

Article

Effects of Downed Log Decomposition on Soil Properties and Enzyme Activities in Southwest China

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Abstract: Downed logs play crucial roles in carbon and nutrient cycling within forest ecosystems, influencing soil nutrients and revealing their functional roles in these environments. This study focuses on an evergreen broadleaf forest at Ailaoshan Station for Subtropical Forest Ecosystem Studies, Yunnan, and specifically examines three dominant tree species whose logs are heavily decayed: *Lithocarpus xylocarpus* (*L. xylocarpus*), *Lithocarpus hancei* (*L. hancei*), and *Castanopsis wattii* (*C. wattii*). Soil samples were collected from three depths (0–10 cm, 10–20 cm, and 20–30 cm) beneath the downed logs and from control plots without downed logs. The physicochemical properties and enzyme activities of these soils were analyzed to explore the effects of downed log decomposition on the soil properties. The results revealed several key findings: (1) Downed logs significantly increased the soil organic carbon (SOC) and total nitrogen (TN) content in the surface soil (0–10 cm), with the SOC and TN contents under *L. xylocarpus* logs being 368.20% and 65.32% higher than those in the CK plots, respectively, substantially increasing soil nutrient accumulation. (2) Downed log decomposition significantly increased the soil enzyme activities, with the highest activities observed in the surface soil (0–10 cm) under *L. xylocarpus*. In deeper soil layers (20–30 cm), *L. xylocarpus* and *C. wattii* still presented higher enzyme activities than those in the CK plots did ($p < 0.05$). (3) The SOC, TN, and C/N were significantly positively correlated ($r > 0.95$ and $p < 0.01$), whereas the correlations were weak or nonexistent in the CK plots. The release of organic acids from downed logs enhanced the microbial activity, significantly reducing the soil pH ($p < 0.05$). (4) Different tree species exhibited distinct effects during downlog decomposition, with *L. xylocarpus* showing the most significant improvements in the SOC, TN, and enzyme activities, followed by *C. wattii*, whereas *L. hancei* limited carbon accumulation due to faster nitrogen release, resulting in a relatively lower C/N. Overall, this study demonstrated that the interaction between downed log decomposition and soil enzyme activity plays a key role in improving soil fertility and promoting nutrient cycling. This research provides evidence for understanding the impact of downed logs on forest soil ecological functions and microbial functional activity and their role, thereby contributing valuable insights into carbon cycling in subtropical forest ecosystems.

Keywords: downed logs; soil physicochemical properties; soil enzyme activity; nutrient cycling; subtropical forest



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1. Introduction

Soil serves as the foundation for tree growth in forest ecosystems, providing essential growth factors such as water, nutrients, air, and heat. The nutrient reserves in forest soil primarily depend on the substantial input of plant residues, which release nutrients into the

soil through the decomposition process. Forest plants return nutrients from plant residues back to the soil via the soil–plant–soil cycle, increasing the soil nutrient content and playing a vital role in nutrient cycling [1].

Downed logs refer to intact woody material that has naturally died or resulted from human disturbances, lying on the forest floor in various stages of decomposition, with a diameter (typically measured at the thicker end) ≥ 10 cm, a length ≥ 1 m, and a tilt angle exceeding 45° [2]. CWD accounts for approximately 14% of the forest vegetation carbon stock and 61% of the plant residue carbon stock [3]. It is a critical structural and functional component of forest ecosystems, an important carbon and nutrient reservoir, and a key medium and link influencing soil development, as well as the interface between vegetation and soil ecosystems. CWD plays a significant role in energy flow, material cycling, and maintaining the integrity and stability of forest ecosystems. Against the backdrop of global climate warming, CWD has garnered significant attention as an essential part of the global carbon cycle [3,4].

The decomposition of downed logs is a key ecological process that transforms plant inputs into stable soil organic carbon (SOC). Through decay and leaching, various substances are added to the soil, altering its composition. Moreover, the increase in soil organic matter changes soil enzyme activities, indirectly affecting soil composition [5]. This process influences soil carbon storage, nutrient availability, net primary productivity, and the sensitivity of ecosystems to global changes [6,7]. Although the carbon stored in downed logs accounts for only 3%–6% of the total carbon pool in the topsoil layer (0–3 m), it is more susceptible to external disturbances and releases carbon more readily, making it more dynamic than the belowground soil carbon pool [7–9]. Studies have shown that nutrient release patterns during the decomposition of downed logs vary among tree species, leading to differences in nutrient contents in adjacent soils. For example, the soil nitrogen and phosphorus levels beneath *Fagus orientalis* Lipsky are significantly greater than those beneath *Carpinus betulus* Lucas [10]. Soil carbon, nitrogen, phosphorus, and their stoichiometric ratios are effective indicators of soil organic matter quality, and the decomposition of downed logs has a significant effect on these metrics [11]. As a result, the decomposition of downed logs is a crucial ecological process in forest ecosystems; it promotes the formation of organic matter in forest soils, regulates nutrient levels, and is essential for maintaining the stability and development of these ecosystems [12]. Research on downed logs spans several climatic zones and involves different types of forest ecosystems. It addresses several aspects, such as downed log reserves [13,14], distribution patterns [15], decomposition processes [16,17], and its role in soil and water conservation [18]. More detailed studies have also examined the mechanisms of downed log decomposition [19–21], including its range of influence and associated environmental factors [10,22,23]. These studies provide important scientific evidence for understanding the material cycling processes in forest ecosystems and the mechanisms underlying the stable maintenance of biodiversity.

The study site is one of the largest subtropical evergreen broadleaf forests in Southwest China, covering an area of 504 km². It also hosts the largest region of primary montane humid evergreen broad-leaved forests in the country. Domestic scholars have focused primarily on the species composition and storage characteristics of downed logs. For example, Yang [24] analyzed log composition, carbon storage characteristics, and sources within these mountainous wet evergreen broadleaf forests, as well as three main types of secondary succession. This study also estimated the decomposition rates and carbon release rates of dominant tree species. However, the effects of downed log decomposition on soil physicochemical properties and enzyme activities in these forests have not been reported.

Our study focuses on the soil beneath heavily decomposed downed logs from three dominant tree species—*L. xylocarpus*, *L. hancei*, and *C. wattii*—as well as soil from a control site without downed logs. Here, we aim to investigate the basic physicochemical properties of the soil under heavily decayed downed logs and compare it to the control site. By analyzing these properties, we seek to understand how downed log decomposition affects soil and its ecological impacts on nutrient cycling in forest soils. This research aims to clarify

the role of downed logs in maintaining soil health, enhancing soil fertility, and promoting the stability of forest ecosystems. It provides fundamental data to support improved forest nutrient management and soil quality optimization.

