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Alteration in Forest Soil Biogeochemistry through Coarse Wood Debris in Northeast China

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Abstract: Coarse woody debris (CWD) has a strong influence on nutrient dynamics and hinders its availability through fixation. The CWD decaying logs, with two states (three and four) impacting on carbon (C) capture, nutrient dynamics and enzymatic properties, were investigated under and away (50 cm) from the logs in three forest types, i.e., the *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF), *Betula costata-Pinus koraiensis* forest (BPF) and *Tilia amurensis-Pinus koraiensis* forest (TPF). The results showed that soil organic carbon (OC), nitrogen (N), soil pH, other soil nutrients and enzymatic activity were significantly affected by the forest types, decay class and distance from decaying logs in three forests. The CWD, with decay class IV under CWD, resulted in the optimum OC 64.7 mg g^{-1}, N 6.9 mg g^{-1} and enzymatic activity in the PAPF forest, and the distance effect was negligible for all the forests. A lower soil pH value of 3.8 was observed at decay class IV in the soil collected from the immediate vicinity of the deadwood. CWD play a key role in decaying logs in forest ecosystems to enhance C and the nutrient budget with the improved enzymatic activity of the soil. It was concluded from this research that CWD is a critical factor in the nutrient cycling process of forest ecosystems that contributes functionally to the forest floor by inducing the spatial heterogeneity of enzymatic activity, C and nutrient turnover.

Keywords: CWD; carbon; nitrogen; forest types

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1. Introduction

Coarse woody debris (CWD) are woody fragments of dead trees or the remains of large branches on forest ground under the decomposition process. Usually, CWD is classified by the decaying wood diameter and length, i.e., a diameter greater than 5 cm and a length of more than 1 m [1]. Deadwood is an important functional and structural component of forest ecosystems, accounting for 20%–30% of tropical and >60% of temperate forest floors [2]. CWD decomposition is considered a continuous and complex process that is characterized by physical and biological processes, i.e., fragmentation, biological respiration and leaching. The initial mass loss of CWD is caused by decomposer organisms [3], followed by biological respiration to transform organic carbon into atmospheric carbon. During this process, microbes or other organisms break down the wood structure, enhance decomposition and change polymeric materials into soluble substances, which are then transported into the soil matrix through leaching [4]. The biological mechanisms and environmental conditions that occur during wood fragmentation cause it to structurally disintegrate with an increased amount of CWD when in contact with the surface of the ground. It creates conducive conditions for different organisms, including invertebrates, bacteria and fungi [5].

Structurally, CWD provides a habitat and substrate to a diversity of organisms, including animals, plants and microorganisms [6]. Functionally, it relates to the nutrient cycling process in forest ecosystems through its role as either a source or a sink of nutrients [7].

Moreover, it has a major role in the soil formation process, as residues from decomposing lignin are precursors for humus synthesis [8]. Coarse woody debris also influences the soil's chemical, physical and hydraulic properties and serves as a site for nitrogen fixation and a cradle for the germination of seeds [9].

Given their important role in soil processes, the chemical characteristics of the underlying forest soils are also significantly impacted by CWD. Such effects mainly occur because of the translocated dissolved organic matter (DOM) originating from decaying wood and their mobility to the soil underneath. The translocated organic matter is considered a major form of mobilizing carbon (C) and nitrogen (N) pools present on the forest floor, and its mobility present to underlying mineral soil is generally carried out by soil fauna [10]. Therefore, inappropriate forest management practices/interventions may adversely affect forest soil ecosystems, and the implications of CWD removal are considered an important area of forest ecosystem research [11]. Any removal of CWD may result in a negative soil nutrient balance of forest soils. The negative effects of CWD elimination have been revealed in recent studies on the availability of soil nitrogen and C pools, moreover as metabolic-potential and microbial communities [12]. Despite that, various studies have found conflicting outcomes concerning the particular impact of decaying logs on the biotic and physicochemical properties of the underlying soil [13].

Microbes play a crucial role in the dead wood decomposition process, while the developmental time is considered a critical factor in the decomposition process, which depends on the fungal associations in the soil. For example, the maximum developmental time of *S. rubra* CWD was reported as 3–4 years, while that of *C. mariana* was 6 years [14]. The longer developmental time for the process of wood decomposition showed an enhanced concentration of other nutrients due to the growth of fungi, inferring the dependence of species and developmental time on soil chemical properties [15]. The role of microbes in producing soil enzymes plays a vital part in organic matter decomposition [16]. The deadwood promotes accessibility of labile carbon in the soil, and the process relies on the deadwood decay class. The strong relationship between the cellulose decomposing enzyme, ß-glucosidase, and the C content, and between the dehydrogenase activity and wood decay classes was previously reported. Moreover, the reports showed that the higher C content with higher deadwood decay classes stimulated the decomposing process of the soil organic matter [17]. The process of the soil organic matter decomposing differs with the temperature, soil moisture content, pH and the availability of electron receptors, such as O_2, humic matters, NO_3 etc., inferring microbe specificity and environmental dependence [18].

A comprehensive understanding of the decay progression of deadwood and the factors influencing these variations is the key to maintaining long-term sustainability of the soil, helping conservation, elucidating the role of deadwood in its C storage, and preserving microhabitat occurrence. This study focused on the impact of CWD on the chemical and biological properties of forest soils, along with the interactions between CWD and forest soils and their respective implications for soil properties. The specific aim of this study is to unravel the influence of the decay wood classes (i.e., decay III and IV) on soil properties (i.e., soil's chemical and enzymatic activities) over the decomposition process. We hypothesized that CWD, while in contact with soil, would affect the nutrient concentration, modulation of soil characteristics and enzyme activities in its sphere of influence. In doing so, in this region, samples from all different types of forests were taken from the same dominant tree species, *Pinus koraiensis* (PK). The specific objectives of the study are: (1) to investigate the soil chemical properties beneath CWD, which differ relative to that of the soil's properties away from the CWD at the two stages of wood decay (i.e., decay III and IV) across forest types; (2) whether the enzymatic activities stimulate in the presence of decayed dead wood.

2. Materials and Methods

2.1. Study Area

The study was carried out in the Liangshui National Nature Reserve (47°10′50″ N, 128°53′20″ E) in the Heilongjiang Province of P. R. China (Figure 1). The research area is considered by a rolling mountains terrain, which ranges from 300 to 707.4 m above sea level (a.s.l), with the terrain declining from north to south, having a typical slope of 10°–15°. The total area of this reserve is about 12.14 km^2, with a forest coverage of 96 percent. The area falls in a temperate continental monsoon climatic zone with a mean air temperature of −0.3 °C, having long and cold winters, resulting in a frozen-soil depth of about 2.0 m. The average annual rainfall in this area is 680 mm, with a precipitation duration of 120 days and cumulative evaporation of about 800 mm. The daily light rate in the research area is about 43.5%, while the yearly sunlight is 1850 h 23.

