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Nutrient Dynamics Assessment of Coarse Wood Debris Subjected to Successional Decay Levels of Three Forests Types in Northeast, China

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Abstract: Coarse wood debris (CWD) plays a critical role in forest productivity, nutrient cycling, decomposition, and carbon sequestration, and shapes the carbon pool in the forest ecosystem. However, the elemental composition of CWD varies among different forest types and decay classes for the same dominant tree species (*Pinus koraiensis*, PK). We compared CWD elemental composition across different forest types (*Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF), *Betula costata-Pinus koraiensis* forest (BPF), *Tilia amurensis-Pinus koraiensis* forest (TPF)), considering four classes of wood decay. Results showed that N, P, Mg, Mn, Na, Zn, S, Al, and Fe concentrations almost totally increased with decay level for all three forest types, except for K in all three forest types and B in *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF). Similarly, maximum concentrations of N, P, B, Mg, K, C, Zn, and Mn of CWD were observed in *Betula costata-Pinus koraiensis* forest (BPF) under varying decay classes, but their maximum concentrations of Fe and S were found in *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF) and *Tilia amurensis-Pinus koraiensis* forest(TPF), respectively. Only C content did not significantly differ in decay classes across all three forest types. The C:N ratio decreased significantly with increasing decay levels across all forest types. The decay rates were significantly related to N concentration and C:N ratio in decay classes across all forest types. These results suggest that C and N concentration are the key factors affecting its decomposition. The variation in nutrient concentrations observed here underscores the complexity of nutrients stored in wood debris in forested ecosystems.

Keywords: coarse wood debris; nutrient concentration; decay class; C; N; P; *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF); *Betula costata-Pinus koraiensis* forest (BPF); *Tilia amurensis-Pinus koraiensis* forest (TPF)

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1. Introduction

Large wood debris, also known as coarse woody debris (CWD), provides a habitat and protection for a wide array of organisms, insects, and fungi in particular [1,2]. CWD provides appropriate substrates, or nurse logs, for recovering vascular plants [3], microclimates that shield life from extraordinary natural conditions [4], which are considered an imperative structural and functional component of forests, controlling soil disintegration and affecting hydrologic and geomorphological cycles [5]. CWD accounts for 20–30% of above-ground litter in the tropics and more than 60% in temperate regions [6].

CWD plays numerous roles in the forest ecosystem in the recycling of nutrients, which stimulates soil properties [5]. It contains huge volumes of C and serves as a source of providing bio-available carbon (C) and enriching the soil by the decomposition of wood for C [7,8]. Owing to its dominant role in forest C cycling, CWD has been examined several times [9,10]. However, it has been less often considered in assessments of the decomposition of fine litter to N and other nutrient cycles [11]. The total global forest C contained in the products of CWD decomposition comprises approximately 36–72% of C [12,13]. Certain factors are involved, which directly and indirectly affect the quality and distribution of CWD, such as site, tree species, age and distribution dynamics, tree mortality, and decomposition rate, which greatly influence the quantity and distribution of CWD [2,14]. However, there are three main processes involved in the changes in nutrients in CWD: (a) C loss, which increases the concentration of other essential elements, (b) N fixation by prokaryotes, and (c) fungal transport of outside nutrients [15]. Different species show different development times; Walczynska [16] reported that the maximum development time ranges from 3 to 4 years for *S. rubra* to 6 years for *C. mariana.* At that long period of development, the process of wood decomposition advances, and the concentration of other nutrients also increases, for example in the case of geomycology, the growth of fungi can increase the concentration of other nutrients in CWD. Over the time corresponding to the larval development of a xylophage, the nutrient concentration may increase by 23-fold for N, 40-fold for P, 6-fold for Cu, 6-fold for K, and 7-fold for Fe as a result of nutrient transport from the outside environment by geomycology [17]. Thus, xylophages develop in a nutritionally dynamic environment [18]. Geomycology includes organic and inorganic alterations related to nutrient cycling, bioweathering of rocks and minerals, and mycogenic biomineral formation. Transformations of nutrients and minerals are central to geomicrobiology, and fungi affect changes in nutrient/metal speciation, in addition to facilitating mineral formation/dissolution. Nevertheless, they also play a vital role in the aquatic environment and are significant components of the deep subsurface and forest environments as well [19].

Studies in temperate and boreal forests (the majority of them dependent on chronological order after recognized aggravation of the system) have focused on wood decomposition along with changes of nutrient content [20]. CWD can serve as a site for the fixation of N, as a support for seed germination, and also for water storage [5]. However, when these indications were reanalyzed on behalf of mass losses for the reason of CO_2 respiration breaking, it was also found that the N concentration was increased by the decomposition [19]. In some cases, with respect to the specific impact of wood decay on the soil's physical, chemical and biotic properties, various investigations have discovered significant results. Some studies have found higher C and N percentages in soil under decaying woods in temperate and boreal forests, but found that the ratio between C and N was not affected [21]. Concerning nutrients, CWD has been studied previously various times [22,23]. However, results rely significantly upon the species of wood debris, specific nutrients, the concentration of nutrients at the initial stage, climate, soil type, and the decomposer community [24,25]. During the decomposition of CWD, a study showed that the nutrients might be leached down, leading to the breakdown of organic matter and the major portion of wood eventually lying on the forest floor and soil [5].

Globally, coarse wood debris has been studied based on its quantity and quality in different forest ecosystems and these studies have predominantly focused on the ecosystem, nutrtient stocks, dynamics, and respiration [26,27]. Nevertheless, less work has been done on the nutrient dynamics of CWD decomposition and nutrient content in forest ecosystem on a long-term basis [28]. In China, different forests have been investigated with respect to CWD, such as Korean pine mixed forest [29], coniferous forest, evergreen broadleaved forest, *Abies fargesii* forest, and *Castano psiseyrei* forest and coniferous forest [30,31]. Considering the importance of CWD, these studies may elaborate an optimum way of dealing with some changes in natural forest ecosystems and forecasting the effects of land usage and climate changes [32], but there is the constraint that without long-term experiments

on CWD dynamics, it is very difficult to obtain quantitative data on the annual influx of CWD because of spatial variability and the fluctuation of CWD according to species [5]. Our study aimed to cover this gap.