2. Materials and Methods

2.1. Study Site

This study was conducted in an evergreen broadleaf forest at Ailaoshan Station for Subtropical Forest Ecosystem Studies, which is located in Ailao Mountain, Jingdong County, Yunnan Province, SW China (24°32′ N, 101°01′ E, and elevation 2480 m), covering an area of 34,483 hectares, which belongs to the native forest area and has little anthropogenic interference. The sampling plots are located in the Southwest Monsoon Climate Zone, which is characterized by a subtropical mountain climate. The annual average temperature is 11.0 °C, with July being the hottest month with an average temperature of 15.3 °C and January being the coldest month with an average temperature of 5.0 °C. The frost periods can last up to 190 days. The annual precipitation averages 1931.1 mm, with distinct dry and wet seasons, while the average annual sunshine percentage is 28%. The climate features long winters (lasting five months) without summer, and the spring and autumn seasons merge for a total of seven months, resulting in a cool climate with a low-light environment. This study focuses on primary subtropical montane humid evergreen broad-leaved forests at elevations of 2200–2800 m. The dominant tree species belong primarily to the *Fagaceae*, *Theaceae*, *Lauraceae*, and *Magnoliaceae* families. The main dominant species in the canopy include *L. xylocarpus*, *L. hancei*, *C. wattii* (*Fagaceae*), *Schima noronhae*, *Hartia sinensis*, *Camellia hsinpeiensis* (*Theaceae*), *Machilus viridis*, *Litsea elongata*, and *Manglietia insignis* and *Michelia floribunda* (*Magnoliaceae*).

2.2. Investigation

The downed logs in the study area were classified into three different grades according to the criteria developed by Sollins et al. [25] and the actual sampling situation (Table S1). The sample plot (1 ha) was selected for the survey; the fallen trees of *L. xylocarpus*, *L. hancei*, and *C. wattii* in the heavy decay class were numbered; the soil underneath 9 fallen trees was collected; and a total of 27 soil samples were collected (3 species × 3 replicates × 3 soil levels) (Figure 1). A control plot without fallen trees, measuring 2 m in diameter, was also selected, resulting in six control soil samples. Before sampling, the soil surface was cleared of impurities, such as dead plant material and animal residues. Soil samples were then collected at three depths, 0–10 cm (first layer), 10–20 cm (second layer), and 20–30 cm (third layer), for physicochemical analyses. All the samples were hand-picked to remove coarse roots and stones and then passed through a 2 mm sieve to remove roots and other debris. The collected soil samples were divided into two subsamples: one subsample was air-dried for the physicochemical property analysis, while the other subsample was stored at 4 °C and sent to the laboratory for a soil enzyme activity assessment.

2.3. Soil Nutrient Content Measurement

2.3.1. Total Nitrogen and Phosphorus Contents (TN and TP)

Concentrated sulfuric acid (H₂SO₄) and hydrogen peroxide (H₂O₂) were used for high-temperature decoction. The total nitrogen and phosphorus contents was then determined via a continuous flow analyzer (SEAL Analytical AA3, Norderstedt, Germany) and calculated via the following equation:

$$N, P(\text{mg/g}) = \frac{C \times V}{m} \quad (1)$$

where *C* is the concentration of the analyte as read on the continuous flow analyzer, measured in mg/L; *V* represents the volume of the liquid sample being measured, in L; and *m* is the mass of the dried sample, measured in g.

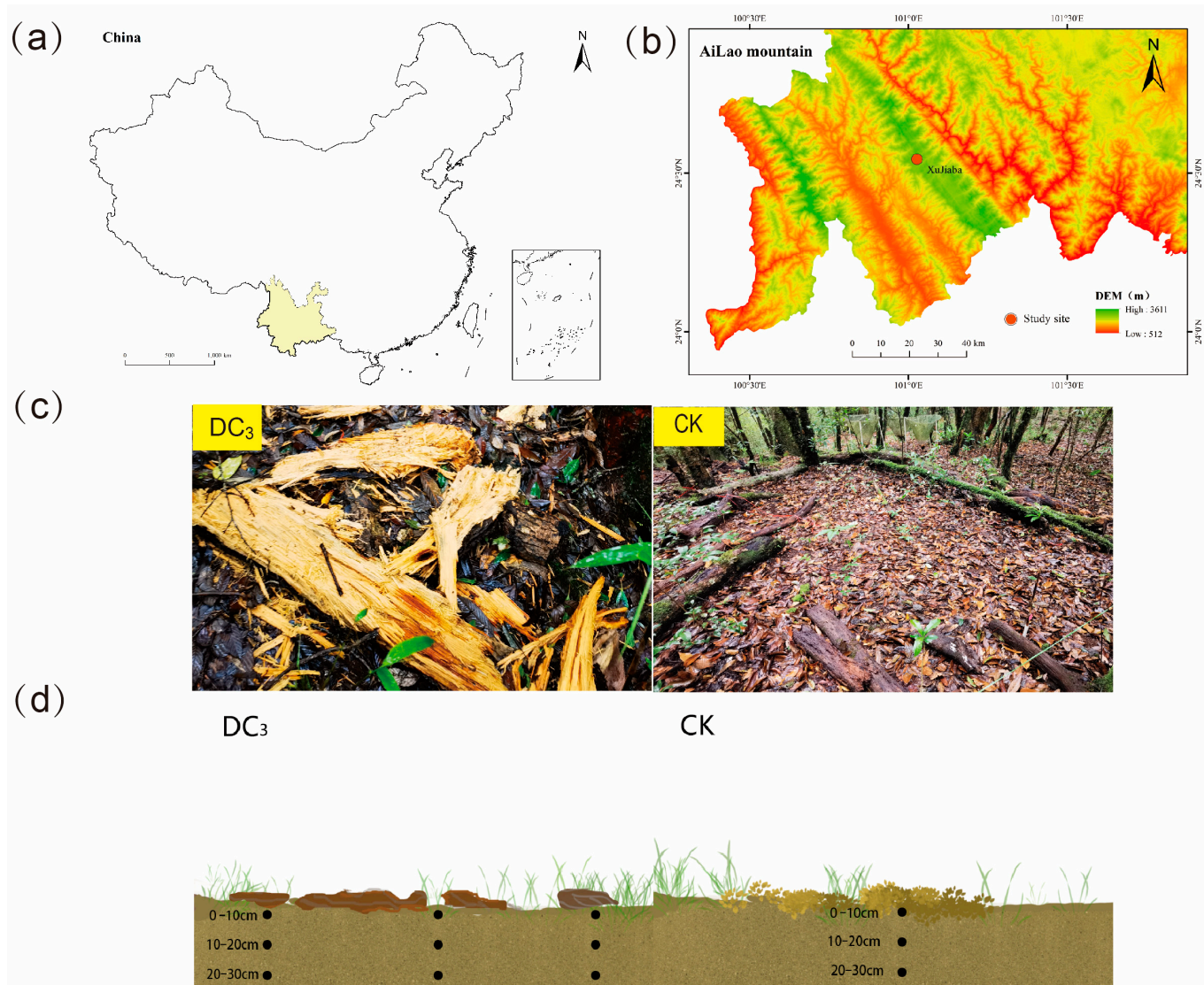


Figure 1. Geographical location (a) and the study site in the Ailao Mountain (b), photographs of the study site for each downed log decay class (c), and a schematic diagram of the soil sampling location (d).

2.3.2. Organic Carbon Content of the Soil (SOC)

To determine the organic carbon content of the soil, a potassium dichromate titration method was used. First, 0.100 g of fine soil (0.1 mm) was weighed into a test tube. Then, 5 mL of potassium dichromate, 5 mL of sulfuric acid, and zeolite were added to the test tube. The mixture was heated in an oil bath at 175–185 °C for 5 min. After boiling, the mixture was transferred to a conical flask, and 2 to 3 drops of an indicator (o-phthalocyanine) were added. Titration was performed using ferrous sulfate, with each sample consuming approximately 20 mL. The organic carbon content was then calculated via the following equation:

$$W_{c,o} = \frac{\frac{0.800 \times 5.0}{V_0} \times (V_0 - V) \times 0.003 \times 1.1}{M_1 \times K_2} \times 1000 \quad (2)$$

where 8000 represents the concentration of potassium dichromate standard solution, in g/kg; 5.0 represents the volume of potassium dichromate standard solution, measured in mL; V_0 represents the volume of desulfurized ferrous solution for blank calibration, measured in mL; V represents the volume of desulfurized ferrous solution for titration of the soil sample, measured in mL; 0.003 represents the molar mass of 1/4 carbon atom,

in g/mmol; 1.1 represents the oxidation correction factor; M_1 represents the mass of the air-dried soil sample, measured in g; and K_2 represents the moisture conversion factor for converting air-dried soil to dry weight.

