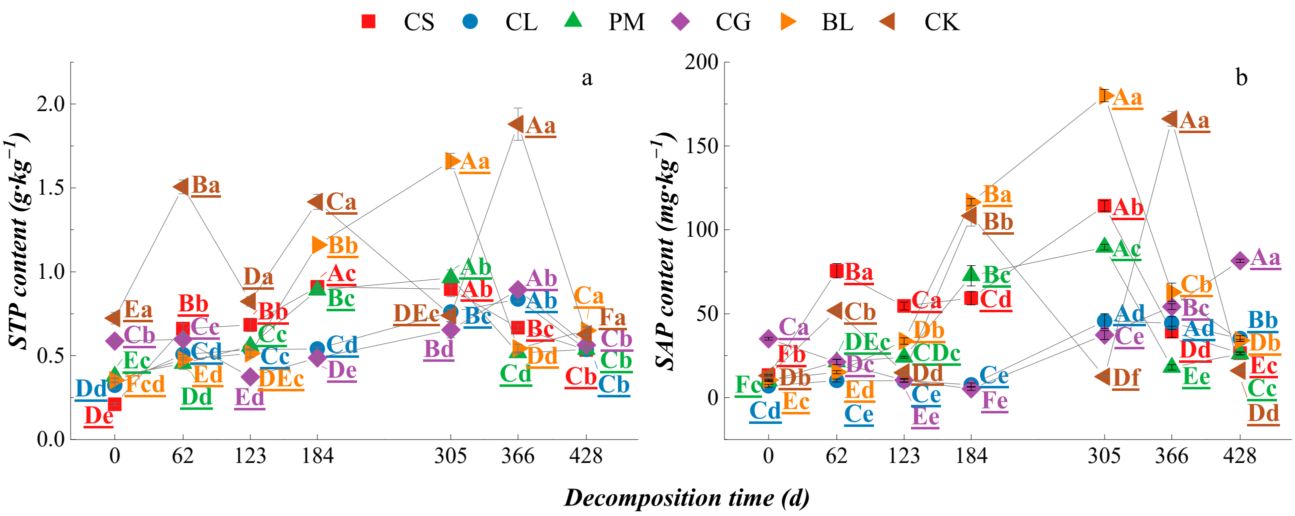

Figure 8. Dynamic changes in soil P content during the litter decomposition process ((**a**)-STP, (**b**)-SAP). CS—*Camellia sinensis*, CL—*Cunninghamia lanceolata*, PM—*Pinus massoniana*, CG—*Cinnamomum glanduliferum*, BL—*Betula luminifera*, CK—control; STP—soil total phosphorus, SAP—soil available phosphorus; A, B, C—differences between decomposition stages of the same treatment; a, b, c—differences between treatments in the same decomposition period.

The dynamics of the soil potassium content during the litter decomposition process are shown in Figure 9. The change in STK content in the *Camellia sinensis*, *Cunninghamia lanceolata*, and *Pinus massoniana* treatments exhibited a "single peak" pattern. During the decomposition period of 0–305 days, the content of STK increased rapidly under the decomposition of *Pinus massoniana*, *Cunninghamia lanceolata*, and *Camellia sinensis* litter, among which *Pinus massoniana* was the fastest. The *Cinnamomum glanduliferum* and *Betula luminifera* treatments showed a "double peak" pattern. The SAK content of *Camellia sinensis*, *Pinus massoniana*, *Betula luminifera*, and *Cinnamomum glanduliferum* litter in the 62–366-day decomposition stage was higher than the initial content, while the SAK content first decreased and then increased under the *Cunninghamia lanceolata* treatment. During the decomposition period of 0–62 days, the SAK content increased rapidly during the decomposition of *Camellia sinensis*, *Pinus massoniana*, *Betula luminifera*, and *Cinnamomum glanduliferum* litter, while that of *Cunninghamia lanceolata* decreased slowly. During the decomposition period of 62–305 days, the content of SAK increased continuously during the decomposition of *Betula luminifera* litter, while that of *Pinus massoniana* and *Camellia sinensis* fluctuated, which slowed down the rate of increase of SAK content overall. The content of SAK increased gradually after 62 days of litter decomposition of *Cinnamomum glanduliferum* and *Cunninghamia lanceolata*.