Mixed forests possess great importance to pure pine forests, and the limited quantities of deciduous species in pine stands can cause huge changes in the cycling of nutrients. Deciduous trees yield rich nutrient forest floors, promoting elevated decomposition due to prominent soil macrofauna, especially earthworms [33]. The noticeable nutrients exhibited higher pH, absolute N, accessible P, extractable Mg, Ca and K, and lower C:N proportions on the forest floor in mixed pine-birch stands contrasted with pure pine stands. The combination of species in mixed forests may elevate rates of litter decomposition by altering the physical and chemical environment. The proficient and elevated utilization of litter substrates by decomposers occurs because of more noteworthy environmental and food variety [34].

Recently, species combinations are gaining growing attention, as they can be more valuable than pure stands. Therefore, the mixing of tree species has been documented as an adaptation policy in the management of forest in response to climate change [35,36]. Expanded foliage N and P concentrations, along with growth increases, have been observed in mixtures with Scot's pine or larch and Sitka spruce in Great Britain. The production and soil acidity have been compared between conifer/deciduous species mixtures and monoculture stands.

Above- and below-ground interactions between species in mixed stand forest ecosystems are the reason for complex nutritional properties [37]. It was reported that the heterogeneity of nutritional characteristics of the forest floor is reflected by the complexity of the greater canopy [38]. Hence, the nutritional properties of forest soils may be affected by canopy composition. Different tree species or even the admixture of species possesses a prominent effect on forest floor quality, along with soil physical, chemical and biological properties [39,40]. Previously, it was observed that mixed pine and spruce stands compared with monoculture stands showed only small gains in cited coniferous species [41]. However, different examinations have recommended that conifer combinations may have a higher volume increase from 10–15% as compared to pure pine or spruce stands. Thus, it was indicated that the efficiency of mixed stands can exceed the mean weighted profitability of pure stands [42]. This over-yielding can reach 50% in mixtures with nitrogen-fixing species [43] and 20–30% in other species [44]. It was reported that the supply of resources, uptake and use efficiency, and stand growth can be improved by mixing tree species rather than using monoculture plantations, when the litter of more than one tree species was typically combined on the forest floor [45]. There have been recommendations that decay rates and nutrient fluxes can be influenced by differing resource quality and the mixing of litter from different species. Klemmed recommended that the release of nutrients through litter decay in ponderosa pine (*Pinus ponderosa*) forests might be accelerated through the accumulative co-occurrence of Gambel oak (*Quercus gambelli*) [46].

In this paper, we aimed to present the elemental stoichiometry of CWD and to understand the CWD decay process across decay levels in contrasting forests. In particular, we aimed to investigate if the elemental composition and dynamics of CWD significantly differed across different decay classes in three forest types. In addition, we wanted to find the interrelations of the nutrient composition of CWD with environmental factors between contrasting forest types for the same tree species (*Pinus koraiensis*, PK). However, we addressed these questions at two levels, (i) interrelations between *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF) and *Betula costata-Pinus koraiensis* forest (BPF), and (ii) between *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF) and *Tilia amurensis-Pinus koraiensis* forest (TPF).

2. Materials and Methods

2.1. Study Site Description

The study was conducted at the Liangshui National Nature Reserve (47°10′50″ N, 128°53′20″ E), in Heilongjiang, northeast China. The study site is characterized by undu-

lating terrain, with an elevation ranging from 300–707 m above sea level (a.s.l) and with a slope of 10°–15°. The annual mean temperature is −0.3 °C, with an annual mean precipitation of 676 mm. Snowfall contributes 10–20% of the total precipitation, and prevails through December to April. The area has a long history of community development, with a variety of forest stands. According to American soil taxonomy, the soil of the study area was classified as dark- brown forest; equivalent to Humaquepts or cryoboralfs [47].

2.2. Experiment Design and Sample Collection

The data were used to calculate changes in nutrient concentrations at different decay levels. The experiment was performed on three 100 m × 120 m, 100 m × 110 m, 100 m × 120 m permanent plots, established in August 2017 in randomly selected *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF), *Betula costata-Pinus koraiensis* forest (BPF), *Tilia amurensis-Pinus koraiensis* forest (TPF), respectively. All the samples were collected from the same dominant tree species (*Pinus koraiensis*, PK) in this area, having different decomposition levels. The decay class system was used to classify the wood debris samples based on their morphology and hardness, according to the field criteria established by [48]. Decay stages/classes of each sample for PK were recorded as follows. In the first decay stage (I), the logs recently fallen with twigs and leaves with hard wood were recorded. In the second decay stage (II), there was bark but no leaves with hard wood. In the third decay stage (III), the bark was partially present, with semi-solid wood. The fourth decay stage (IV) was classified as no bark with partially soft wood, and the fifth decay stage (V) comprised soft and fragmented wood, having a bowl shape, or oval to flat. Based on the visual observation and distinguishing between decay classes, we usually identified 4 decay classes. In the fifth decay class, decay classes were often indistinguishable and therefore we did not consider this class in our study.

2.3. Sample Processing and Analyses of Nutrients

For the elemental determination of coarse wood debris (CWD), we used log samples of approximately 10 cm in diameter for each decay class of the same dorminant tree species (*Pinus koraiensis*, PK) in *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF), *Betula costata-Pinus koraiensis* forest (BPF), and *Tilia amurensis-Pinus koraiensis* forest (TPF). Nutrient concentrations of CWD from *Pinus koraiensi* with different decay levels in each forest type were determined and was separately compared within the same forest type and between different forest type. A total of five samples were collected per decay class in each forest type. All samples were labeled and placed in sealed plastic bags, transported to the laboratory, and stored in a refrigerator (at 4 °C) until being processed. To avoid contamination, samples were handled with nitrite gloves, both in the field and in the laboratory.