2.4. Soil Enzyme Activity Measurement

The soil enzymes studied in this study included oxidases such as CAT-peroxidase, and POX-polyphenol oxidase, as well as hydrolases, such as CB-cellobiose hydrolase, AG- α -glucose shikimate, BG- β -glucosidase, XS- β -xylosidase, glycosidase, and XS- β -xylose shikimate lyase. The soil enzyme activities were determined via the method described by DeForest [26].

2.4.1. Measurement of Soil Oxidase Activity

After the soil samples were reacted with L-DOPA as the substrate, the absorbance at 460 nm was measured via a multifunctional full-wavelength microplate reader, and the soil oxidase activity was subsequently calculated. The calculations were performed via the following equation:

$$\text{Activity} = \frac{\text{Final ABS} \times \text{Buffer vol}}{k \times \text{Homogenate vol} \times \text{Time} \times \text{Soil mass}} \quad (3)$$

$$\text{Final ABS} = \text{ABS of assay} - \text{ABS of negative control} - \text{ABS of sample control} \quad (4)$$

where Activity is the measured enzyme activity ($\mu\text{mol h}^{-1} \text{g}^{-1}$); ABS is the absorbance value at 460 nm; Buffer vol is the total volume of the soil suspension; k is the molar extinction coefficient ($7.9 \mu\text{mol}^{-1}$); Homogenate vol is the volume of the soil suspension added to the plate; Time represents the incubation time (h); Soil mass is the fresh weight of the soil (g); ABS of the assay is the absorbance value of the sample wells; ABS of the negative control is the ABS of the negative reference wells; and ABS of the sample control is the absorbance value of the control wells.

2.4.2. Measurement of Soil Hydrolase Activity

The hydrolase activity was determined via a 96-well microplate fluorescence method, based on the calibration curve, soil dry weight, and incubation time. The calculations were performed via the following equation:

$$\text{Activity} = \frac{\text{Net fluor.} \times \text{Buffer vol}}{\epsilon \times \text{Homogenate vol} \times \text{Time} \times \text{Soil mass}} \quad (5)$$

$$\text{Net fluor.} = \left(\frac{\text{Sample assay} - \text{Soil control}}{\text{Quench coefficient}} \right) - \text{Neg. control} \quad (6)$$

$$\epsilon = \frac{\text{Reference standard}}{M} \quad (7)$$

$$\text{Quench coef.} = \frac{(\text{Quench standard} - \text{Soil control})}{\text{Reference standard}} \quad (8)$$

where Activity represents the soil enzyme activity ($\text{nmol h}^{-1} \text{g}^{-1}$), Net fluor. refers to the net fluorescence value, and the Buffer vol indicates the total volume of the soil suspension. ϵ denotes the slope of the standard curve-emission coefficient (fluor.nmol^{-1}). The Homogenate vol is the volume of soil suspension added to the enzyme plate, and Time refers to the incubation period (h). The Soil mass is the fresh weight of the soil (g), Sample assay denotes the fluorescence value of the sample wells, and the Soil control represents the fluorescence value of the control wells. Quench coefficient is the quenching coefficient, Neg. control indicates the fluorescence value of the negative reference wells, and the Reference standard refers to the fluorescence value of the reference standard wells. M represents the molar number of the standard (nmol), Quench standard vol. indicates the volume of quenching standard in moles.

2.5. Data Processing

Two-way analysis of variance (ANOVA) was used to analyze the significance of the differences in the basic soil physicochemical properties and soil enzyme activities and, in particular, the effects of the interaction of fallen tree species and soil depth. The Partial Eta Squared was used to express the differences caused by factors such as tree species, soil depth, or the combined effects of the two and to measure the magnitude of the treatment effects [27]. The significance of the differences between different tree species was assessed via one-way analysis of variance (ANOVA) followed by Duncan's multiple range test. Additionally, one-way ANOVA and Duncan's multiple range test were used to analyze the differences in basic soil physical and chemical properties and soil enzyme activities across various tree species and soil depths under downed logs [28]. Pearson's correlation analysis was used to determine the relationships between basic soil physical and chemical properties and soil enzyme activities in both the downed logs and the control sites. Principal Component Analysis (PCA) was used to explore the relationships among the test characteristics and to group the samples on the basis of enzyme activity and basic chemical properties. The PCA confirmed the uniqueness of soils enhanced by downed logs in improving soil health. The data were analyzed by SPSS 24.0 software.

3. Results

3.1. Significance and Effect Sizes of Downed Log Species, Soil Depth, and Their Interactions on Soil Physicochemical Properties and Enzyme Activities

The effects of tree species, soil depth, and their interaction on soil physicochemical properties and enzyme activities significantly differed. This study revealed distinct variations among tree species, with *Lithocarpus xylocarpus* (*L. xylocarpus*) and *Castanopsis wattii* (*C. wattii*) exhibiting significantly greater SOC and TN contents than did *Lithocarpus hancei* (*L. hancei*) and the control (CK). Different tree species had highly significant impacts on the soil organic carbon (SOC), the total nitrogen (TN), the total phosphorus (TP), the carbon-to-nitrogen ratio (C/N), the carbon-to-phosphorus ratio (C/P), and the nitrogen-to-phosphorus ratio (N/P) ($p < 0.01$). Significant differences were also observed in the enzyme activity indicators, such as polyphenol oxidase (POX), β -glucosidase (BG), and β -xylosidase (XS) ($p < 0.05$) (Tables 1 and S4).

Table 1. Differential significance of fallen tree species, soil depth, and their interaction on soil physicochemical properties.

Parameters	Tree Species		Soil Depth		Tree Species $\times$ Soil Depth	
	F-Value	Partial Eta Squared	F-Value	Partial Eta Squared	F-Value	Partial Eta Squared
SOC	43.608 **	0.829	32.228 **	0.782	4.588 **	0.505
TN	22.213 **	0.712	30.263 **	0.771	0.691	0.133
TP	8.277 **	0.479	12.348 **	0.578	2.302	0.338
C/N	38.467 **	0.81	17.615 **	0.662	2.851	0.388
C/P	30.93 **	0.775	15.961 **	0.639	3.224 *	0.417
N/P	22.429 **	0.714	9.469 **	0.513	0.847	0.158
pH	3.19	0.262	2.773	0.236	0.161	0.035
CAT	3.18	0.261	3.499	0.28	0.156	0.034
POX	5.254 *	0.369	3.033	0.252	0.045	0.01
CB	1.751	0.163	0.812	0.083	0.704	0.135
AG	1.933	0.177	0.198	0.022	0.136	0.029
BG	5.263 *	0.369	0.189	0.021	0.262	0.055
XS	4.459 *	0.331	1.177	0.116	0.372	0.076

** Significant correlation at the 0.01 level; * significant correlation at the 0.05 level. The tree species studied were *L. hancei* (Y), *L. xylocarpus* (M), *C. wattii* (B), and the control sample site (no downed logs) (CK) soil. The abbreviations represent the following variables: SOC = organic carbon, TN = total nitrogen, TP = total phosphorus, C/N = carbon-to-nitrogen ratio, C/P = carbon-to-phosphorus ratio, N/P = nitrogen-to-phosphorus ratio, pH = soil pH, CAT = catalase, POX = polyphenol oxidase, CB = cellobiose hydrolase, AG = α -glucosidase, BG = β -glucosidase, and XS = β -glucosidase.