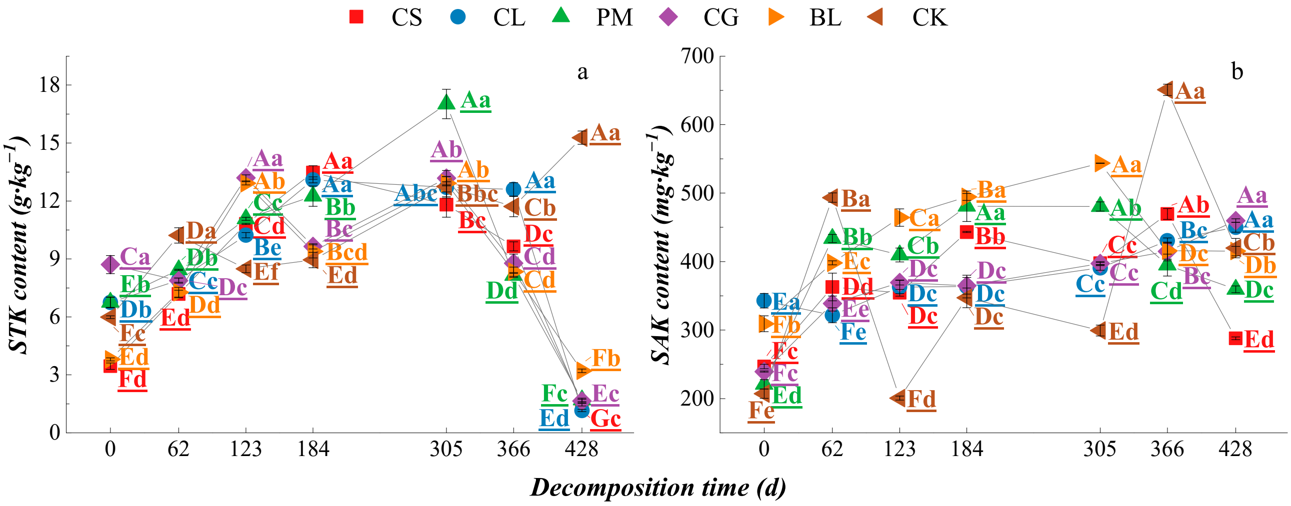

Figure 9. Dynamic changes in soil K content during the litter decomposition process ((**a**)-STK, (**b**)-SAK). CS—*Camellia sinensis*, CL—*Cunninghamia lanceolata*, PM—*Pinus massoniana*, CG—*Cinnamomum glanduliferum*, BL—*Betula luminifera*, CK—control; STK—soil total potassium, SAK—soil available potassium; A, B, C—differences between decomposition stages of the same treatment; a, b, c—differences between treatments in the same decomposition period.

3.4. Relationship between Nutrient Release from Litter and Soil Nutrients

The correlation between the litter nutrient release rate and soil nutrients varied among the litter treatments (Figure 10). The LTC release rates of *Camellia sinensis*, *Pinus massoniana*, and *Cinnamomum glanduliferum* litter were negatively correlated with the SOC content, and the LTN release rates of *Camellia sinensis*, *Cunninghamia lanceolata*, *Pinus massoniana*, and *Cinnamomum glanduliferum* litter were also negatively correlated with the soil nitrogen content. There was a significant negative correlation between the LTP release rate of *Pinus massoniana* litter and the SAP content ($p < 0.05$). The release rate of LTP of *Betula luminifera* was extremely significantly positively correlated with the content of STP and SAP ($p < 0.01$). The release rate of LTK of *Camellia sinensis* and *Betula luminifera* was extremely significantly positively correlated with the content of STK and SAK ($p < 0.01$). The LTK release rate of *Cunninghamia lanceolata* and *Cinnamomum glanduliferum* litter was extremely significantly positively correlated with the STK content ($p < 0.01$) and negatively correlated with the SAK content. In addition to the factors that directly affect soil nutrient content, LL and LC release rate also have a certain impact on soil nutrients, and there are species differences among different litters.