To determine the nutrient concentration in CWD, we collected log samples of approximately 10 cm in diameter for each of *Pinus koraiensis* decay classes. The samples were carefully handled, stored, and transported to the laboratory for further analysis. The collected samples were carefully brushed to remove the soil particles. Subsequently, samples were oven-dried at 65 °C and ground by mills into powder for biochemical analysis. The ground samples were weighed and digested with a mixed acid (HNO_3 + $HClO_4$ in the ratio of 5:1 (v/v)). The concentrations of phosphorus (P), potassium (K), magnesium (Mg), sodium (Na), manganese (Mn), aluminum (Al), boron (B), iron (Fe), and zinc (Zn) were determined using an inductively coupled plasma optical emission spectrometer (ICP-AES, Optima-8300 DV; PerkinElmer, Inc., Waltham, MA, USA). To determine total carbon (C) and total nitrogen (N), a LECO C/N, 2000 analyzer was used. The concentrations of each nutrient based on decay class for the same tree species (*Pinus koraiensis*, PK) were compared. The whole experiment was replicated three times for each decay class.

2.4. Soil Sampling and Analysis

Soil samples were collected using a soil core that was 5 cm in diameter. Soil was collected from a 10-cm depth at three different locations near each log sample location. Soil

samples were pooled to create one sample to analyze the soil's chemical properties. In the field, all the soil samples were put in plastic bags and transported to the laboratory. In the laboratory, soil samples were divided in to two sub-samples—one sample was stored at 4 °C to measure soil moisture, whereas the other soil samples were air-dried and sieved through 2-mm mesh to determine soil physical and chemical properties. Soil moisture was measured by oven-drying fresh soil samples at 105 °C. Soil pH was determined by taking 1 g soil at ratio of 1:2.5 (v/v) and placing it in a mechanical shaker for 30 min using a calibrated pH meter (S220 Seven Compact pH Meter, Shanghai, China). The total nitrogen content of the soil was determined using a Hanon k9840 Auto kjeldahl analyzer (Jinan Hanon instruments Co., Jinan, China). Soil temperature was determined by inserting the thermometer through the block, gently pushing in the thermometer until the tip was 7 cm below the soil surface, reading the soil temperature at 5 cm, waiting at least 2 min, then reading the thermometer every minute until consecutive readings were within 0.5 °C–1.0 °C of each other (Table 1). Note: Dry mass was not obtained prior to preparing analytical samples.

Table 1. Mean data of soil physical and chemical properties across different forest types; Abbreviations: C, carbon and N, Nitrogen.

Forest Type	Decay Classes	Soil Temperature (°C)	Soil Moisture (%)	Soil Organic C (g/kg)	Total N (g/kg)	Soil pH
PAPF *	I	11.70	35.57	52.03	6.58	5.48
	II	11.52	35.78	56.47	6.37	5.33
	III	11.96	37.52	59.50	8.32	5.23
	IV	12.17	38.86	62.09	8.33	5.11
TPF **	I	13.23	41.43	63.06	8.75	5.82
	II	13.44	41.06	55.87	8.85	5.72
	III	13.72	42.30	66.59	9.03	5.57
	IV	13.96	44.47	67.66	9.27	5.48
BPF ***	I	12.4	41.72	52.44	7.55	5.74
	II	12.47	41.63	53.26	7.87	5.68
	III	12.57	42.38	59.16	8.22	5.42
	IV	12.73	44.71	61.66	8.70	5.46

* PAPF represented *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest; ** TPF represented *Tilia amurensis-Pinus koraiensis* forest; *** BPF represented *Betula costata-Pinus koraiensis* forest. The same below.

2.5. Statistical Analyses

A two-way analysis of variance (ANOVA) was used on normally distributed data (Shapiro–Wilk test) to study the effect of forest species, decay classes, and their interactions. Tukey's honest significant difference (HSD) test was used to analyze the significant differences between nutrient concentration in forest types and different decay classes. Redundancy analysis (RDA) was used to identify soil properties (i.e., soil temperature, soil moisture, pH, total nitrogen) that predicted the variations in the nutritional status of decay classes. The RDA was performed using the vegan package in the program R. v. 3.6.1. Pearson's correlation coefficients were calculated to determine significantly positive (blue color) or negative (red color) correlations of the nutritional composition of CWD for the same dominant tree species (*Pinus koraiensis*, PK) in different forest types, using the "corrplot" package in R. v.3.6.1. The program R. v. 3.6.1 [49] was used for all statistical analyses. For graphical representations, Sigma plots v. 12.4 (Systat Software Inc., San Jose, CA, USA) was used. Mean data are displayed as mean ± standard error (SE).

3. Results

3.1. Nutrient Concentration across Different Decay Classes

The majority of nutrient concentrations significantly differed among all decay classes across all forest types (Figure 1; Table 2). Coarse wood debris was collected that epitomized all decay stages. Nutrient concentrations generally increased with increasing decay class. The concentration of most of the nutrients remained stable in lower decay classes (i.e., class I and II), but significantly increased in higher decay classes (i.e., class III and IV) (Figure 1;

Table 2). Nitrogen, phosphorus, and sodium concentrations in decay classes I and II remained stable, whereas they significantly increased in decay classes III and IV across all three forest types (Figure 1A–C).