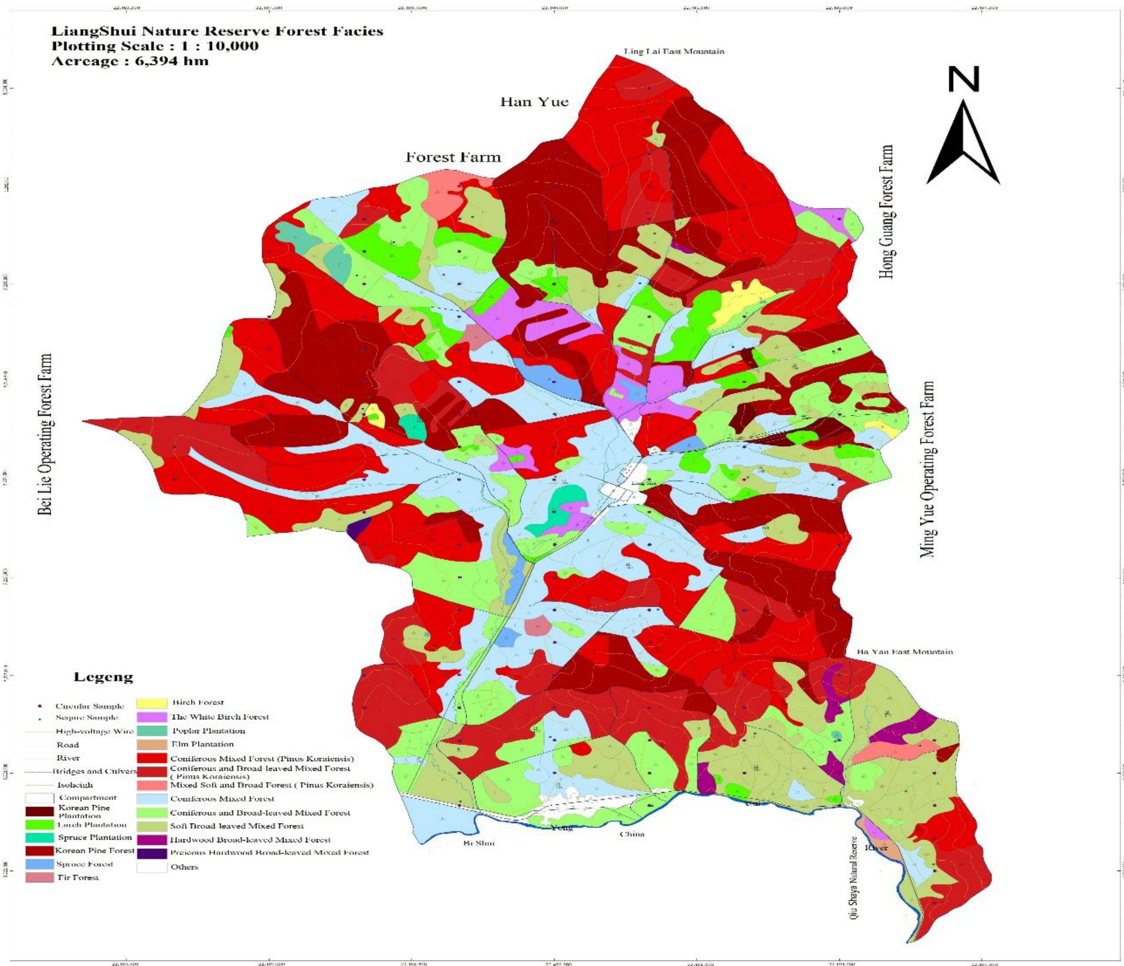

Figure 1. A map of forest distribution in Liangshui National Nature Reserve of Northeast China.

2.2. Experimental Design and Sample Collection

A factorial experiment was performed in October 2019 on three permanent plots in randomly selected *picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF), *Betula costata-Pinus koraiensis* forest (BPF) and *Tilia amurensis-Pinus koraiensis* forest (TPF), respectively. The size of the plots was kept at 100 m × 120 m, 100 m × 110 m and 100 m × 120 m [19]. In order to determine the alterations in the concentration of nutrients at different decay levels, data were obtained from three different forests. The *Pinus koraiensis* (PK) represents the dominant tree species in this area. The samples collected from the PK represent different decomposition levels. To collect samples, we used the advanced decay class. Based on the morphology and hardness of the wood, we used the decay class system to categorize the wood debris samples; the criteria established by [20]. According to Carmona, in the third decay class (III), the bark is partially present on the logs with semi-solid wood. The fourth decay class (IV) was classified as there is no bark with partially soft wood. The two decay classes were identified by visual observation. To meet the objectives of this study, the logs in decay class III (DC-III) and decay class IV (DC-IV) were selected.

2.3. Sample Processing and Analysis of Nutrients

Samples of mineral soils were collected from a lateral distance under the decay logs and 50 cm away from each decay class log in October 2019. For each decay class, we used log samples of approximately >20–50 cm in diameter of the same dominant tree species PK in PAPF, BPF and TPF forest types, respectively. In each forest type, twenty logs were randomly selected (i.e., 10 logs for each decay class III and IV), five soil samples were taken from each log, and the samples were pooled to create one soil sample. Thus, a total of 20 soil samples were collected at a depth of 0–20 cm in each forest type. After that, the soil samples were properly labeled and sealed in plastic bags, immediately taken to the laboratory, and refrigerated at 4 °C until they were processed. Nitrite gloves were used to handle the soil samples in order to avoid contamination, both in the field and laboratory. To analyze the chemical properties of the soil, the soil samples were combined to create one sample. The soil samples were allocated into a number of parts. To examine the soil's exchangeable cations, NH_4^+-N and NO_3^--N, one set of the soil sample was air-dried, ground and sieved through 2-mm mesh, while the second set of soil samples was processed through a 0.5-mm sieve and used to measure phosphorus and the soil pH. The third set of samples was simultaneously oven-dried and passed through a 0.25-mm sieve to figure out the total nitrogen and soil organic carbon. Meanwhile, another set of fresh soil was stored in a refrigerator at 4 °C to evaluate the enzymatic activity.

2.4. Soil Analysis

In the laboratory, the collected soil samples were air-dried at room temperature. After that, the samples were passed through a 2-mm sieve. The pH of the soil was determined in distilled water and 1 M KCl by taking 1 g of soil at a ratio of 1:2.5 (*v/v*) and placed on a mechanical shaker for 30 min using a calibrated pH meter (S220 Seven Compact pH Meter, Shanghai, China). The soil organic carbon (SOC) was measured with an Elementar High II TOC (Elementar, Germany), whereas the total N content of the soil was determined using a Hanon k9840 Auto Kjeldahl analyzer (Jinan Hanon Instruments Co., Jinan, China). The NH_4^+ -N (ammonium; mg kg^{-1}) and NO_3^--N (nitrate; mg kg^{-1}) were measured by using 2-M KCl, as determined by an auto-analyzer III Bran (Luebbe GmbH, Norderstedt, Germany). To examine the exchangeable cations Ca^{2+}, Mg^{2+} and Mn^{2+}, the one-step method was used, i.e., 0.1-mol L^{-1} $BaCl_2$ (50:1, solution:soil). The extract was then filtered with an acetate filter. The cations were measured by coupled plasma-mass spectrometry (Agilent Technologies Co. Ltd., Santa Clara, CA, USA). Other nutrients, such as phosphorus (P), sulfur (S) and potassium (K), were determined using an inductively coupled plasma-optical emission spectrometer (ICP-AES, Optima-8300 DV; PerkinElmer, Inc., Waltham, MA, USA).

The activity of the enzymes was determined by the colorimetric measurement of the product released by the enzyme, according to the [21] methods. The activity of urease (EC 3.5.1.5) was identified using 200 mM of urea as a substrate under scientific standard conditions (2 h at 37 °C). The invertase activity (EC 3.2.1.26) was estimated using sucrose as the substrate. Pyrogallol solution and 2,3,5-triphenyltetrazolium chloride were used as a substrate for the determination of the activity of polyphenol oxidase (EC 1.10.3.1) and dehydrogenase (EC 1.1.1.1), respectively. Acid phosphatase activity (EC 3.1.3.2) was identified following the soils' incubation with p-Nitrophenyl phosphate disodium (15 mM) as a substrate in modified universal buffer (MUB) at a pH of 6.5 for 1 h at 37 °C. The activity of the enzymes was expressed as micrograms of the product produced per gram of oven-dry weight per specified time.