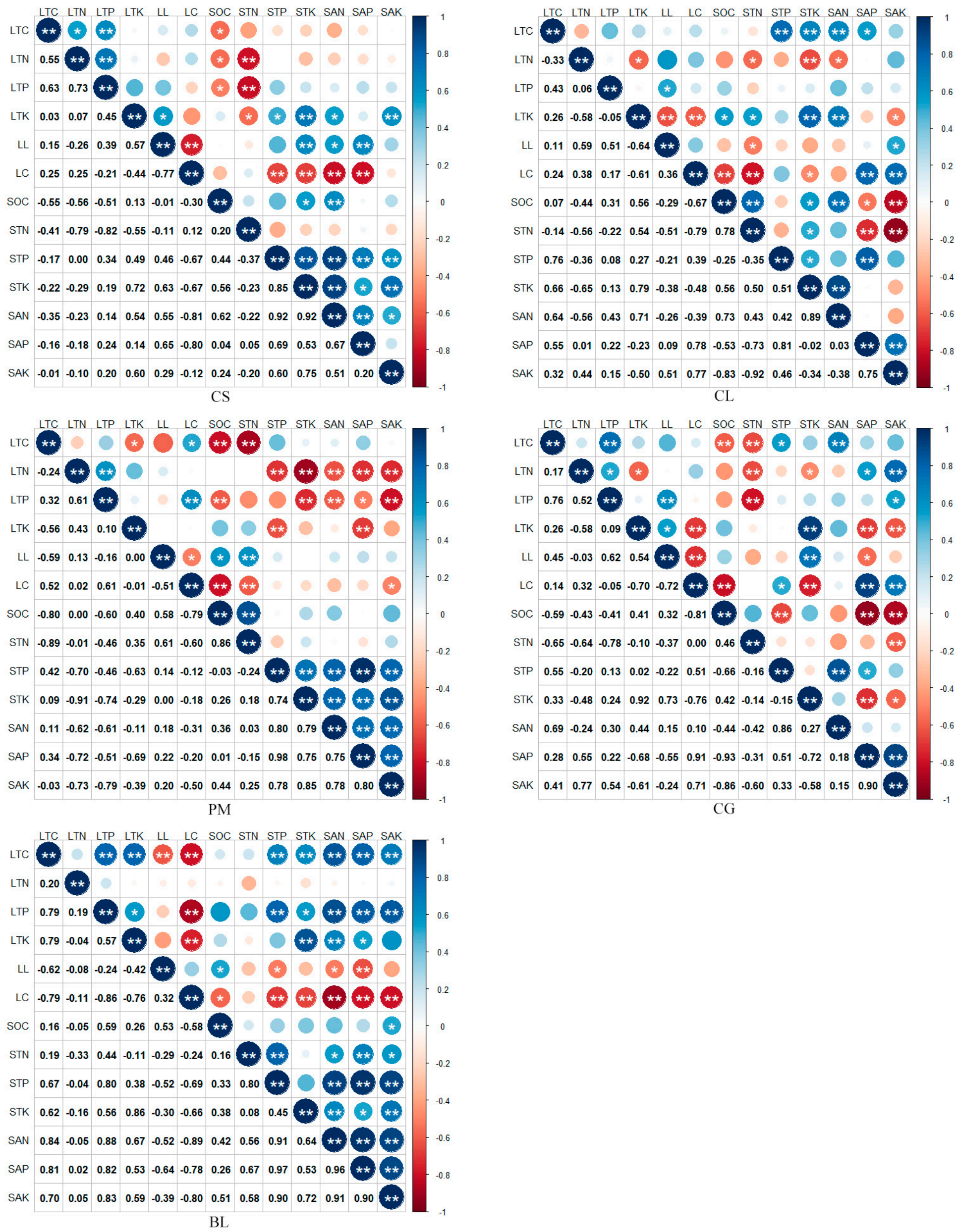

Figure 10. Correlation between the nutrient release rates of litter and soil nutrient contents. CS—*Camellia sinensis*, CL—*Cunninghamia lanceolata*, PM—*Pinus massoniana*, CG—*Cinnamomum glanduliferum*, BL—*Betula luminifera*; LTC—litter total carbon, LTN—litter total nitrogen, LTP—litter total phosphorus, LTK—litter total potassium, LL—litter lignin, LC—litter cellulose; SOC—soil organic carbon, STN—soil total nitrogen, STP—soil total phosphorus, STK—soil total potassium, SAN—soil hydrolyzed nitrogen, SAP—soil available phosphorus, SAK—soil available potassium; on the right side of the figure is the correlation coefficient, and the circle size represents the correlation coefficient. ** indicates that the significant level is 0.01 ($p < 0.01$); * indicates that the significant level is 0.05 ($p < 0.05$).