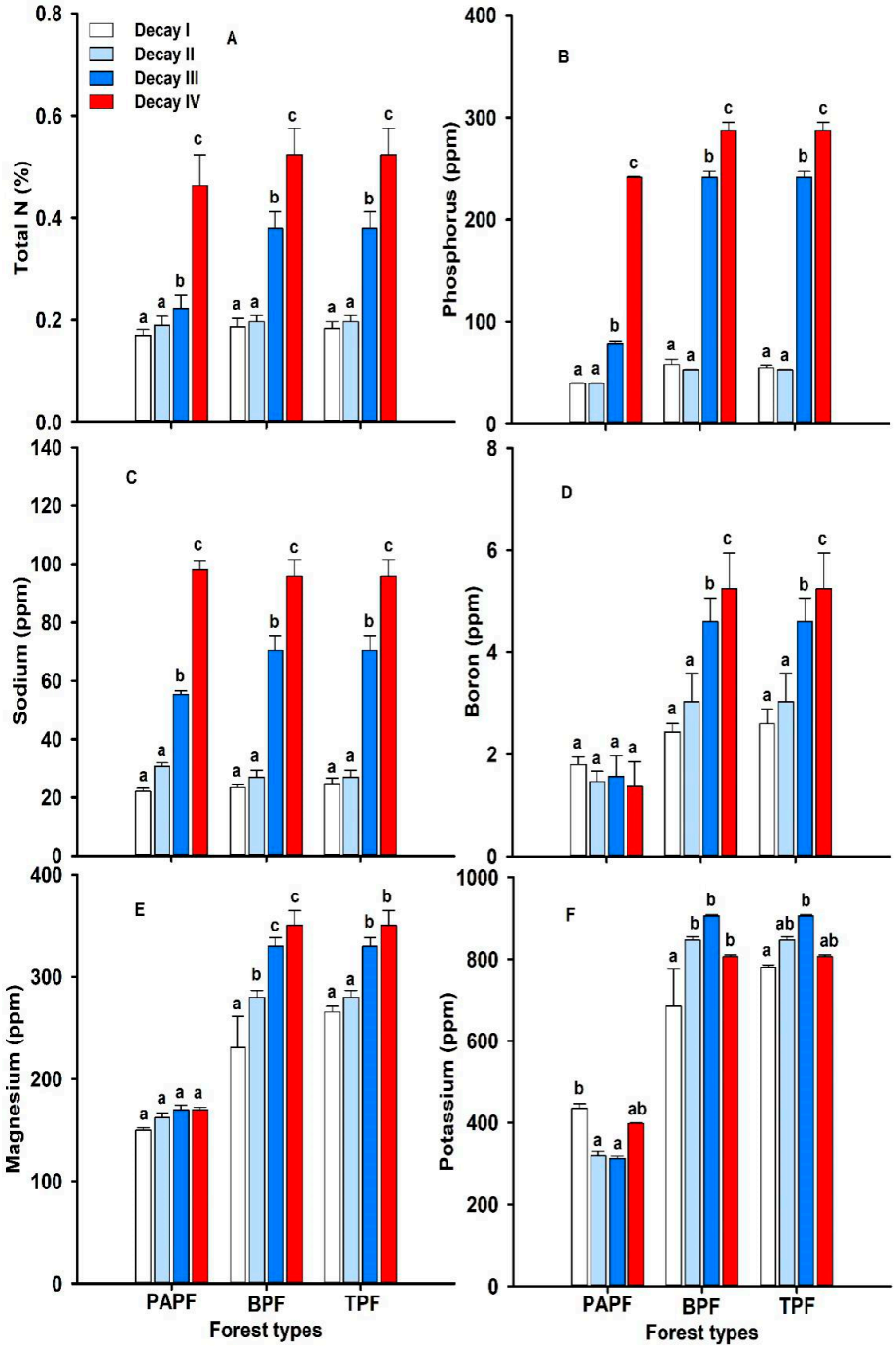

Figure 1. Total N (%) (**A**), phosphorus (ppm) (**B**), sodium (ppm) (**C**), boron (ppm) (**D**), magnesium (ppm) (**E**), and potassium (ppm) (**F**) concentrations of the same dominant tree species (*Pinus koreaensis*, PK) with different decay classes in contrasting forest types of *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF), *Betula costata-Pinus koraiensis* forest (BPF), and *Tilia amurensis-Pinus koraiensis* forest (TPF) in northeastern China. Within the same forest type, significant differences between treatments are indicated by different lower-case letters. Values are means of three replicates, and the bars indicate standard error (Tukey's honest significant difference (HSD) post hoc; $p < 0.05$, mean ± SE).

Table 2. Mean data (ppm) for the elemental composition of coarse wood debris among *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF), *Betula costata-Pinus koraiensis* forest (BPF), and *Tilia amurensis-Pinus koraiensis* forest (TPF) in Northeastern China. Abbreviations: C: carbon; C:N: carbon to nitrogen ratio; Al: aluminum; Cu: copper; Fe: iron; Zn: zinc; S: sulfur; Mn: manganese.

Forest Type	Decay Classes	C	C:N	Al	Cu	Fe	Zn	S	Mn
PAPF *	I	51.5 ± 0.2 a	305.7 ± 20.3 a	45.3 ± 1.2 c	0.6 ± 0.1 b	90.0 ± 1.5 c	14.0 ± 1.2 b	125.3 ± 0.3 c	105.0 ± 1.5 b
	II	50.8 ± 0.4 a	271.6 ± 23.5 b	40.7 ± 0.9 c	1.0 ± 0.1 b	75.0 ± 1.2 d	10.7 ± 0.9 b	180.0 ± 0.6 b	70.3 ± 1.8 c
	III	50.7 ± 0.4 a	232.9 ± 25.7 c	55.0 ± 1.2 b	2.7 ± 0.9 a	130.3 ± 1.9 b	28.3 ± 2.0 a	190.0 ± 1.0 b	105.7 ± 0.9 b
	IV	49.7 ± 0.6 a	111.0 ± 14.4 d	371.0 ± 5.5 a	1.9 ± 0.7 a	270.7 ± 1.5 a	30.0 ± 1.2 a	340.0 ± 1.2 a	250.0 ± 7.9 a
BPF **	I	51.0 ± 0.8 a	278.0 ± 26.0 a	31.0 ± 1.2 c	0.4 ± 0.0 b	30.7 ± 1.7 d	210.3 ± 5.2 c	33.7 ± 1.5 d	140.3 ± 1.2 d
	II	51.4 ± 0.1 a	263.2 ± 14.9 a	25.3 ± 0.9 c	0.6 ± 0.0 b	48.4 ± 1.9 c	215.7 ± 3.8 c	45.7 ± 3.5 c	355.0 ± 1.5 c
	III	52.1 ± 0.4 a	139.2 ± 12.9 b	44.3 ± 1.2 b	2.1 ± 0.5 a	85.0 ± 1.6 b	250.3 ± 6.4 b	87.0 ± 5.5 b	510.0 ± 1.7 a
	IV	50.2 ± 0.6 a	98.2 ± 11.3 c	100.3 ± 4.5 a	2.5 ± 0.6 a	120.3 ± 1.3 a	390.7 ± 7.2 a	112.0 ± 11.4 a	390.7 ± 1.8 b
TPF ***	I	51.4 ± 0.6 a	283.2 ± 20.9 a	33.0 ± 3.1 c	0.5 ± 0.1 b	56.0 ± 1.0 c	72.7 ± 40.2 c	102.3 ± 37.2 d	183.0 ± 23.2 d
	II	51.4 ± 0.1 a	263.2 ± 14.9 a	25.3 ± 0.9 c	0.6 ± 0.0 b	48.4 ± 1.9 c	45.7 ± 3.5 d	355.0 ± 1.5 c	215.7 ± 3.8 c
	III	52.1 ± 0.4 a	139.2 ± 12.9 b	44.3 ± 1.2 b	2.1 ± 0.5 a	85.0 ± 1.6 b	87.0 ± 5.5 b	510.0 ± 1.7 a	250.3 ± 6.4 b
	IV	50.2 ± 0.6 a	98.2 ± 11.3 c	100.3 ± 4.5 a	2.5 ± 0.6 a	120.3 ± 1.3 a	112.0 ± 11.4 a	390.7 ± 1.8 b	390.7 ± 7.2 a