2.5. Statistical Analyses

Statistical analysis was performed by using a two-way analysis of variance (ANOVA) on normally distributed data (Shapiro–Wilk test) to study the effect of forest types, decay classes and their interactions. To analyze the significant differences between nutrient concentrations in forest types and decay classes, a Tukey's honest significant difference (HSD) test was used. Pearson's correlation coefficients were calculated to determine significantly positive (blue color) or negative (red color) correlations of the soil properties for the same dominant tree species PK in different forest types, using the "corrplot" package in R. v. 3.6.1. All statistical analyses were performed by using SPSS v. 25. Sigma plots, v. 12.4 (Systat Software Inc., San Jose, CA, USA) was used for the graphical representations. Mean data are displayed as mean ± standard error (SE).

3. Results

3.1. Soil pH

Under various studied conditions, the soil pH in water (pH_w) and in KCl (pH_{kcl}) varied significantly among the forest types (F), decay classes (DC) and distance (D) from the CWD (Figure 2). Overall, the pH_w was in the range of 6.9 (DC-III of BPF away) to 5.1 (DC-IV of PAPF under CWD). Similarly, in the solution of pH_{kcl}, the values were in the range of 4.6 (DC-III of BPF away) to 4.1 (DC-III of TPF under CWD). On average, across DC and D, the BPF had a higher pH_w (6.4 ± 0.11) and pH_{kcl} (4.4 ± 0.05) as compared with the TPF pH_w and pH_{kcl} (6.0 ± 0.1 and 3.8 ± 0.2), whereas the PAPF pH_w and pH_{kcl}, 5.3 ± 0.07 and 4.0 ± 0.06, were recorded, respectively. Among the decay classes, the pH_w and pH_{kcl} were higher for the less decomposed DC-III (pH_w 6.1 ± 0.13; pH_{kcl} 4.3 ± 0.5) compared to DC-IV (pH_w 5.7 ± 0.11; pH_{kcl} 3.9 ± 0.19). Regardless of the F and DC, the soil pH was lower in the soil collected from the immediate vicinity of the deadwood. The individual effect of distance from the CWD showed a pH_w and pH_{kcl} of 5.8 ± 0.11 and 3.8 ± 0.18, respectively, for under CWD, and 6.1 ± 0.14 and 4.3 ± 0.06 for 50 cm away. The interactive effect of F × DC × D showed a higher pH_w (6.8 ± 0.15) in DC-III of the BPF away, followed by TPF × DC-III× away (6.4 ± 0.03), which was non-significantly different from the BPF × DC-IV × D away (6.3 ± 0.14). The overall mean pH_w was lower in PAPF × DC-IV × under CWD (5.1 ± 0.11) (Figure 2).

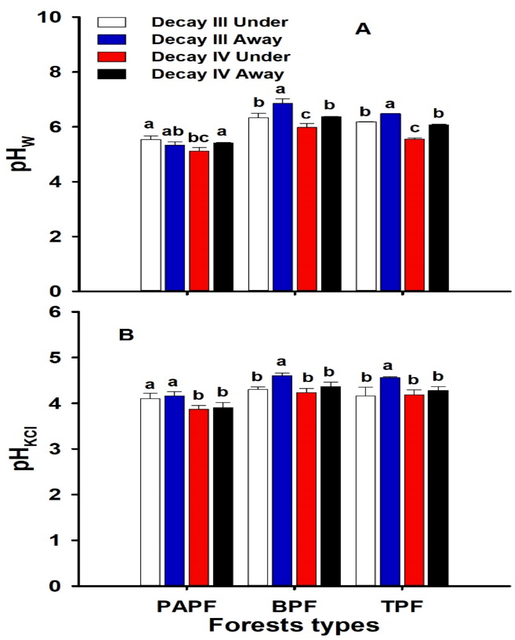

Figure 2. (**A**) pH in water (pH_w) and (**B**) pH in KCl (pH_{KCl}) values of the same dominant tree species PK with different decay classes at different distances in contrasting forest types of PAPF, BPF and TPF forest types in northeastern China. Significant changes between treatments within the same forest type are denoted by various lowercase letters. Tukey's honest significant difference (HSD) post hoc; $p < 0.05$, mean ± SE = 3; the bars show standard errors.

3.2. Soil Nutrients Concentration

The SOC differed significantly among the forest types, decay class and distances from the CWD. The interactions between F, DC and D were different, i.e., F × DC, DC × D were found significant, while F × D and F × DC × C were non-significant for soil organic C (Table 1, Figure 3). When averaged across DC and D, PAPF, with a mean value of 64.7 ± 4.08 mg g^{-1}, had 14% higher C than the BPF forest and 16% higher than the TPF forest. Among the decay classes, the mean C was higher for DC-IV (63.2 ± 3.13 mg g^{-1}) compared to the less decomposed DC-III (53.1 ± 0.78 mg g^{-1}). Regardless of the forest types and decay classes, the carbon values were higher in the soil collected from the immediate vicinity of the CWD. The individual effect of distance from the CWD showed a C value of 64.04 ± 2.75 mg g^{-1} under CWD, which was 18% higher than that of the 50 cm away from CWD (Figure 3B).

Table 1. Results of an ANOVA on the nutritional contents of distance, decay classes, their interactions and forest types of PAPF, BFF and TPF in Northeastern China.

Source of Variation	**Df**	**C**	**N**	**C:N**	**NH_4-N**	**NO_3-N**	**pH (phW)**	**pH (KCl)**	***P***	**K**
Forests types (F)	2	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Decay class (Dc)	2	<0.001	0.007	0.02	<0.001	<0.001	<0.001	0.005	<0.001	<0.001
Distance (D)	2	<0.001	0.005	0.004	0.001	0.001	0.001	<0.001	<0.001	<0.001
F × Dc	2	<0.001	0.059	0.416	0.292	0.057	0.109	<0.001	0.014	0.157
F × D	2	0.383	0.985	0.758	0.114	0.567	0.039	<0.001	<0.001	<0.001
Dc × D	1	<0.001	0.086	0.100	0.113	0.052	0.152	<0.001	0.007	<0.001
F × Dc × D	2	0.117	0.973	0.489	0.899	0.442	0.174	<0.001	0.007	0.014
Source of variation	Df	S	Mg	Ca	Mn	Urease	Invertase	Poly oxidase	Dehydrogenase	Phosphatase
Forest types (F)	2	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Decay class (Dc)	2	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Distance (D)	2	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.022	0.001
F × Dc	2	<0.001	0.16	0.005	0.245	0.947	0.483	0.148	0.737	0.611
F × D	2	<0.001	0.012	0.644	0.023	0.243	0.593	0.025	0.399	0.928
Dc × D	1	0.424	0.002	<0.001	0.351	0.451	0.265	0.284	0.676	0.107
F × Dc × D	2	0.272	0.491	0.24	0.929	0.686	0.786	0.279	0.932	0.442

The interaction between the forest types and decay class revealed that PAPF was significantly high at DC-IV (75.0 ± 5.4 mg g^{-1}), while the BPF was non-significant at DC-IV (58.1 ± 3.9 mg g^{-1}), followed by the TPF at DC-IV (56.5 ± 3.6 mg g^{-1}), PAPF at DC-III (54.4 ± 1.3 mg g^{-1}), BPF at DC-III (53.1 ± 1.5 mg g^{-1}) and TPF at DC-III (52.1 ± 1.3 mg g^{-1}). Similarly, for F × D, the mean carbon for the PAPF under CWD (71.5 ± 7.0 mg g^{-1}) was 14% and 17% higher compared to the SOC under CWD for the BPF and TPF, respectively.