The SOC, TN, TP, C/N, C/P, and N/P ratios under the downed logs at the different soil depths exhibited highly significantly differed ($p < 0.01$). This study revealed that all the tree species demonstrated the highest enzyme activity in the surface soil (0–10 cm), while the differences gradually diminished in the deeper soil layers. The interaction between tree species and soil depth had a significant effect on the SOC ($p < 0.01$) and C/P ($p < 0.05$), whereas the other indicators did not reach significant levels ($p > 0.05$) (Tables 1 and S3).

The estimated F-values indicate that among the two single factors, tree species had a greater significant effect on the SOC (43.608), C/N (38.467), C/P (30.93), N/P (22.429), POX (5.254), BG (5.263), and XS (4.459). In contrast, soil depth had a greater impact on the TN (30.263) and TP (12.348). The significant effects of the interaction between tree species and soil depth were smaller than those of the individual factors (Table 1).

3.2. Effects of Downed Log Decomposition on Soil Physicochemical Properties and Enzyme Activities

The results revealed that downed logs from different tree species and soil depths had significant effects on the soil carbon, nitrogen, and phosphorus dynamics and pH. *L. xylocarpus* coverage significantly increased the soil total organic carbon (SOC) and total nitrogen (TN) contents, particularly in the surface soil layer (0–10 cm), where the SOC and TN contents reached 568.26 ± 34.11 g/kg and 8.58 ± 0.74 g/kg, respectively. These values were 368.20% and 65.32% greater than those in the control plots without downed logs (CK) and significantly greater than those of *C. wattii* ($p < 0.05$) and *L. hancei* ($p < 0.05$). The soil C/N and C/P ratios exhibited similar trends, with the highest values occurring in the 0–10 cm soil layer under *L. xylocarpus*, indicating that its decomposition contributed the most to carbon accumulation. As the soil depth increased, the SOC, TN, C/N, and C/P ratios significantly decreased, whereas the N/P ratios exhibited minimal changes. However, in the 0–10 cm soil layer, the N/P ratio under *L. xylocarpus* remained significantly greater than that in the other plots ($p < 0.05$). Changes in the total phosphorus (TP) and pH were relatively stable, with the TP showing little variation across tree species and soil depths. The soil pH slightly decreased in the surface layer, with the *L. xylocarpus* plots exhibiting slightly lower pH values than those of the *C. wattii* and *L. hancei* plots (Figure 2).

3.3. Effects of Downed Log Decomposition on Soil Enzyme Activity

In terms of enzyme activity, the results revealed that logging from different tree species and soil depths had significant effects on soil enzyme activity ($p < 0.05$). The variation in oxidase activity among tree species and between downed logs and control plots (CK) was smaller than that in hydrolase activity. In the surface soil (0–10 cm), the enzyme activity in *L. xylocarpus* soils was generally the highest, particularly for POX and CB activities, which were significantly greater than those in soils under other tree species ($p < 0.05$), whereas the control plots (CK) presented the lowest activity. The soils under *L. hancei* presented the lowest enzyme activity among all the tree species and were close to the levels observed in the CK soils. As the soil depth increased, the enzyme activity decreased across all the plots. However, the soils under *L. xylocarpus* maintained relatively high enzyme activity at all depths, especially the POX and CB activities at 10–20 cm, which remained significantly greater than those in the CK soils ($p < 0.05$). Other enzyme activities (e.g., CAT and XS) differed less among the tree species, but the soils under the downed logs consistently presented greater activity than did the CK plots. These findings indicate that the decomposition of downed logs plays a positive role in increasing soil enzyme activity (Figure 3).