Note: significant differences among columns are indicated by significant lowercase letters, Tukey's HSD $p < 0.05$, mean ± SE. * PAPF represented *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest; ** BPF represented *Betula costata-Pinus koraiensis* forest. *** TPF represented *Tilia amurensis-Pinus koraiensis* forest; The same below.

Interestingly, B and Mg concentrations remained stable in decay classes I and II, but increased significantly in decay classes III and IV across *Betula costata-Pinus koraiensis* forest (BPF) and *Tilia amurensis-Pinus koraiensis* forest (TPF), whereas they remained stable across all decay classes in *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF) (Figure 1D,E). K concentration was significantly modified among all four decay classes in all three forests (Figure 1F). K concentration in decay classes I and II across *Betula costata-Pinus koraiensis* forest (BPF) and *Tilia amurensis-Pinus koraiensis* forest (TPF) remained relatively stable, whereas it decreased insignificantly across decay classes III and IV.

However, carbon concentrations remained unaffected in all four decay classes across all three forest types (Tables 2 and 3).

Table 3. ANOVA results for forest types, decay classes, and their interactions on nutritional compositions of different forest types of *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF), *Betula costata-Pinus koraiensis* forest (BPF), and *Tilia amurensis-Pinus koraiensis* forest (TPF) in Northeastern China. Abbreviations: N: nitrogen; C: carbon; C:N: carbon to nitrogen ratio; Al: aluminum; B: boron; Cu: copper; Fe: iron; K: potassium; Zn: zinc; Na: sodium; S: sulfur; Mn: manganese.

Source of Variation	**df**	**N**	**C**	**C:N**	**P**	**Al**	**B**	**Cu**
Forest Type(FT)	2	**<0.001**	**0.003**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Decay classes (Decay)	3	**0.024**	0.189	**0.016**	**<0.001**	**<0.001**	**<0.001**	0.900
FT× Decay	6	0.233	0.647	0.191	**<0.001**	**<0.001**	**0.021**	0.812
Source of variation	**df**	**Fe**	**K**	**Mg**	**Zn**	**Na**	**S**	**Mn**
Forest Type(FT)	2	**<0.001**	**0.022**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Decay classes (Decay)	3	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.462	**<0.001**	**<0.001**
FT × Decay	6	**<0.001**	**<0.001**	**0.006**	**<0.001**	0.122	**<0.001**	**<0.001**

Note: *p* values in bold indicate significant effects.

The C:N ratio remained relatively stable in decay classes I and II and significantly decreased in decay classes III and IV (Tables 2 and 3).

Al concentration remained stable between decay classes I and II in all three forest types, whereas it increased significantly from decay level II to IV in all forest types (Tables 2 and 3).

Cu concentration also remained relatively stable between decay classes I and II and between decay classes III and IV in all studied forest types, but increased insignificantly from decay classes I to II and from III to IV in BPF and TPF, decreased insignificantly in decay classes III and IV in PAPF (Tables 2 and 3). Fe concentration significantly increased across decay levels in all forest types except for in decay class I and II in TPF. Zn concentration remained relatively stable in decay class I and II in PAPF and BPF, while significantly increased from decay levels II to IV in BPF and TPF (Tables 2 and 3). Similarly, S and Mn increased significantly in all four decay classes across all forest types except for S from decay level II to III and Mn in decay class II in PAPF (Table 2).

3.2. Nutrient Concentration across Different Forest Types

The greatest concentration of N, P, B, Mg, and K were observed in *Betula costata-Pinus koraiensis* forest (BPF), whereas their lowest concentration was observed in *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF) (Figure 1). In comparison, no significant differences in Na concentration were observed across forest types. Furthermore, the greatest concentrations of B, Mg, and K were more or less similar in *Betula costata-Pinus koraiensis* forest (BPF) and *Tilia amurensis-Pinus koraiensis* forest (TPF), whereas the lowest concentrations were observed in *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF). In addition, the significantly highest C:N ratio was observed in *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF) relative to the other two forest types. The maximum Cu and Fe concentrations (i.e., 2.7 and 270.7 ppm) were observed in *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF), whereas the maximum Zn concentration (390.7 ppm) was observed in *Betula costata-Pinus koraiensis* forest (BPF) (Table 2).

3.3. Interrelations of the Nutrient Composition of CWD with Environmental Factors

Among forest types, RDA showed an interrelationship in the nutritional composition of coarse wood debris (CWD) and their responses to environmental factors (i.e., soil organic carbon (SOC), soil temperature (ST), soil moisture (SM), soil pH, and soil total nitrogen (TN); Figure 2). The first and second axes accounted for 26.7% and 4.4% of the total variations, respectively. Soil pH, total nitrogen, soil temperature, and moisture showed a strong positive correlation with Al, Fe, N, P, Na, Mn, Cu, B, Mg, K, and S, whereas they were negatively correlated to C. SOC had a strong correlation with S, Cu, Mn, Al, and C, whereas it was weakly correlated to B, Mg, N, Na, Fe, Zn, K, and P. Based on RDA, up to 31.1% of the variations in the nutritional composition of coarse wood debris (CWD) were explained by the environmental factors.