Redundancy analysis of the litter nutrient release rate and soil nutrients revealed differences among the five kinds of litter (Table 3). The LTC release rate of *Cunninghamia lanceolata* and *Pinus massoniana* litter had the maximum explanation rate, indicating that the change in soil nutrients with the decomposition of those species was mainly limited by carbon elements; the LL release rate of *Camellia sinensis* and *Betula luminifera* litter had the maximum explanation rate. This result shows that the change in soil nutrients was mainly limited by the LL content. This further shows that there are differences in the effects on soil nutrients of the decomposition of broad-leaved tree species and coniferous tree species.

Table 3. Explanation rates of the litter nutrient release rate for soil nutrient changes.

Litter Type	Factor	Explanation Rate/%	P
Camellia sinensis	LTC release rate	43.75	0.005
	LTN release rate	31.88	0.027
	LTP release rate	44.61	0.005
	LTK release rate	53.36	0.002
	LL release rate	58.58	0.002
	LC release rate	39.34	0.023
Cunninghamia lanceolata	LTC release rate	62.02	0.002
	LTN release rate	40.74	0.010
	LTP release rate	55.56	0.003
	LTK release rate	51.39	0.003
	LL release rate	48.00	0.005
	LC release rate	51.78	0.003
Pinus massoniana	LTC release rate	76.96	0.003
	LTN release rate	45.63	0.012
	LTP release rate	57.96	0.003
	LTK release rate	64.55	0.003
	LL release rate	52.24	0.003
	LC release rate	75.22	0.003
Cinnamomum glanduliferum	LTC release rate	59.94	0.004
	LTN release rate	58.64	0.004
	LTP release rate	60.82	0.003
	LTK release rate	46.70	0.005
	LL release rate	23.13	0.107
	LC release rate	55.23	0.004
Betula luminifera	LTC release rate	38.34	0.013
	LTN release rate	19.69	0.120
	LTP release rate	42.59	0.006
	LTK release rate	28.76	0.036
	LL release rate	89.33	0.001
	LC release rate	11.59	0.355

LTC—litter total carbon, LTN—litter total nitrogen, LTP—litter total phosphorus, LTK—litter total potassium, LL—litter lignin, LC—litter cellulose.

4. Discussion

Plant litter is a very important part of forest ecosystems, and its decomposition is key to the material circulation and energy flow in forest ecosystems, which play important roles in maintaining forest ecosystem productivity and soil fertility and promoting nutrient cycling in the system [1]. Different plants affect the process of soil nutrient cycling via their litter quality and decomposition rate [19]. In the process of natural decomposition, litter is accompanied by the release of nutrients, but it does not always release nutrients, and the speed and amount of various nutrient elements released from litter to soil are different. This release process is restricted by many factors, such as the type of litter, decomposition stage, chemical composition, soil environment, soil biological activity, and other factors [20]. The nutrient release law of litter is generally determined by plant species, decomposition stage, and environmental factors [21,22], but also depends on its own nutrient properties [23]. In this study, the changes of nutrient content and the release of five kinds of litter were different with the decomposition time. The LTC, LTN, and LTP of five kinds of litter were all released directly. The LTC release rate of different litters was different, which is related to the chemical properties of litter and its decomposition rate. In the process of decomposition, the organic carbon mineralization rate of different litter is different with the decrease of the content of decomposable matter [24]. Some studies have shown that the C/N ratio of litter is low, which can promote the release of N element and P element from litter [15,25]. In this study, the initial C/N ratio in descending order was *Pinus massoniana* (45.49), *Cinnamomum glanduliferum* (31.11), *Cunninghamia lanceolata* (29.70), *Camellia sinensis*