When considering the forest types, decay classes and distances simultaneously (Table 1), the mean SOC values differed significantly among the studied variables except for the 50 cm (away) of the BPF and TPF forests. The highest SOC was observed at DC-IV of the PAPF under CWD (86.7 ± 2.5 mg g^{-1}), with the lowest at DC-IV of the TPF at 50 cm (48.5 ± 1.4 mg g^{-1}), which was non-significantly different for the DC-III of TPF at 50 cm (49.5 ± 1.5 mg g^{-1}).

The nitrogen (N) concentration had a similar trend as SOC (Figure 3A,B). The mean data of the N concentrations in forest types showed that the PAPF, with a mean value, was 6.9 ± 0.28 mg g^{-1}, had a 28% higher N concentration compared to BPF (5.0 ± 0.15 mg g^{-1}) and was 33% higher than that of TPF (4.6 ± 0.31 mg g^{-1}). Among the decay classes, the N values were lower for DC-IIII (5.2 ± 0.21 mg g^{-1}) compared to the more decomposed DC-IV (5.9 ± 0.4 mg g^{-1}). The mean N concentration (5.9 ± 0.31 mg g^{-1}) was higher in the soil collected under the CWD from decaying logs compared to the soil samples 50 cm away (5.1 ± 0.30 mg g^{-1}).

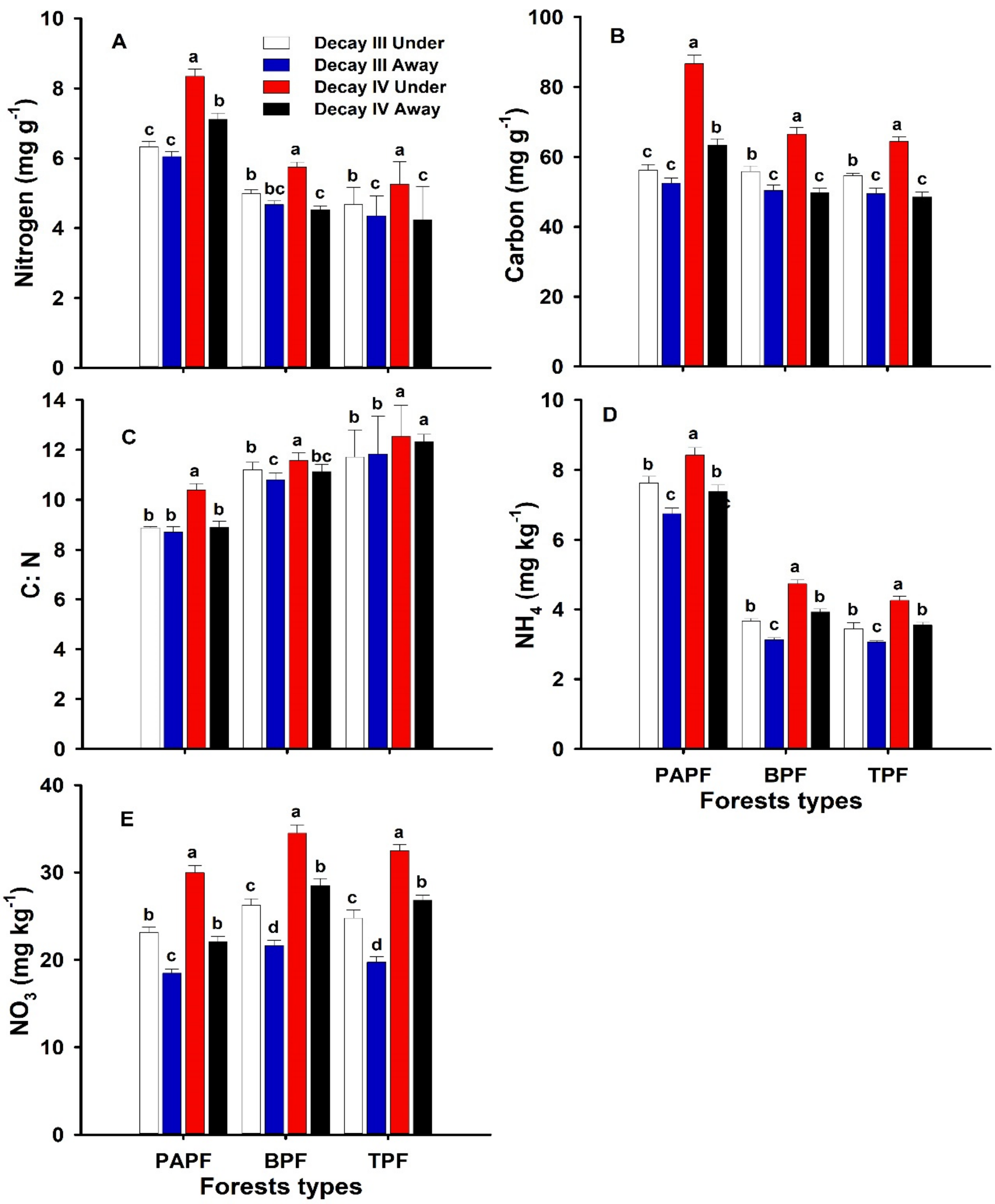

Figure 3. N (mg g^{-1}) (**A**), SOC (mg g^{-1}) (**B**), C:N (**C**), NH_4-N (mg kg^{-1}) (**D**) and NO_3-N (mg kg^{-1}) (**E**) concentrations of the same dominant tree species PK with different decay classes at different distances in contrasting forest types of PAPF, BPF and TPF in northeastern China. Significant changes between treatments within the same forest type are denoted by various lowercase letters. Tukey's honest significant difference (HSD) post hoc; $p < 0.05$, mean ± SE = 3; the bars show standard errors.

The C:N values of soil under different forest types, decaying class, distance from the decaying logs, as well as all possible interactions, was found significant. When averaged across DC and D, the TPF, with a mean value of 12.1 ± 0.6, had 8% higher values when compared to the BPF, and 24% higher values when compared to the PAPF, whereas the BPF, with a mean value of 11.2 ± 0.1, had approximately 18% higher values when compared to the PAPF. In the case of the decay classes, C:N was higher for DC-IV (11.1 ± 0.5) when compared to the less decomposed DC-III (10.5 ± 0.4) (Figure 3C). While comparing the distance from the decaying logs, the C:N values were higher under the CWD (11.1 ± 0.4) as that measured for higher distance, i.e., 50 cm away from deadwood with a mean value of 10.6 ± 0.5 mg g^{-1} (11). Both decay classes for PAPF had significantly lower values for C:N, with a mean of 9.6 ± 0.3 for DC-IV and 8.8 ± 0.1 for DC-III. Similarly, for F × D, the higher C:N ratio was observed under the CWD of TPF (12.2 ± 0.8). The highest soil C:N ratio was observed at 12.6 ± 1.3 DC-IV for the TPF forest under CWD.

The variations in the soil's P, K, S, Mg, Ca and Mn concentrations varied significantly for the forest types, decay classes and distance from CWD (Figure 4). Among the forest types, the soil P concentration in PAPF was almost double (1.20 ± 0.08 mg g^{-1}) compared to the BPF (0.90 ± 0.07 mg g^{-1}) and TPF (0.80 ± 0.06 mg g^{-1}) (Figure 4A). Similarly, among the decay classes, the soil P concentration increased in DC-IV (1.07 ± 0.06 mg g^{-1}) when compared to DC-III (0.80 ± 0.06 mg g^{-1}). Comparing the distance from the decaying logs, the overall P concentration under the CWD (1.15 ± 0.06 mg g^{-1}) was about 36% higher than the 50 cm away from decaying logs (0.73 ± 0.05 mg g^{-1}). Similarly, a higher concentration of K, S and Mg was observed in the PAPF forest at DC-IV under (0.88 ± 0.044, 0.86 ± 0.043 and 0.38 ± 0.019), respectively (Figure 4B).