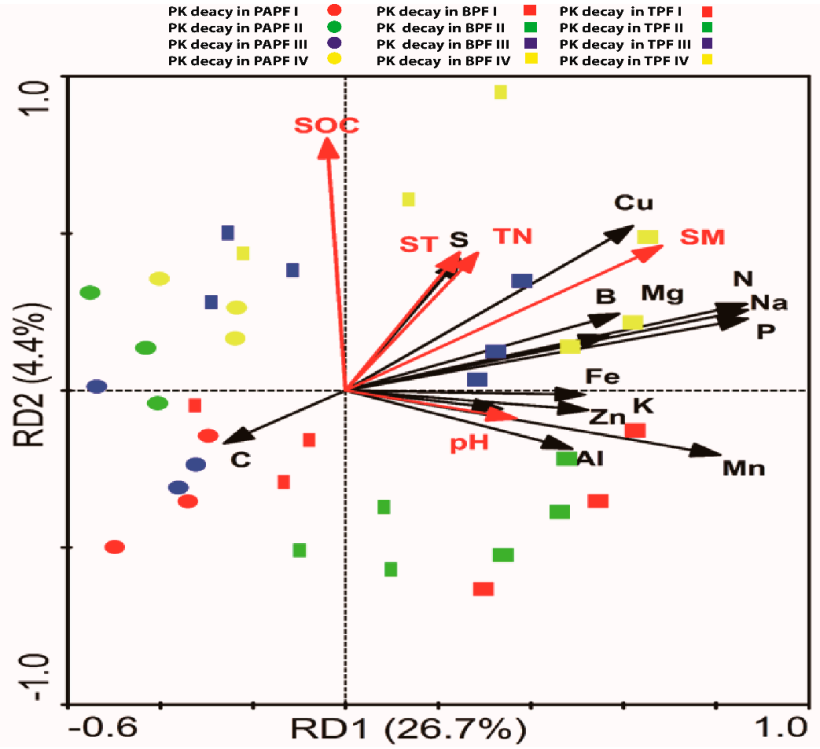

Figure 2. Redundancy analysis for nutritional status of the decay classes of contrasting forest types of *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF), *Betula costata-Pinus koraiensis* forest (BPF), and *Tilia amurensis-Pinus koraiensis* forest (TPF) in Northeastern China. Abbreviations: Al: aluminum; Zn: zinc; Fe: iron; N: nitrogen; P: phosphorus; Na: sodium; Mn: manganese; Cu: copper; B: boron; Mg: magnesium; K: potassium; C: carbon; S: sulfur; SOC: soil organic carbon; ST; soil temperature; TN: soil total nitrogen; SM: soil moisture; and pH: soil pH.

3.4. Correlations between the Nutrient Compositions of CWD across Forest Types

Looking at the trait interrelations between the nutritional status of decay classes of the same dominant tree species (*Pinus koraiensis*, PK) in *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF) and *Betula costata-Pinus koraiensis* forest (BPF) (Figure 3A), nitrogen was significantly negatively correlated to carbon and C:N, whereas it was significantly positively correlated to P, Al, B, Cu, Fe, Mg, Zn, Na, S, and Mn and was not significantly correlated to K. Carbon was significantly positively correlated to C:N and significantly negatively correlated to Al, Cu, Fe, Na, and S, while not being significantly correlated to P, B, K Mg, Zn, and Mn. Al was significantly positively correlated to Fe, Na, and S, and was not significantly correlated to B, Cu, K, Mg, Zn, or Mn. B was significantly positively correlated to Cu, K, Mg, Zn, Na, and Mn, and was not significantly correlated to Fe or S. Cu was significantly positively correlated to Fe, Mg, Zn, Na, S, and Mn, whereas it

was not significantly correlated to K. Fe was significantly positively correlated to Na and S, whereas it was not significantly correlated to K, Mg, Zn, and Mn. Zn was positively correlated to Mn and negatively correlated to S, whereas it was not significantly correlated to Na (Figure 3A).

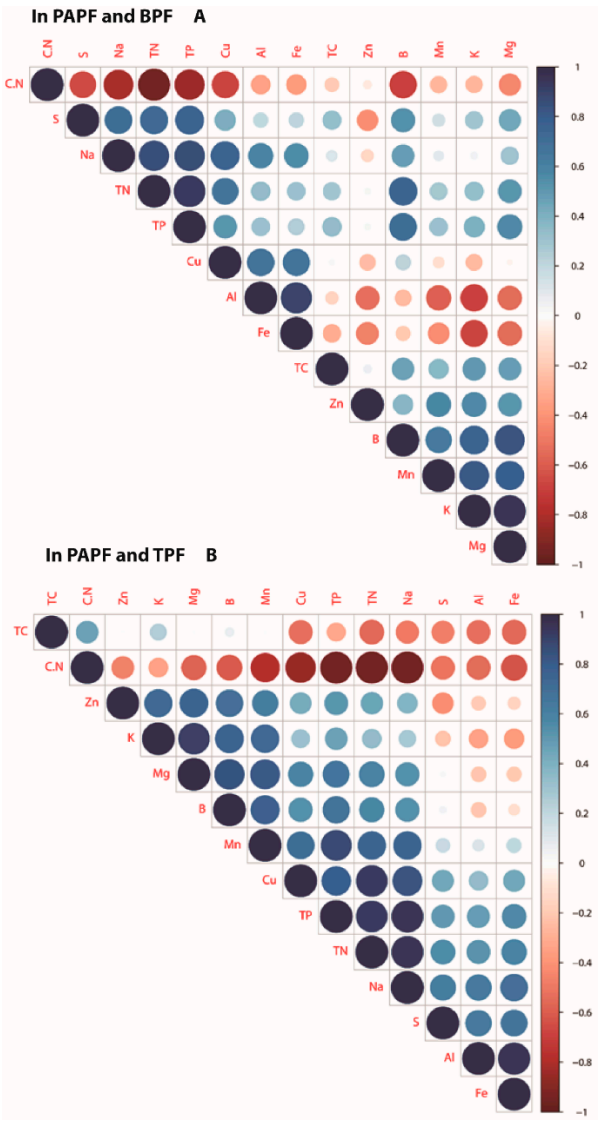

Figure 3. Pearson's correlation of elemental compositions of coarse wood debris from the same dominant tree species (*Pinus koraiensis*, PK) between in *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF), and in *Tilia amurensis-Pinus koraiensis* forest (TPF) (**A**) and between in *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF), and in *Betula costata-Pinus koraiensis* forest (BPF) (**B**) in Northeastern China. The significant positive (blue color) or negative (red color) correlations are indicated by colors and circle sizes. Abbreviations: TC: total carbon; C:N: carbon to nitrogen ratios; Zn: zinc; K: potassium; Mg: magnesium; B: boron; Mn: manganese; Cu: copper; TP: total phosphorus; TN: total nitrogen; Na; sodium; S: sulfur; Al: aluminum; and Fe: iron.