(25.35), and *Betula luminifera* (22.33), which was inconsistent with Xie Tingting's study [26]. The reason may be that in the process of litter decomposition, the microorganisms involved in litter decomposition will absorb some inorganic nitrogen from the environment, thus adjusting the C/N ratio [27]. In addition, the physical comminution and leaching process at the initial stage of decomposition will also cause the loss of mineralized nitrogen element with rainfall [14,28], so that the C/N ratio in the litter during decomposition changes constantly. The nutrient release of litter was affected not only by the C/N ratio, but also by the content of lignin [20]. *Cinnamomum glanduliferum* has less lignin content, so the nutrient release of litter in this study is affected by the C/N ratio and the content of lignin. In the process of litter decomposition, K element was easily released [3]. In this study, the LTK of five kinds of litter were all released directly. In the leaching stage, soluble sugar and mineral K^+ were leached into the soil under the action of rainwater. This is the reason for the rapid release of potassium element at the initial stage of decomposition [29]. These factors that affect the nutrient concentration of litter in the decomposition process make the nutrient concentration change dynamically, so the nutrient release rate of litter also changes dynamically, thus affecting the nutrient release patterns of litter. Some studies have shown that the decomposition rate of litter is mainly controlled by the initial C content and LL content. In general, litter with a high initial LL content will has a low decomposition rate [30]. Litter with a high N content, low C/N ratio and low LL content is usually called high-quality litter, and vice versa [31,32]. In this study, broad-leaved tree species produce high-quality litter, coniferous tree species produce low-quality litter, and the decomposition rate is higher in broad-leaved tree species and lower in coniferous tree species, which was consistent with the results of Yang Lin [30]. The rapid release of LC from *Camellia sinensis*, *Betula luminifera*, and *Cinnamomum glanduliferum* litter in the process of decomposition also promoted the decomposition of the litter. In this study, the decomposition half-life and turnover period of broad-leaved tree species were significantly lower than those of coniferous tree species, and the decomposition of broad-leaved tree species litter could accelerate the process of nutrient cycling. Therefore, in the construction of ecological tea gardens, choosing broad-leaved tree species with faster decomposition rates can improve the soil fertility.