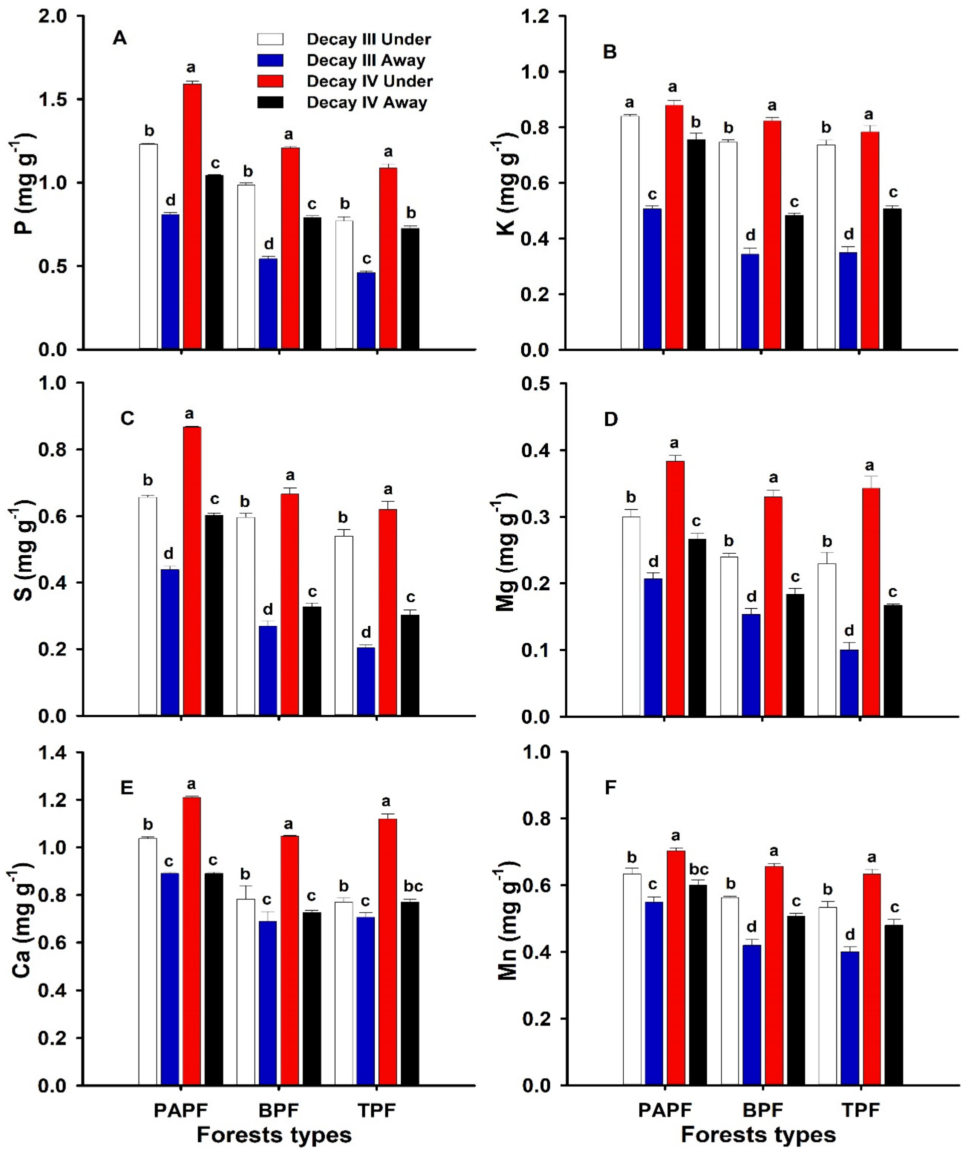

Figure 4. P (mg g^{-1}) (**A**), K (mg g^{-1}) (**B**), S (mg g^{-1}) (**C**), Mg (mg kg^{-1}) (**D**), Ca (mg kg^{-1}) (**E**) and Mn (mg g^{-1}) (**F**) concentrations of the same dominant tree species PK with different decay classes at different distances in contrasting forest types of PAPF, BPF and TPF in northeastern China. Significant changes between treatments within the same forest type are denoted by various lowercase letters. Tukey's honest significant difference (HSD) post hoc; $p < 0.05$, mean ± SE = 3; the bars show standard errors.

3.3. Enzyme Activity

The results showed that the enzyme activity decreased with distance from the CWD. The urease and invertase enzyme activity were recorded as the maximum in the BPF forest at DC-IV under CWD, with the mean values of 0.177 ± 0.01 mg g^{-1} and 29.5 ± 1.47 mg g^{-1}, respectively. Conversely, the polyphenol oxidase and phosphates enzymes were significantly high (0.256 ± 0.012 mg g^{-1} and 11.93 ± 0.596 mg g^{-1}) at DC-IV under CWD in the PAPF forest. When averaged across the decaying class for PAPF, the DH content decreased by 20% at a distance of 50 cm compared to the immediate vicinity of the CWD. However, the percentage difference was comparatively lower, i.e., 15% for the BPF, with a mean value of 0.33 ± 0.02 at 10 and 0.28 ± 0.03 at 50 cm, while the difference was also 15% for the TPF, with a mean value of 0.34 ± 0.01 under CWD and 0.29 ± 0.01 at 50 cm, respectively. A similar trend was observed for other enzymes studied in this experiment (Figure 5).