Looking at the trait interrelations between the nutritional status of decay classes of *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF) and *Tilia amurensis-Pinus koraiensis* forest (TPF) (Figure 3B), nitrogen was significantly negatively correlated to C:N and significantly positively correlated to P, B, Cu, Mg, Na, and S, whereas it was not significantly correlated to C, Al, Fe, K, Zn, and Mn. Carbon was significantly positively correlated to B, K, and Mg and not significantly correlated to C:N, P, Al, Cu, Fe, Zn, S, and Mn. C:N was significantly negatively correlated to P, B, Cu, Mg, Na, and S, whereas it

was not significantly correlated to Al, Fe, K, Zn, and Mn. P was significantly positively correlated to B, Cu, Mg, Na, and S and not significantly correlated to Al, Fe, K, Zn, and Mn. Al was significantly positively correlated to Fe, Na, and S, and was significantly negatively correlated to K, Mg, and Zinc, whereas it was not significantly correlated to B, Cu, K, Mg, Zinc, and Mn. B was significantly positively correlated to K, Na, Mg, S, and Mn, and not significantly correlated to Cu, Fe, and Zinc. Cu was significantly positively correlated to Fe, Na, and S and not significantly correlated to K, Mg, Zn, and Mn. Fe was significantly negatively correlated to K, Mg, Zn, and Mn, whereas it was significantly positively correlated to Na and not significantly correlated to S. Zn was positively correlated to Mn and negatively correlated to S, whereas it was not significantly correlated to Na (Figure 3B).

4. Discussion

Wood is comprised of almost 90–99% polysaccharides (cellulose, hemicellulose, and lignin) [50,51]. In the mid-latitude zone, elements other than C, H, O, N, and S may comprise approximately 0.1–0.6% of wood; however, tropical wood may be more nutritious, setting forth up to 5% ash [52]. Our results revealed that nutrient concentrations among three forest types showed that the majority of maximum nutrient concentrations of the coarse wood debris of *Betula costata-Pinus koraiensis* forest (BPF) was significantly greater than those of *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF) and *Tilia amurensis-Pinus koraiensis* forest (TPF) (Figure 1). A similar study conducted by Klockow [53] reported that most elements' nutrient concentrations significantly increased among the decay classes of three different species. This is because of mass loss, the contribution of throw fall and litterfall, and the colonization of roots [54]. Harmon [55] added the most conceivable clarification, that is, the presence of basidiomycetes, which are rich in nutrients, within the log itself. Our outcomes show that the storage of nutrients generally declined, whereas most nutrient concentrations increased with decomposition (Table 2). Swift [56] and Boddy [57] assumed that the richness of wood is observed via the loss of CO_2, respiration, and digestion of polysaccharides by microorganisms during the decomposition process. Our results also have a few contradicting outcomes with numerous past studies of nutrient dynamics in wood debris. For instance, Van Hess [58] reported no certain inclination in the concentration of K with decomposition. Moreover, Ganjejunte [59] reported that the P concentration remained the same in wood logs throughout the decay period. These prior studies failed to discover a reliable pattern in various species and geographic regions; they all showed considerable variations in nutrient concentrations and may report inconsistent behavior, and some revealed statistically significant increments in nutrient content [60].

4.1. Decay Class's Effect on Nutrient Dynamics

We observed a significant increase in most of the nutrient concentrations with increasing decay class (Figures 1 and 2; Table 2). Our results were in line with those of Butler, who proposed that the advancement in decay levels significantly increased the nutrient concentrations in both soft and hard wood types [61]. Similarly, Lagomarsino [62] indicated that the increment in decay levels increases the elemental concentrations in coarse wood debris. The reasonable cause of the decay increment might be some special microorganisms (i.e., basidiomycetes) affecting the forest's wooden logs [53,54]. Previously, it was also reported that the increment in the nutrient concentrations with decay classes is due to the greater duration of decomposition for the trees that exist in the forest, through the activity of the microorganisms [55]. The K level decreased along with the decay classes in all types of forests under observation (Figure 1F), which was in line with Chen [63], who reported that among nutrients, the availability of potassium was lower in the samples, compared to other elements, because of high losses through leaching over time. All the nutrient concentrations in the forest-decayed species are dependent on the species type and decay duration [56]. Some previous studies reported a reduction in the C:N ratio and

an increase in N:P ratios across the decay classes. This consistent behavior of the C:N ratio with other studies is due to the activity of fungal hyphae, root colonization, and N fixation. The increasing pattern has been frequently observed in some previous studies, although these observations have not always been statistically significant or consistent across species [22,57].

Early nutrient availability and release are associated with the decomposition processes and are strongly correlated with decay classes. Environmental conditions also have a direct impact on nutrient availability because the activity of the microorganisms in soil is hampered under adverse environmental conditions [58,59]. The nutrient release from coarse wood debris is also affected by the action of insects and fungi acting on the debris and secreting certain compounds that are responsible for its rapid decomposition [64,65].