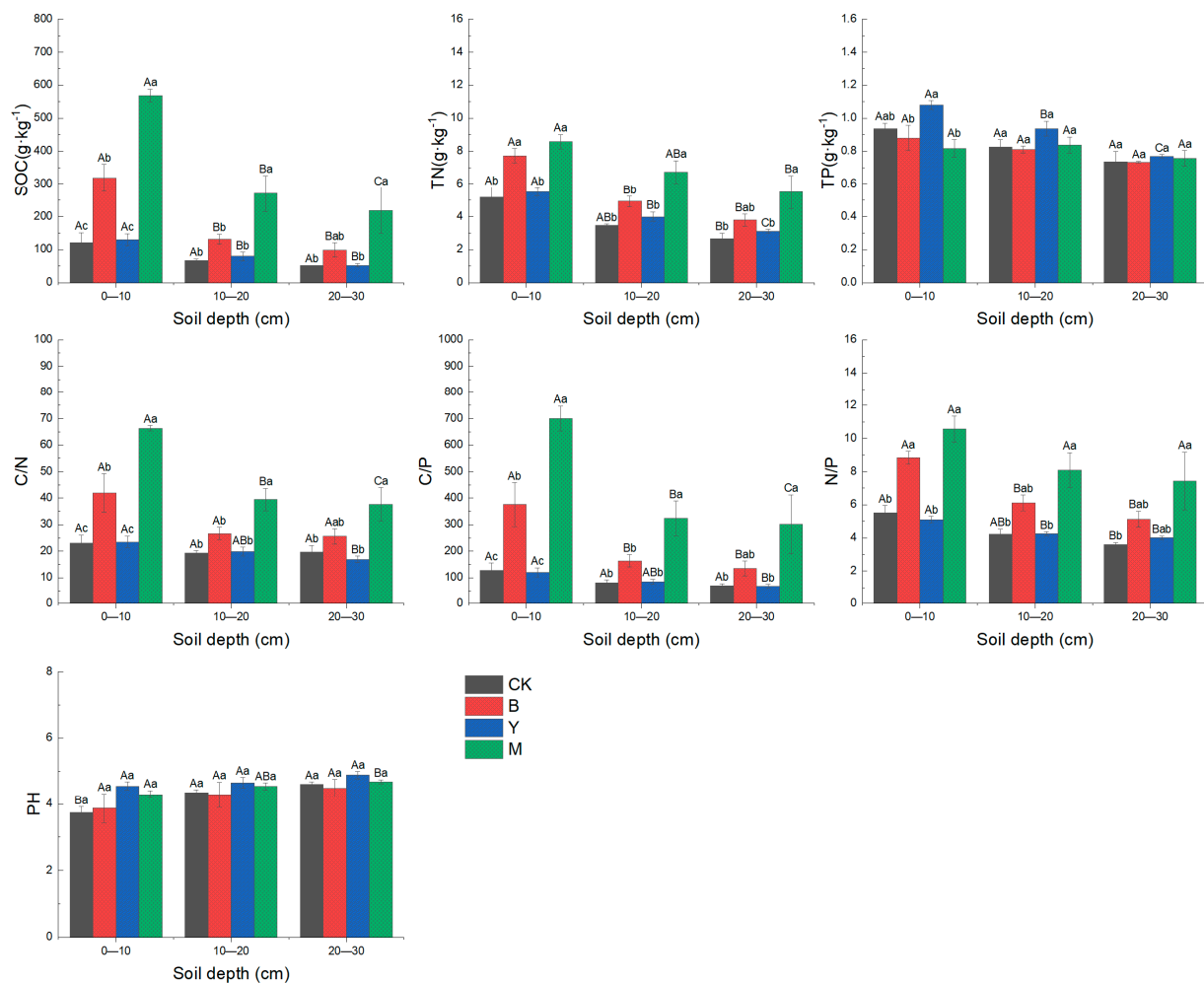


Figure 2. The effect of downed log decomposition on the soil physicochemical properties. Uppercase letters indicate significant differences between different soil depths for the same tree species, while lowercase letters signify significant differences between different tree species at the same soil depth. The data presented in the graphs are shown as the mean $\pm$ standard deviation. The tree species included are *L. hancei* (Y), *L. xylocarpus* (M), *C. wattii* (B), and the control sample site (no downed logs) (CK). The key parameters measured were as follows: TOC (organic carbon), TN (total nitrogen), TP (total phosphorus), C/N (carbon-to-nitrogen ratio), C/P (carbon-to-phosphorus ratio), N/P (nitrogen-to-phosphorus ratio), and pH (soil pH).

Figure 4 illustrates the significant effects of downed log type and soil horizon on soil physicochemical properties and enzyme activities, as revealed through the PCA. The first principal component (DIM1) accounted for 48.8% of the variance, whereas the second principal component (DIM2) explained 15.2%. Together, these components effectively capture the variance characteristics of the data. The results revealed that the decomposition of downed logs affects important physicochemical indicators, such as organic carbon (SOC) and total nitrogen (TN), as well as the activities of many enzymes in the soil. Chemical properties such as the SOC, TN, TP, C/N ratio, C/P ratio, and N/P ratio and indicators of soil enzymes (CAT, POX, CB, AG, BG, and XS) were distributed in different directions, and soil enzymes such as CAT, POX, and CB had relatively high loading values in the first axis in the positive direction, which indicated that these enzymes had relatively high activities in the surface soil (0–10 cm). The loading values of the SOC and TN decreased with increasing soil depth (10–20 cm and 20–30 cm), indicating that soil depth had a negative effect on these factors. The sample points at different soil depths (0–10 cm, 10–20 cm, and 20–30 cm) were more dispersed in the graph, indicating that the effect of the soil level on

the samples was significant. The samples from 0–10 cm were concentrated in the positive direction of the first axis, whereas the samples from 20–30 cm were mostly distributed in the negative direction of the first axis, which reflected the effects of the soil depth on the soil physicochemical properties and enzyme activities.

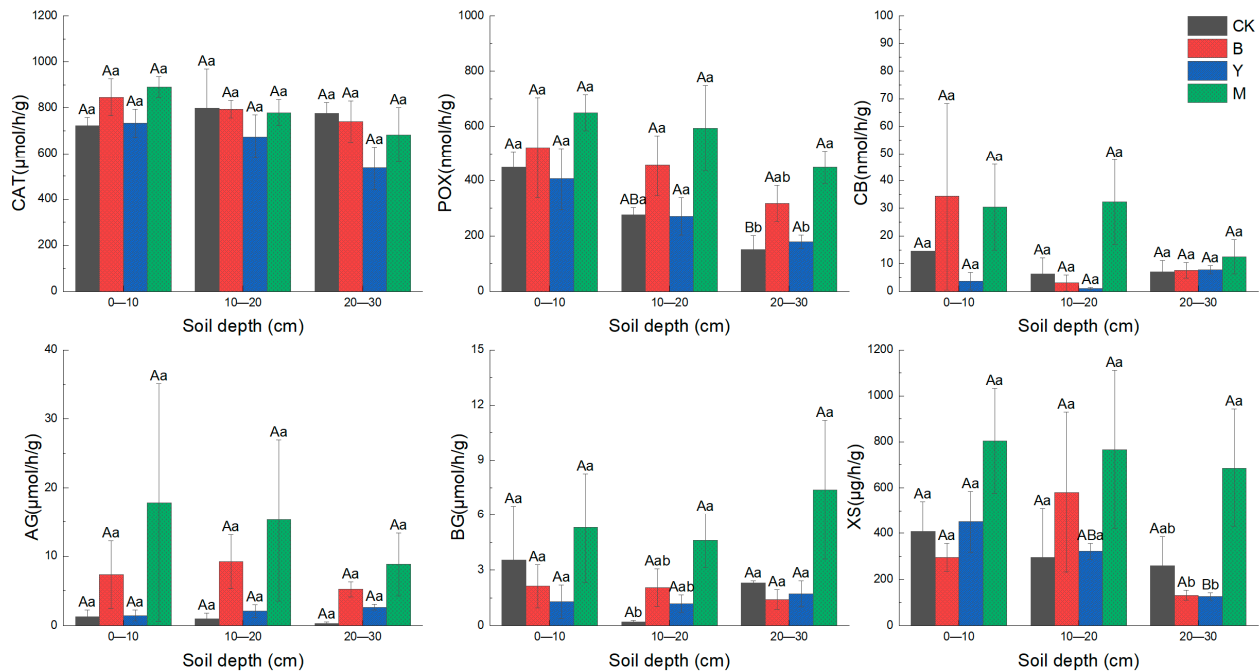


Figure 3. Significance plot of the effect of downed log decomposition on soil enzyme activity. Uppercase letters indicate significant differences between different soil depths for the same tree species, while lowercase letters denote significant differences between different tree species at the same soil depth. The data presented in the graphs are expressed as mean $\pm$ standard deviation. The tree species analyzed include *L. hancei* (Y), *L. xylocarpus* (M), *C. wattii* (B), and the control sample site (without downed logs) (CK). The enzymes measured are CAT (catalase), POX (polyphenol oxidase), CB (cellobiose hydrolase), AG (α -glucose xylanase), BG (β -glucosidase), and XS (β -xylulose).

The distributions of the different tree species also clearly differed, indicating that there were significant differences in the chemical properties and enzyme activities of the soil under the lower logs of the different tree species. For example, the loading values of SOC, TN, CAT, POX, AG, and BG were different among the soils of different tree species, indicating that these chemical properties and enzymes were more different. The samples of *C. wattii* (B) and *L. hancei* (Y) presented high loading values for the SOC, TN, and enzyme activity indices (e.g., CAT and AG), whereas the control sample plot (CK) presented relatively low SOC and enzyme activity indices. The sample points in the CK plot were in the negative direction of the first axis near the areas with lower loading values for SOC and TN, indicating that the CK plot presented lower values for these factors. On the other hand, the samples of *C. wattii* (B), compared with those in the CK plots, and the *L. hancei* (Y) and *L. xylocarpus* (M) plots were distributed in the positive direction of the first axis, indicating that the sample plots of these tree species had greater effects on the soil organic carbon, nitrogen contents, and enzyme activity.