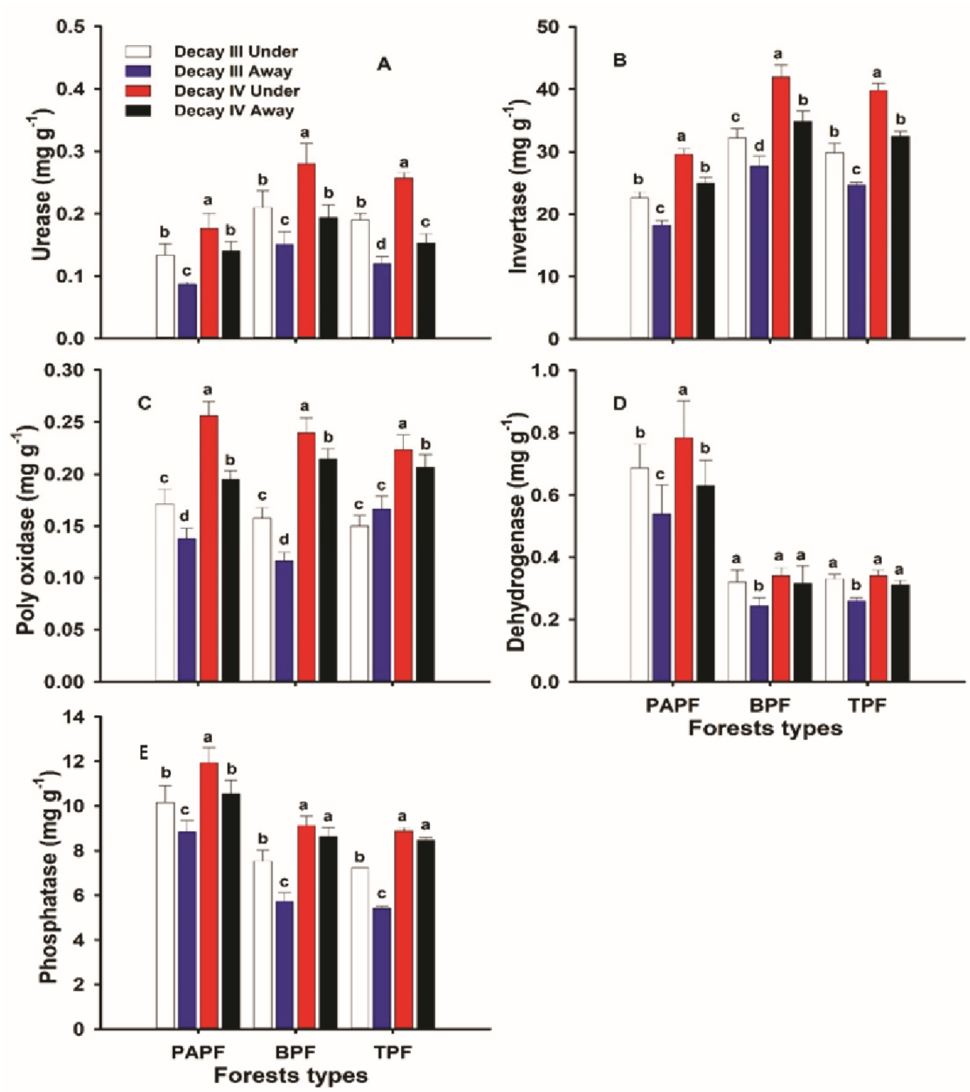

Figure 5. Urease (mg g^{-1}) (**A**), invertase (mg g^{-1}) (**B**), poly oxidase (mg g^{-1}) (**C**), dehydrogenase (mg kg^{-1}) (**D**) and phosphatase (mg kg^{-1}) (**E**) concentrations of the same dominant tree species PK with different decay classes at different distances in contrasting forest types of PAPF, BPF and TPF in northeastern China. Significant changes between treatments within the same forest type are denoted by various lowercase letters. Tukey's honest significant difference (HSD) post hoc; $p < 0.05$, mean ± SE = 3; the bars show standard errors.

3.4. Interaction of Soil Properties

Looking at the trait interactions, C, N, ammonium and nitrate were positively related significantly to P, K, S, Mg, Ca, Mn and phosphatase (Figure 6). The pH was negatively related significantly to C, N, P, K, S, Mg, Ca, Mn, dehydrogenase and phosphatase. C and Mg were positively related significantly to poly oxidase and phosphatase. N and NH_4 were positively related significantly to dehydrogenase and phosphatase. Nitrate was positively related significantly to urease, invertase and poly oxidase. P, Ca and Mn were significantly positively related to poly oxidase, dehydrogenase and phosphatase. K and S were positively related significantly to phosphatase. Urease and invertase were positively related significantly to poly oxidase, while invertase was considerably negatively correlated to dehydrogenase. Poly oxidase and dehydrogenase were found to be considerably positively correlated to phosphatase (Figure 6).

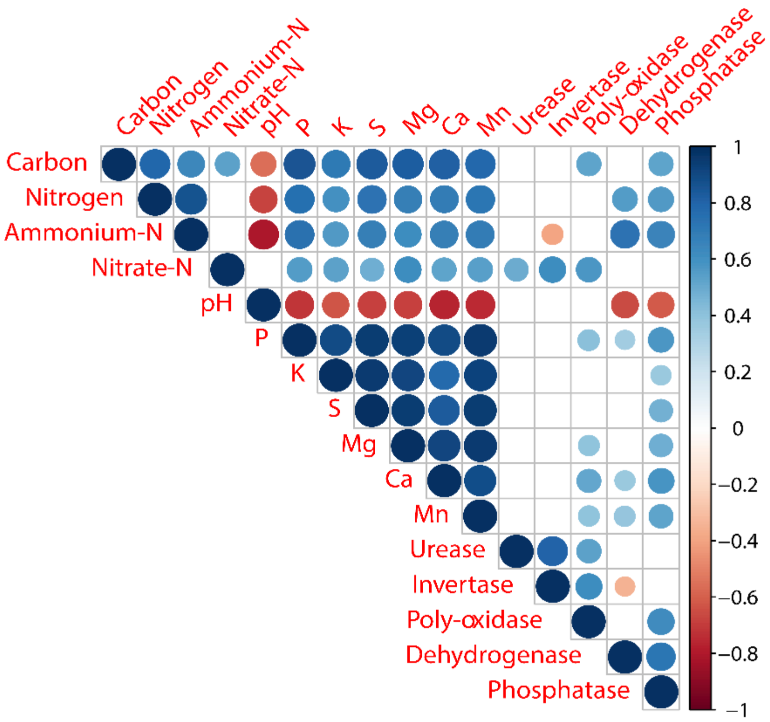

Figure 6. Pearson's correlation of soil properties and enzymatic activities of the dominant tree species PK between PAPF, BPF and TPF in northeastern China. The significant ($p < 0.05$) positive (blue color) or negative (red color) correlations are indicated by colors and circle sizes, while no significant correlations are omitted. Acronym's definitions are as defined in Table 1.

3.5. Interaction of Soil Properties across Forest Types

For the traits of the interaction across types, C was found to be significantly positively correlated to N in the PAPF and BPF, while considerably negatively correlated to the soil pH in the TPF (Figure 7A,B). N was found to be noticeably positively correlated to NH_4, NO_3, P, K, S, Mg, Ca, Mn and invertase in the PAPF and BPF. The soil pH was found to be noticeably negatively correlated to P, K, S, Mg, Ca, Mn, urease, invertase, poly oxidase and phosphatase in the BPF and TPF (Figure 7B,C). P was found to be considerably positively correlated to poly oxidase in the TPF. Dehydrogenase was found to be significantly positively correlated to P, K, S, Mg, Ca, Mn and urease in the TPF. Poly oxidase was found to be noticeably positively correlated to K and S in the PAPF (Figure 7A). Dehydrogenase was found to be considerably positively correlated to phosphatase in the TPF (Figure 7C).