Litter is an important source of soil fertility in forest ecosystem, and the dynamic changes of its nutrient elements affect the balance of the whole nutrient pool [33]. The mass loss of litter in the process of decomposition is accompanied by the migration and release of nutrients, which is an important part of the material cycle of the ecosystem and can improve soil fertility. The elements of litter migrate in the process of decomposition, and there are three main release modes of elements in forest litter during decomposition: (1) leaching–release, that is, direct release [34]; (2) enrichment–release [35]; (3) leaching–enrichment–release [36]. Litter decomposition can provide necessary nutrients for plant growth. The main nutrients of tea garden soil include SOC, STN, SAP, and SAK [37]. SOC is the material basis of soil microbial life and many kinds of nutrient elements of *Camellia sinensis*, and it is one of the important indexes to reflect soil maturity and fertility. SOC can enhance the ability of soil water and fertilizer conservation, has a strong buffer capacity for acid and alkali, and can promote the absorption of mineral nutrients by roots. Nitrogen is one of the three elements needed for *Camellia sinensis* growth, the main component of protein, and an important component of protoplast. It plays a key role in the yield and quality of tea. SAP promotes *Camellia sinensis* seedling growth, root branching and root absorption capacity, and has a great effect on yield and quality. Potassium is an activator of many enzymes, which can not only promote photosynthesis and respiration and improve the stress resistance of *Camellia sinensis*, but also improve the aroma of tea [38]. In this study, litter from different species contributed to soil nutrients to different degrees. The release patterns of LTC, LTN, LTP, LTK, and LC in the five kinds of litter were all released directly, which provided more possibilities for the increase in soil nutrient content. The rapid release of LTC from *Cinnamomum glanduliferum* and *Betula luminifera* litter in the process of decomposition makes the content of SOC increase rapidly. The STN content in the five litter treatments increased to different degrees compared with that in the initial decomposition stage, and the STN content in the treatments with litter from the broad-leaved tree species *Camellia sinensis*, *Cinnamomum glanduliferum*, and *Betula luminifera* was significantly higher than that in the control treatment ($p < 0.05$). The results showed that the decomposition of litter from broad-leaved tree species increased the soil N content. After 428 days of decomposition, the SAN content in the five litter treatments was significantly higher than that in the control treatment ($p < 0.05$), which was related to the net release of the LTN content. This finding is consistent with the results of Liu Shuyuan [39]. During the entire process of decomposition, broad-leaved tree species had a better increasing trend of SAN content. The SAP content is an important index for measuring the level of soil P supply [39]. In this study, at the end of the experiment, the SAP content in all treatments was higher than that in the initial stage and significantly higher than that in the control treatment ($p < 0.05$), which was consistent with the net release of LTP. The continuous release of LTP from *Cinnamomum glanduliferum* and *Betula luminifera* led to a rapid increase in STP and SAP. Overall, the STK content increased faster under the decomposition of *Pinus massoniana*, *Cunninghamia lanceolata*, and *Camellia sinensis*, and the SAK content increased faster under the decomposition of *Pinus massoniana* and *Betula luminifera* litter. However, the LTK release rate of *Pinus massoniana* was significantly lower than that of the other four kinds of litter. This may be because the slowly available potassium and ineffective potassium in the soil are transformed into available potassium, which is easily absorbed by plants under the action of microorganisms, resulting in an increase in SAK when LTK is enriched. In addition to the release rates of LTC, LTN, LTP, and LTK, which directly affect soil nutrients, the release rates of LL and LC also have certain effects on soil nutrients. From the correlation analysis, it was found that the release rates of LL and LC from different litters had significant effects on soil nutrients. Lignin and cellulose are difficult to decompose, and their content affects the decomposition rate of litter [30], thus affecting soil nutrients. The lignin/N ratio could also reflect the litter decomposition rate, and there was a significant negative correlation between lignin/N value and litter decomposition rate [40]. In this study, different litter LTN was direct release, and different litter LTN and LL had different release rates in each decomposition stage, which made the lignin/N value change constantly. Therefore, different litter LL and LC release rates had different correlations with soil nutrients. According to the explanation rate of the litter nutrient release rate to soil nutrient change, the LL release rate of broadleaf tree species *Betula luminifera* litter has the highest explanation rate, indicating that during its decomposition, soil nutrient change is mainly limited by LL content. On the other hand, the *Betula luminifera* litter has a lower LL content and higher decomposition rate, which can promote nutrient cycling and increase the soil nutrient content.

Research shows that ecological tea gardens can improve the safety and quality of tea [41] and can yield positive social, economic, and ecological benefits. The tea-forest model is the primary ecological tea garden construction model. Presently, there are not much data to inform the selection of tree species for ecological tea garden construction, and tree species collocation is unreasonable, resulting in soil erosion, soil fertility decline, and other problems. In the construction of ecological tea gardens, using tree species with a faster litter decomposition rate and faster return of nutrients can not only improve soil fertility, but also lead to a greener ecological tea garden by reducing the environmental pollution caused by the application of exogenous fertilizers. *Betula luminifera*, a broad-leaved tree species, is a good choice.

5. Conclusions

One of the ecological roles of litter is to return nutrients to the soil and provide nutrients for forest growth, which is also an important mechanism of forest self-fertilization. This study shows that the decomposition rate of litter from broad-leaved tree species in the ecosystem is higher than that of litter from coniferous tree species, and the decomposition of litter is largely controlled by the quality of the litter matrix. The addition of different litters promoted soil nutrient cycling and increased nutrient availability in the Jiu'an ecological tea garden, with litter from *Betula luminifera*, *Cinnamomum glanduliferum*, *Pinus massoniana*, and *Cunninghamia lanceolata* improving soil nutrient levels, among which *Betula luminifera* had the best effect. This conclusion confirms our hypothesis. Therefore, *Betula luminifera* was selected to adjust the tree species allocation of ecological tea gardens to promote their sustainable growth, achieve the simultaneous management of forests and tea crops, and to solve the ecological problems of existing tea gardens. The decomposition of litter from this species can increase nutrient return, thereby maintaining fertility and supporting the ecological development of tea gardens.

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