3.4. Correlation Between Soil Physicochemical Properties and Enzyme Activities Under Downed Logs and Control Plots

The correlation analysis results revealed significant relationships between soil physicochemical properties and enzyme activities ($p < 0.05$), highlighting the critical role of decreased log decomposition in regulating carbon, nitrogen, and phosphorus cycling and enzyme activities. There were significant positive correlations between the SOC, TN, C/N

ratio, C/P, and N/P in soils under downed logs ($r > 0.95$ and $p < 0.01$), suggesting a close link between SOC accumulation and the increases in the C/N and C/P ratios. SOC was also significantly positively correlated with several enzyme activities, including POX, BG, and XS ($r = 0.67, 0.42$, and 0.68 , respectively; $p < 0.05$ or $p < 0.01$), reflecting the role of SOC in promoting carbon transformation-related enzyme activities. The soil pH was negatively correlated with TN ($r = -0.34$ and $p < 0.05$), likely due to the organic acids released during log decomposition causing soil acidification, which in turn regulated enzyme activity. BG and XS activities exhibited a strong positive correlation ($r = 0.65$ and $p < 0.01$), suggesting their synergistic role in carbohydrate transformation processes. No correlations were detected between any of the soil indices under the downed logs and TP, CB, or AG (Figure 5).

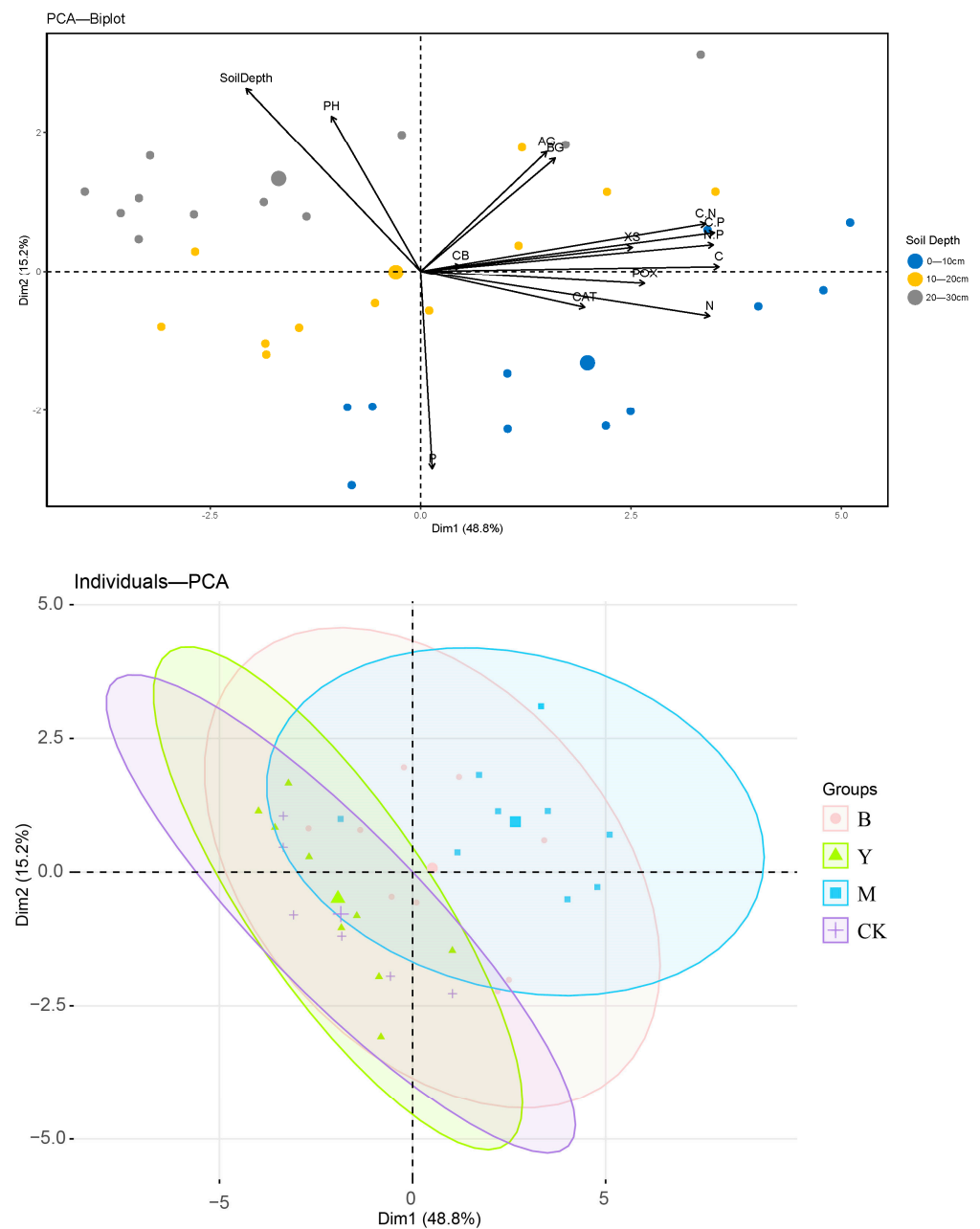


Figure 4. PCA analysis and variable contribution of downed log mulch on soil physicochemical properties and enzyme activities.

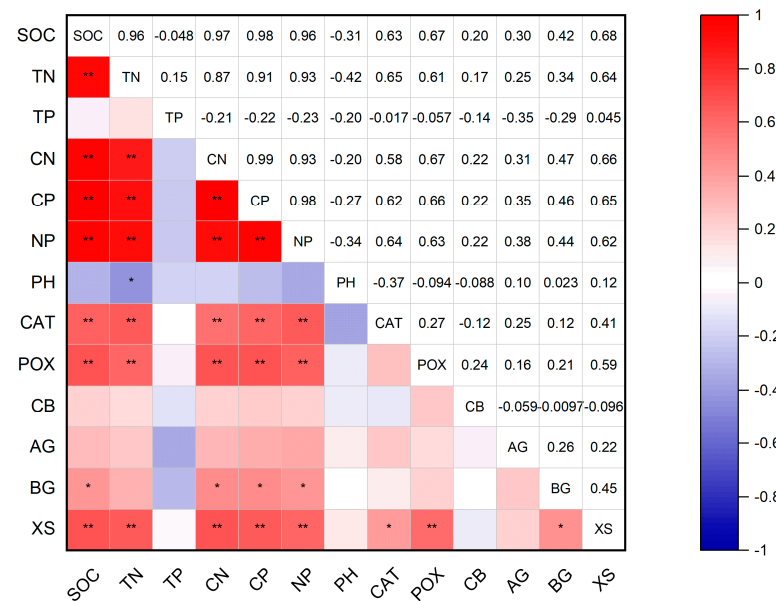


Figure 5. Pearson's correlation coefficients between the soil elemental contents under downed logs. (*) denotes significance at the 0.01 level, while (**) represents significance at the 0.05 level.

In the CK plots, soil pH was highly significantly negatively correlated with SOC, TN, N/P, and C/P ($r = -0.99$, -0.27 , -0.75 , and -0.75 , respectively; $p < 0.01$), and it was significantly negatively correlated with POX activity ($r = -0.82$ and $p < 0.01$). SOC exhibited highly significant positive correlations with TN, the C/P ratio, and the N/P ratio ($r = 0.93$, 0.97 , and 0.97 , respectively; $p < 0.01$) and was also positively correlated with POX activity ($r = 0.86$ and $p < 0.01$), indicating that SOC accumulation might increase oxidase activity. SOC was significantly negatively correlated with pH ($r = -0.99$ and $p < 0.01$). Among the soil enzyme activities, only POX was significantly correlated with the soil physicochemical properties, with strong synergies with SOC, TN, and N/P ($r = 0.86$, 0.97 , and 0.93 , respectively; $p < 0.01$). No significant correlations were found between other soil enzymes (Figure 6).