The colonization of dead wood mostly by arthropods, or at least strongly favored by prior microbial conditioning, was reported by Swift [62]. The results indicated that there were four primary ways which favored colonization and the feeding of wood-dwelling arthropods through microbial activity. These were the production of attractant materials, wood softening by the activity of enzymes, destruction of allelopathic substances, and improvements in resource nutritional quality. Thus, deadwood is not nutritionally stable, and microbial activity is responsible for the nutritional enrichment of deadwood [66]. The symbiotic relationship with microbes also means there is a preference for the infested wood exhibited by fungi and other microorganisms [67,68]. It was found that dry wood termites consume approximately twice as much wood decayed by brown-rot fungi compared to non-decayed wood. After 18 months, it was observed that the colonies consumed five times more decayed wood compared to their counterparts in non-decayed wood [69].

Similarly, Smythe and colleagues [63] found that the subterranean termite *Reticulitermes flavipes* (Kol.) showed a similar preference for decayed wood. The *Zootermopsis* termites feeding on pinewood containing fungi were found to be healthier than those feeding on uninfected wood [70]. During the larval growth of saproxylic beetles, it has been revealed that promoting growth and maturation affects the dynamic changes in the nutritional composition of deadwood [71]. The decomposing fungi may be responsible for all these changes [72]. The low concentration of the nutrients in the soil and decay rates have little or no effect on the availability of the nutrients, thereby affecting nutrient cycling. Furthermore, past studies reported that during the regeneration of forests, woody debris and material can immobilize the essential nutrients (i.e., N, P) and these can be significantly increased across decay classes [73,74]. The nutrient concentrations of N and K released from CWD are about two times smaller than the nutrients cycled in the natural ecosystem. Nevertheless, our study suggests that nutrients released from woody detritus could supply a large proportion of N and K that accumulates in live forest biomass and thus is temporarily removed from circulation under different decay classes. The nutrient release patterns of N and P are dependent upon the N and P availability in the parent materials subjected to decay.

4.2. Effect of Species on Nutrient Dynamics

Nutrient concentrations among forests types showed significant variation in our studies. Specifically, the *Betula costata-Pinus koraiensis* forest (BPF) contained the highest nutrient concentrations for the most of our studied elements. This is because, on average, hardwood (birch) had a more significant nutrient concentration than softwood (pine). Similar supportive work conducted by Harmon and colleagues outlined the two major reasons for this commonly cited pattern [5]. First, hardwoods generally have more living parenchymas and other tissues per unit volume within wood and bark tissues, leading to higher initial nutrient concentrations in both standing trees and recently fallen materials [75,76]. Second, the anatomical features of hardwoods, including radially oriented rays and large-diameter vessels, facilitate fungal colonization much more rapidly than softwood [5]. Further, the component of wood decay fungal communities found on hardwoods differs from that found on softwoods; in fact, many fungi are fairly host-genus specific [66]. These factors all contribute to species-specific differences in nutrient immobilization and mobilization [5,77].

Only one dominant tree species (*Pinus koraiensis*, PK) was investigated and analyzed in this study, but more tree species will be included in our future researches in order to find their decomposition differences in elemental composition of CWD in different forest types and multiple factors' interactive mechanism.

CWD has an important influence on the soil inorganic N and microbial C availability. We found that the nutrient availability of the CWD in the forest under the *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF) and *Tilia amurensis-Pinus koraiensis* forest (TPF) differed significantly (Tables 2 and 3). Dhiedt [78] reported that the reason for variation in nutrient concentrations is that soil microorganism's underneath CWD may not be able to completely use extra C sources in the short term, since soil N accessibility could function as a restricting component for microbial development under N-restricted conditions caused by CWD. The mixed forest system pine trees' CWD exhibited a high nutrient concentration relative to the pine forest CWD (Table 3), which is in line with the results reported by Dhiedt [78] and Lo Monaco [79] suggesting that this is because of high atmospheric nitrogen deposition in this forest, and variations among the tree species in nutrient concentrations validate the composition of either plant species. Our results showed that the coniferous species demonstrated (Figure 1) an incredible range in forest floor C, N, and P contents, and the results do not uphold the mutual conception that in the forest floor, conifers store more elements than deciduous species (Table 2) [80]. Similarly, C, N, and P in forest floors within the range of the deciduous species resulted in higher levels. The pine species would, in general, have more C contents on the forest floor than those in the mixed forest, and these discoveries compare sensibly well with different investigations in similar species [81,82].

5. Conclusions

CWD is an important part of the forest ecosystem that plays a vital role in enhancing forest productivity, C sequestration, nutrient cycling, and decomposition. Its decomposition is affected by various factors, i.e., physical and chemical characteristics. The possible reason for this may be due to the decomposition processes in different geographical forests that define the microbial activity, thereby affecting the overall nutrient concentrations across varying decay classes. We concluded that the dead *Pinus koraiensis* (PK) in three different forest types of *Picea koraiensis-Abies nephrolepis-Pinus koraiensis* forest (PAPF), *Betula costata-Pinus koraiensis* forest (BPF), and *Tilia amurensis-Pinus koraiensis* forest (TPF) contained the chemical elements, i.e., Al, B, C, Cu, Fe, K, N, Mg, Mn, Na, P, S, and Zn, with differing dynamics and concentrations, and with decay alterations. The N, P, Mg, Mn, K Na, Zn, B, S, Al, and Fe concentrations were increased for *Betula costata-Pinus koraiensis* forest (BPF) with the increase in decay class, with no prominent differences for carbon. The CWD in *Tilia amurensis-Pinus koraiensis* forest (TPF) contained N, B, C, Fe, K, Mg, S, Zn, P, and Mn concentrations, although Al, Cu, and Na did not differ across decay classes and forests. Na and K accumulate in the live forests and are attenuated with the circulation and decomposition process. In this study, we observed that CWD can sequester carbon and contribute to functional diversity in the flora of the different forests. Future examination is needed to decide whether this deficiency of nutrients adds to the deficiency of site efficiency or if these nutrients can be supplied from another ecosystem. Because of spatial variability and the fluctuations of CWD, it is therefore necessary to conduct long-term experimentation on CWD dynamics in order to obtain quantitative data on the annual influx of CWD. Nevertheless, discoveries from the current investigation will add to the understanding of the relations between coarse wood debris and the composition of nutrients, an area of study in which some questions remain unclear.

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tion, W.B.D.; funding acquisition, W.B.D. All authors have read and agreed to the published version of the manuscript.

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