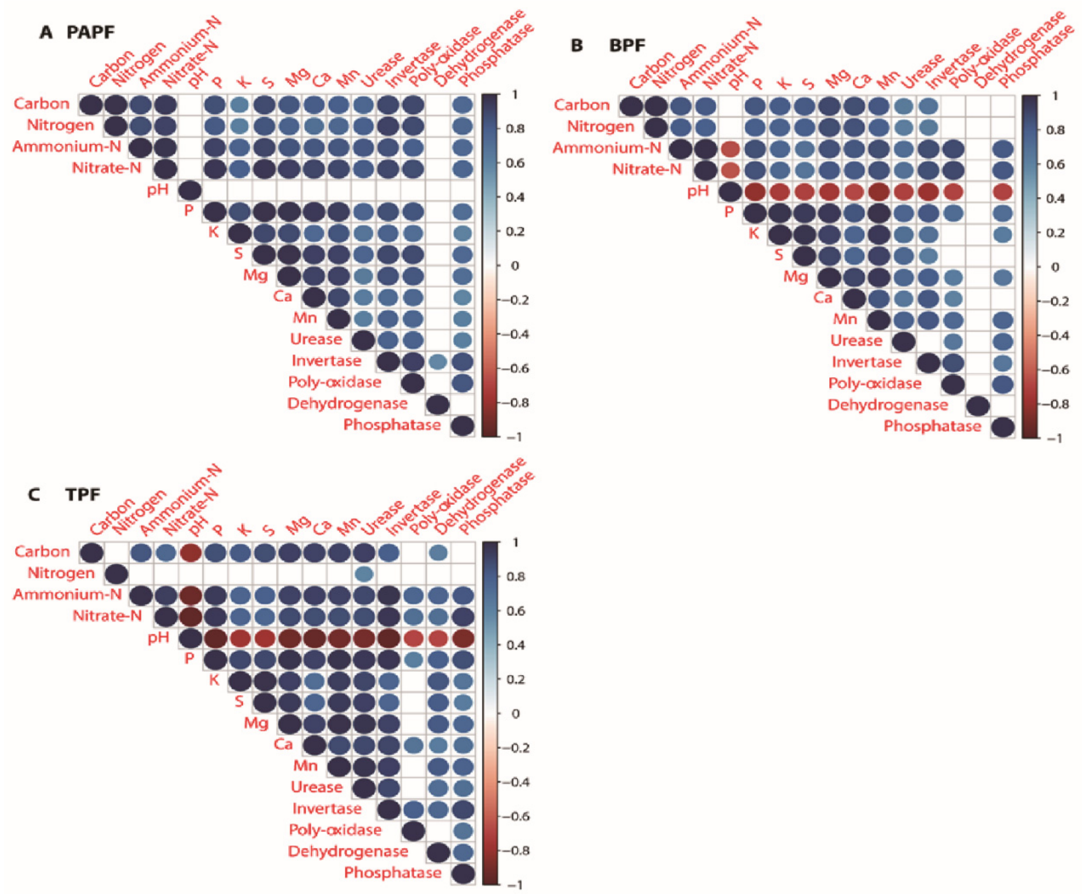

Figure 7. Pearson's correlation of soil properties and enzymatic activities of dominant tree species (**A**)PAPF, (**B**) BPF and (**C**) TPF in northeastern China. The significantly ($p < 0.05$) positive (blue color) or negative (red color) correlations are indicated by colors and circle sizes, while the not significant correlations are omitted. Acronym's definitions are as defined in Table 1.

4. Discussion

Wood is a three-dimensional biopolymer complex and mainly comprises cellulose, hemicelluloses and lignin, and minor quantities of inorganics. The wood cell walls possess carbohydrates (65–75%) and lignin (18–35%). Generally, wood contains carbon (50%), hydrogen (6%), oxygen (44%), and smaller quantities of inorganics. The distinction between angiosperms (hardwood tree species) and gymnosperms (softwood tree species) can be made through a simple chemical analysis. Generally, a coniferous type may possess higher cellulose (40–45%), lignin (26–34%) and smaller quantities of pentosan (7–14%) compared to the hardwoods type of deciduous species in which the quantities of cellulose, lignin and pentosan may range from 38–49%, 23–30% and 19–26%, respectively. Depending on the location, elements other than carbon, hydrogen, oxygen, nitrogen and sulfur may comprise approximately 0.1–0.6% of wood [22].

Generally, the factors responsible for which the density of wood decreases by the decay progression are leaching, fragmentation and the loss of matter through respiration [23]. The results obtained in this study revealed that the carbon and nutrient dynamics, as well as the soil enzymatic activities, were affected by the deadwood form/species, decaying class and the distance from the decaying log/deadwood. Among the three forest types, higher nutrient concentrations of the coarse woody debris of the PAPF were compared to the forests of BPF and TPF. Earlier studies also mentioned a strong influence of deadwood on the physical, chemical and enzymatic activity of forest soils. Khan et al. reported significantly different nutrient concentrations for the different tree species and the decaying class [24]. The change in nutrient concentration may arise from differential weight loss depending on the wood type, variation in nutrient contents of decaying logs, the contribution from falling litter and root colonization [25]. Moreover, the presence of nutrient-rich fungi (*basidiomycetous*) within the decaying logs also has a significant effect on the nutrient dynamics in the vicinity of wood debris. Our results showed that significantly higher nutrient concentrations were observed at a higher decay level, i.e., DC-IV. Similar results were reported in earlier studies, showing higher nutrient concentrations at higher decay levels of coarse woody debris due to the presence of specific microorganisms, i.e., *basidiomycetes* affecting the decomposition rate of decaying logs [26]. It is also reported that, in the forest-decayed, the concentration of the nutrient species is reliant on the duration of the decay and species type [27].

4.1. Soil pH

Generally, a decreasing trend in the soil pH and enzymatic activity closer to the decaying logs was observed in this study. Earlier studies on tree species and their effect on soil properties also reported decreased soil pHs close to the decaying logs, which was associated with the activity of mycorrhizal fungi and acidic-dissolved OM leaching from the decaying logs [28]. Properties of soil, such as the availability of cations, can be altered by lower soil pH values and some processes, such as nitrification. We found lower pHs near the older decayed logs, which could be a result of the leaching of acidic-dissolved organic matter from decaying wood [29]. Our results align with those of Zalamea et al., who found more humic and fulvic acid in soil under older logs. Soil properties, such as cation availability, as well as some processes, such as nitrification, can be altered by lower soil pH values [30].

4.2. Soil Nutrients Concentration

Coarse wood debris (CWD) actually affects soil cycling through organic carbon dissolving, which leads to N immobilization [31]. The outcomes advocated that the ecological assessment of CWD for nutrient cycling and carbon was relatively imperative. The results of this study confirmed that soil C depends on the type of deadwood and the decay class. At a higher decaying class, more C was accumulated in the soil, which stimulated the SOM decomposition. Moreover, prevalent environmental conditions of the area (temperature, humidity), soil pH, the presence of electron acceptors, i.e., O_2, SO_4^{2-}, NO_3^{-}, humic substrates, and the microorganism's accessibility and related enzymes are other major factors on which the decomposition of OM depends [32].

In the present study, the soil C contents around the decaying logs of PAPF, BPF and TPF varied significantly, which may be related to the physical characteristics of the deadwood. Generally, the density of the decaying wood from a specific tree type and the presence of saturated resin compounds play an important role in this regard [33]. The spread of fungi in the wood is restricted mechanically in the presence of resinous compounds. Moreover, these compounds have a toxic effect on fungi, resulting in inhibited fungal development. There was a relatively higher C content near the logs of decaying class IV, relative to that in decaying class III. These differences may arise because of the changes in the density of decaying logs. Associated with the advancement of log decay, at higher log decay, the wood density decreased, and the phenomenon has been reported in the fourth and fifth decaying classes [34]. It can be suggested that, in the presence of cerambycid frass and fungi present in wood, the xylem may increase the C concentration [35]. It was observed that DC-III had larger, hard fragments of a circular shape and bark under different levels of fragmentation compared to the logs of DC-IV with no bark and small oval-shaped pieces. The differences in shape and size of the decaying logs were associated with the change in wood density. In the process of evaluation, it was observed that within the same decay class, the PAPF and BPF differed with respect to wood hardness. The PAPF had a slightly harder texture compared to the BPF, which may be the reason for the prevailing higher C values in the soil under the decaying log's CWD, which are caused by the changes in the soil's C content around the decomposing logs.