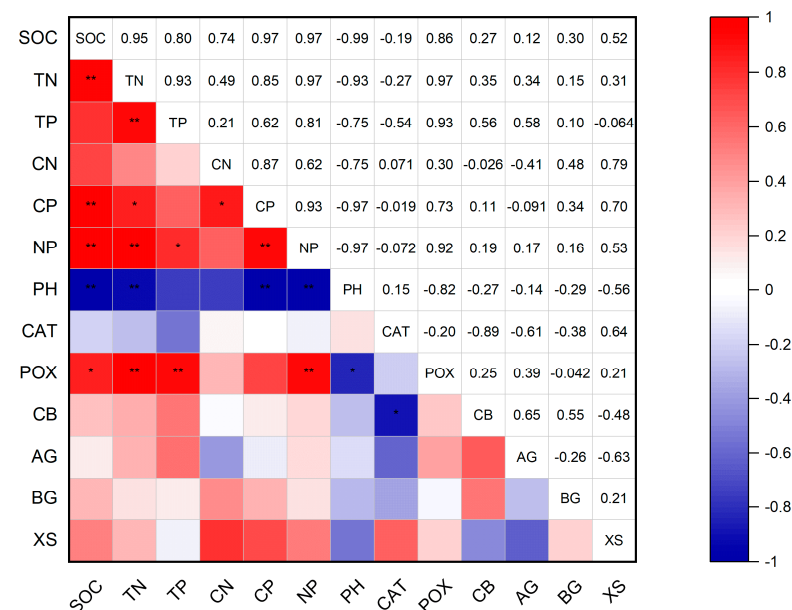


Figure 6. Pearson's correlation coefficients between the soil elemental contents in the control sample plots. (*) denotes significance at the 0.01 level, while (**) represents significance at the 0.05 level.

4. Discussion

4.1. Effects of Downed Logs on Soil Physicochemical Properties

This study revealed that downed log decomposition significantly affects soil physicochemical properties, especially in the surface layer (0–10 cm), where the SOC content was significantly greater than that in the control plots without downed logs (CK), which is consistent with the findings of Wall et al. and Seongjun et al. [29–31]. Additionally, there were significant differences among tree species. The basic soil physicochemical properties in *L. xylocarpus* downed logs were generally greater than those in *C. wattii*, *L. hancei*, and the CK plots, suggesting the suitability of *L. xylocarpus* for long-term carbon sequestration. This might be due to the higher carbon content, lower density, and higher moisture content of *L. xylocarpus* than those of the other two species [32,33]. This indicates that its decomposition releases substantial organic matter, increasing soil organic carbon accumulation [34]. Compared with *L. xylocarpus*, *C. wattii* logs also promoted SOC and TN but to a lesser extent, suggesting a balanced carbon-nitrogen input effect that helps regulate soil nutrient dynamics. In contrast, *L. hancei* logs presented SOC and TN levels similar to the CK, indicating a smaller contribution to soil carbon and nitrogen inputs, with higher nitrogen release efficiency benefiting short-term nutrient supply.

The TP content in the soils below *L. hancei* logs at different depths was greater than that in the *L. xylocarpus*, *C. wattii*, and CK soils, but it was significantly different only in the 0–10 cm layer ($p < 0.05$). The differences in TP contents between the soils under downed logs and the CK were minor, possibly because the relationship between the TP contents in the downed logs and the soil TP content is not simply one of release and uptake. The proximal effects of log decomposition enhance microbial activity and soil enzyme activity, indirectly increasing soil TP content under downed logs, although the increase is limited [35]. Moreover, other studies also suggest that phosphorus is relatively stable and resistant to leaching, and that content does not change significantly during leaching processes, which reduces the effect of downed logs on the soil phosphorus content.

As the soil depth increased, the soil physicochemical properties in both the downed log plot and CK plot generally tended to decrease, which is consistent with previous studies [5,23]. The significant differences in the soil properties across the soil layers were attributed to the decreasing SOC and TN content with depth, whereas the TP content did not significantly change [36]. Organic matter from soil fauna and flora, microbial residues, and plant root exudates are the primary sources of soil organic carbon. Decomposed material from downed logs accumulated in the surface soil provides abundant organic matter, but the nutrient content decreases with depth, limiting the survival of soil microbes and fauna. This leads to reduced sources of soil organic matter and decreased biological nitrogen fixation, resulting in gradually declining SOC and TN contents [37]. The soil TP content is influenced by various factors, including parent material, climate, biological activity, and geochemical processes in the soil. In this study, *L. xylocarpus* depleted logs significantly increased the surface soil TP content, with significant reductions in the TP content as the soil depth increased, which is consistent with the findings of Moghimian [10].

The effects of downlog decomposition on the C/P, N/P, and C/N varied by tree species. *L. xylocarpus* and *C. wattii* significantly increased the ecological stoichiometric ratios in the surface soils, likely because the later stages of decomposition release more recalcitrant organic materials (e.g., lignin) that are carbon-rich and nitrogen-poor. Within certain soil layers, this can increase the C/N, particularly in surface soils. Conversely, the C/N under the *L. hancei* logs was lower than that under the CK logs at all soil depths and decreased with depth. Insufficient nitrogen availability for microbial reproduction may slow soil organic matter mineralization and decomposition, resulting in a C/N exceeding 30:1 [38]. Alternatively, the downed logs may have been in an advanced stage of decomposition with slower decomposition rates and higher organic carbon content [39].

Soil pH is an important factor influencing nutrient availability, but the effects of downed logs on soil pH are not significant. In surface soils (0–10 cm), only *L. xylocarpus*

presented a slight pH decrease (approximately 5.2), likely due to the release of organic acids during decomposition.

4.2. Effects of Downed Logs on Soil Enzyme Activities

The decomposition of heavily decayed logs provides a continuous source of energy and carbon for soil microorganisms, breaking down complex carbon compounds into simpler forms that can be utilized by plants and microbes. This process significantly enhances the activities of catalase (CAT), polyphenol oxidase (POX), and cellobiohydrolase (CB), which play vital roles in promoting organic matter decomposition and soil nutrient cycling, thereby improving soil fertility and microbial activity [40–42]. The results indicate that downed logs from different tree species play varying roles in soil nutrient cycling, with *L. xylocarpus* showing the most significant impact on the soil carbon and nitrogen cycles, whereas *L. hancei* may impose certain limitations on the utilization of carbon sources by soil microorganisms.

Compared with those in the CK plots, the soil enzyme activities in the *L. xylocarpus* plots were consistently greater than those in the *C. wattii*, *L. hancei*, and CK plots; the enzyme activity under the *C. wattii* plots was also greater than that in the CK plots. In contrast, the soils below the *L. hancei* logs presented the lowest enzyme activities across the different soil depths, except for the XS activity in the 0–10 cm layer, which was similar to that in the CK. This is likely due to the limited organic input from decayed *L. hancei*, where microorganisms adjust their extracellular enzyme activities to obtain the carbon and nitrogen necessary for growth. Under nutrient limitations, microorganisms may secrete more extracellular enzymes into the soil to facilitate carbon mineralization [43]. In comparison, *C. wattii* and *L. xylocarpus* input large amounts of organic matter into the soil, prompting microbes to produce more hydrolases to break down the organic material. However, the prolonged decomposition of *L. hancei* results in limited organic matter input, leading to lower hydrolase activities. CK soils, which lack organic matter input from downed logs, also exhibit low hydrolase activities. Furthermore, the decline in soil pH accompanies increased organic matter accumulation and enzyme activity.

As the soil depth increased, the enzyme activities in the CK and the soils in the three types of downed logs generally tended to decrease. Enzyme activities and physicochemical properties were most notably affected in the 0–10 cm surface soil, indicating that downed logs have a more significant impact on surface soil. This may be due to the direct contact between downed logs and surface soil, higher microbial activity, and faster nutrient cycling. *L. xylocarpus* downed logs most significantly promoted the activities of multiple enzymes (e.g., POX and CAT), which were markedly greater than those under *C. wattii* and *L. hancei*, suggesting that *L. xylocarpus* releases more organic matter during decomposition, stimulating microbial decomposition activity. With increasing soil depth, the SOC, total nitrogen (TN), total phosphorus (TP), and enzyme activities gradually decreased, indicating that the influence of downward logging diminished in deeper soil layers. The changes in enzyme activity in *L. hancei* were not significant, and the activities of most enzymes, particularly BG and XS, were comparable to or lower than those in the CK. This may be attributed to the faster nitrogen release during *L. hancei* decomposition, leading to a sufficient nitrogen supply for microbial communities, but limited carbon input, which suppresses certain enzyme activities. In contrast, the logs of *C. wattii* and *L. xylocarpus* maintained relatively high enzyme activities in deeper soils (20–30 cm), particularly for CB and AG hydrolases. This finding is consistent with the findings of Gartzia-Bengoetxea et al. [44], who reported that the activity of extracellular enzymes secreted by soil microbes decreases with increasing soil depth, leading to reduced soil carbon mineralization rates. Soil enzyme activities are also influenced to varying degrees by vegetation and soil physicochemical properties. Indicators such as the SOC, TN, TP, and others decrease with increasing soil depth, causing a corresponding decline in enzyme activity [30,45]. In this study, the soil hydrolase activity did not significantly differ with increasing soil depth. The correlation between the hydrolase activity and SOC, combined with the limited number of heavily decayed logs in the

plots, resulted in a large standard deviation for the SOC, which also extended to hydrolase activity. Consequently, no significant differences in hydrolase activity were observed with increasing soil depth.

4.3. Discussion of the Correlation Analysis Between Downed Log Cover and CK

In this study, Pearson's correlation analysis was used to compare the effects of three heavily decomposed downed logs and CK plots on soil physicochemical properties, enzyme activities, and nutrient cycling. The results revealed significant differences between them. The SOC, TN, C/N ratio, C/P, N/P, CAT, POX, XS, and BG in the soils under the downed logs at the different depths were significantly positively correlated ($p < 0.01$), indicating that the organic matter released during the downed log decomposition promoted microbial activity, which in turn increased the organic carbon accumulation. This finding aligns with previous research conclusions [5,42,46]. In contrast, the SOC content and enzyme activities in the CK soils were relatively low, suggesting that downed log coverage had a significant positive effect on soil carbon storage.

There was no significant correlation between the TN and TP in the soils under the downed logs, whereas the TN and TP in the CK soils were significantly correlated. This occurred because the TN and TP availability in the CK soils tended to balance and remain relatively stable. However, under downed logs, the TN content significantly increased due to the influence of log coverage, whereas the TP content remained low as phosphorus in downed logs is strongly immobilized, limiting its transfer to the soil [35].

The SOC and C/N in the soils presented a highly significant positive correlation, whereas those in the CK soils presented no such correlation. This is attributed to the higher C/N under the downed logs, where the organic carbon accumulation rate exceeded that of the TN, especially in the surface soil layer (0–10 cm). This phenomenon is related to the faster release of carbon than of nitrogen during log decomposition. Conversely, the CK soils presented a relatively low C/N ratio and no significant correlation. In the soils under the downed logs, the TP content was significantly negatively correlated with the N/P ratio, whereas in the CK soils, the TP content and N/P ratio were significantly positively correlated. This may be due to the significant positive correlation between the TN and TP in the CK soils, where the nitrogen increase rate exceeds that of phosphorus. Thus, even with an increase in total phosphorus, the N/P ratio increases because nitrogen increases more than phosphorus does.

The correlation between the soil enzyme activities and the basic physical and chemical properties of the soil under the downed logs was stronger than that between the soil enzyme activities and the basic physical and chemical properties of the soil in the CK plot. This is because at the same time the downed logs supplied large amounts of organic carbon and total nitrogen to the soil, whereas the soil microorganisms, soil fauna, and decomposed plant residues released large amounts of soil enzymes, increasing enzyme activity [47]. The enzyme activities in the lower log-covered areas were significantly positively correlated with the SOC and TN contents, indicating that log decomposition promoted the transformation of organic carbon and nitrogen, increasing the microbial degradation activities. Conversely, the enzyme activity in the CK soils was relatively low, with weaker correlations with SOC and TN, suggesting that the lack of inputs from downed logs and plant residues limits microbial activity and nutrient cycling.

The soil pH in downed log-covered areas was generally lower than that in the CK soils, which was related to the release of organic acids and other acidic substances during log decomposition. The correlation analysis revealed significant negative relationships between the soil pH and SOC, TN, and enzyme activities, particularly in the log-covered areas. These findings suggest that soil acidification may promote the activity of certain microbial communities, especially those adapted to acidic environments, thereby accelerating the mineralization and decomposition of carbon and nitrogen.

5. Conclusions

Our study systematically analyzed the soil physicochemical properties and enzyme activities of downed logs from three dominant tree species (*L. xylocarpus*, *L. hancei*, and *C. wattii*) and CK plots in the montane humid evergreen broad-leaved forests of the Ailao Mountains in Yunnan, Southwest China. This study explored the effects of downed log decomposition on forest soil nutrient contents and enzyme activities in detail. The results revealed that downed log decomposition significantly improved key soil physicochemical indicators, with the effects being particularly pronounced in the 0–10 cm soil layer beneath the logs.

Additionally, downed log coverage significantly enhanced soil enzyme activities, indicating that downed log decomposition provides organic matter and energy sources essential for microbial growth and metabolism. Downed logs play a significant role in promoting soil carbon and nitrogen accumulation, increasing the soil C/N ratio, and increasing enzyme activities. However, different tree species have varying ecological effects in this process. The soil under *L. xylocarpus* presented the highest physicochemical properties and enzyme activities, followed by those under *C. wattii*, whereas *L. hancei* had a relatively weaker effect but still performed better than did the CK without downed logs.

Nutrient release during the decomposition of downed logs is closely related to microbial activity. *L. xylocarpus* significantly increased the soil SOC and TN contents and promoted enzyme activity, indicating a strong regulatory effect on carbon and nitrogen cycling. In contrast, *L. hancei*, with faster nitrogen release, limited carbon accumulation and presented a lower C/N.

The correlation analysis of various indicators revealed that downed log decomposition not only influenced soil nutrient storage and distribution but also significantly enhanced microbial community activities. This, in turn, promoted organic matter decomposition and nutrient cycling, strengthening the interconnections and constraints between different soil properties.

Overall, downed logs play crucial roles in maintaining forest soil health, improving soil fertility, and promoting ecosystem stability. The presence of downed logs in forest ecosystems positively contributes to improving nutrient-poor soils, enhancing soil structure and functionality, and increasing the long-term sustainability of forest ecosystems.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/f15122182/s1>, Table S1: Basic information about 4 species of downed logs; Table S2: Standards for classifying decay grades of downed logs (DC₁ to DC₃); Table S3: Characterization of the enzymatic activity about downed logs; Table S4: Characterization of fallen wood decomposition on soil physicochemical properties.

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