We hypothesized that decaying logs could increase the nutrient concentrations in the underlying soil. The concentration of N and P were comparable to the views described in other studies [36]. The percentage of N found in our studies was similar to that described in earlier studies [37]. The results of Garrett et al. showed that the content of N also increased with the decay class, which was conceivably associated owing to the fungal and bacterial fixation of N as well as the input from rainfall [38]. Our result is supported by Uroz et al., who found the same nitrogen concentration under decaying logs compared to the soil taken 50 cm away from the logs [39]. The change in the nutrient concentration may arise from the differential weight loss depending on the wood type, variation in nutrient contents of decaying logs, the contribution from falling litter and root colonization. Moreover, the presence of nutrient-rich fungi (*basidiomycetous*) within the decaying logs also has a significant effect on nutrient dynamics in the vicinity of wood debris

From the previous studies, it was concluded that during the early phase of decomposition, Ca, K, Na, and in some cases, Mg easily leach down from decaying logs [25]. Coarse wood debris (CWD) can also have an influence on the relative abundance of other nutrients, such as Ca^{2+} and Mg^{2+}. We found a higher availably of Ca^{2+}, Mn^{2+} and Mg^{2+} (Figure 4D–F) in decay class IV near all the decaying logs of the three forests. The same results were proposed by Zalamea et al. [40]. This may be due to the fact that during the early stage of decomposition, these nutrients are easily leached down [41], which enhances the soil enrichment beneath the decaying wood. Our findings concur with those of Zalamea et al. [40], who proposed that divalent cations were affected differently by the advancement of the decay classes. He suggested that this pattern is the consequence of biotical and chemically facilitated progressions. The accessibility of the cations can be associated with the creation of complexes with the soil organic matter. Furthermore, it is plausible that soils affected by degradation class IV, where the concentration of humic compounds is larger, hold divalent cations more tightly. Other woods have seen a trend very similar to this one [42]. In contrast to lignin pedons, exchangeable cations (Ca^{2+}, Mg^{2+} and K) were discovered by Kayahara et al. in aligned pedons [43].

On the other hand, we found higher NO_3^- and NH_4^+ at decay class IV in all three forest types. This could be attributed to the following two reasons. Firstly, when the clay structure tends to collapse, the NH_4^+ is easily immobilized in the interlayer of the clays. Secondly, it may be due to the fact that, from the decaying logs, more of the dissolved organic nitrogen leaks into the soil, where it is subsequently aggressively metabolizes to $NH4^+$ [44]. The absence of labile C would facilitate the process by forcing the breakdown of organic N (amino acids, amino sugars and peptides) into the carbon skeleton and ammonia. This is supported by the fact that, indeed, DOC leaching from decaying wood is really low in labile carbon and high in hydrophobic acid components [45]. Since other parameters remained constant, it appears that enhanced N mineralization was not accompanied by increased nitrification, as indicated by the higher amounts of $NH4^+$ in decay class IV (Figure 7A–C).

The distance from the decaying logs also had a significant effect on the soil carbon, nutrient and enzymatic activities. A higher C storage was measured in the soil present in the immediate vicinity compared to that away from the deadwood. At a distance of 50 cm from the decaying log, the influence of the deadwood on the soil C contents was lesser. It is reported that the presence of deadwood is a major source of C [45], and nutrient release from the decaying logs may take place in several ways. The release and mobility of nutrients may be enhanced by the mycelia of fungi responsible for log-decomposing and *ectomycorrhizal* fungi [46]. Gradual decomposition and the release of nutrients generally occur in the zones closer to decaying logs and at a higher distance from the logs; little mixing usually occurs between decomposed organic substrates and the soil surface. The C:N measured under the CWD of decaying logs was also higher compared to that measured at a higher distance from the decaying logs (50 cm). The partly decomposed OM occurred near the decaying logs, and organic substrates were supplied directly by the deadwood. Therefore, at a higher distance from the logs, the accumulation of lower organic matter and biological activity occurred within the soil. The result obtained demonstrated that coarse wood debris influenced the soil's organic carbon and biological activity reliant on its form, decay class and species, as well as the distance from the deadwood logs. Lajtha et al. [47] proposed a strong, interesting effect of coarse woody debris on the biological activity of the soil. The amount of available carbon revealed that C depends on the decay class of deadwood. As the decay class is processed, more carbon substrates are contained in the soil, which stimulates organic matter decomposition. The results from the previous studies recommended that the activity of soil enzymes is the sensor of soil organic matter decomposition [48].

4.3. Soil Enzymatic Activity

There are numerous potential mechanisms that could clarify the enrichment of microbial enzyme activity and decomposition due to the proximity effects of CWD (Figure 4). It may be due to two possible reasons; the first one is the buffering of environmental variation; the second is the increased DOC and higher soil moisture content in soils underneath CWD, which have been investigated in other studies regarding a woody debris addition, and due to increased labile carbon availability, might have stimulated the microbial activity. Additionally, the soil environment can be more favorable for microbial life by improving the soil's physical properties. Another possible reason that enhances microbial activity is the atmospheric temperature and precipitation [49]. For example, Wei et al. [50] showed that soil temperature directly impacts enzyme activity by altering enzyme kinetics. CWD on the forest floor increased the soil fungal/bacterial ratio, as well as increased respiration and the soil microbial biomass [51], which is in line with our results. In another study, De Beeck [51] reported that the Phosphatase enzyme increased under CWD, which might be due to the spatial distribution of the soil organic matter affected by temperature. Another possible amplification might be that the soil's vegetation condition and nutrient status in the forests influence soil acid phosphates activity [52]. Urease is an important enzyme that regulates soil N transformation and comes mainly from plants and microorganisms, playing a vital role in the process of nutrient cycling. The increase in urease activity can be explained because urease has a strong positive correlation with the pH, N and other nutrients [49]. Thus, the increase in urease and dehydrogenase activities of underlying soil (Figure 4A,D) may have been caused by a drop in diverse substrate availability as compared with single Chinese fir leaf litter. There are large effects of mixed leaf litter on the pattern of mass loss, changes in nutrient concentration, and decomposition abundance and activity. Comparatively higher dehydrogenase (DH) values, as well as high organic C, were recorded in the soil around (PAPF) logs. These differences in the enzymatic activity, reflected in the amount and quality of the organic matter in the soil, may be related to the characteristics of the wood species, i.e., PAPF, BPF or TPF. Similarly, a high-quality OM with lower C:N, which is generally used to define litter quality, was measured for the PAPF. The quantity and quality of OM are important factors, affecting the energy supply for microbial growth and enzymatic activity and production. Moreover, the accumulated OM and related biological processes occurring in the soil can be affected by the bryophytes community in the vicinity of decaying logs, which have a strong influence on the decomposition rate of deadwood and soil enzymatic activity in the soil [53].

Course woody debris is an important component of forest ecosystems and the principal source of organic matter in the soil. The litter present on forest floors and decaying logs is a major source of OM that contains certain compounds, including soluble sugars, organic acids, celluloses and lignin. The results obtained in this study showed the important role of decaying logs in forest ecosystems in enhancing soil C accumulation and simultaneous improvement in other biological activities in a forest soil environment. Decaying logs in the advanced decaying stage strongly influenced the soil's physical, chemical, biological and enzymatic properties [54]. The data explaining the certain mechanisms and other factors affecting the organic C dynamics accumulated in forest ecosystems may be used to calculate C budgeting to develop technologies for reducing the impact of climate change on forest ecosystems and servicing. The deadwood and decaying logs present in the forests may be considered cheap and sustainable resources that should be protected to increase soil carbon stocks.

5. Conclusions

The coarse wood debris (CWD) significantly contributes to the forest ecosystem by enhancing productivity, carbon sequestration and nutrient cycling. Therefore, we unlocked the role of CWD and came up with the conclusion that it represents a substantial C and N pool in forests, which significantly influences microbial and biotic processes affecting carbon and nutrient turnover in biogeochemical reservoirs. Furthermore, the pH, NH_3, urease, phosphatase and dehydrogenase enzyme activities along with the N, C, NH4, P and K concentrations were increased in the *Betula costata-pinus koraiensis* forest (BPF) with increasing decay class, while Ca, Mg and Mn and the poly oxidase enzyme did not show any significant changes across decay classes and forest types. The accumulation of C and enzymatic activity were higher when closer to highly decayed deadwood and logs. Thus, this CWD existence has an ecological significance in carbon sequestration and functional diversity in natural forest ecosystems. This study also clarifies the relationship between CWD, carbon capture, nutrient composition and enzymatic activity in the forest ecosystem.

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