

Article

Effects of Nitrogen Deposition on Leaf Litter Decomposition and Soil Organic Carbon Density in Arid and Barren Rocky Mountainous Regions: A Case Study of Yimeng Mountain

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Abstract: The ecological impact of nitrogen (N) deposition has gained significance since the advent of the industrial revolution. Although numerous studies have examined the impact of N deposition on soil organic carbon (SOC), certain arid and barren rocky mountainous regions, which experience more pronounced N limitations, have been overlooked. This study was conducted in the Yimeng Mountains, examining eight treatments created by four N addition levels (0 kg N ha⁻¹ yr⁻¹, 50 kg N ha⁻¹ yr⁻¹, 100 kg N ha⁻¹ yr⁻¹ and 200 kg N ha⁻¹ yr⁻¹) and two tree species (*Quercus acutissima* Carruth. and *Pinus thunbergii* Parl.). The research revealed variations in the effect of N addition on leaf litter decomposition and SOC density (SOCD) between different tree species. Notably, N addition stimulated the decomposition of leaf litter from *Quercus acutissima* Carruth. However, the decomposition of *Pinus thunbergii* Parl. leaf litter was enhanced at N addition levels below 100 kg N ha⁻¹ yr⁻¹, while it was hindered at levels exceeding 100 kg N ha⁻¹ yr⁻¹. In the *Quercus acutissima* Carruth. forest, the N addition levels of 50 kg N ha⁻¹ yr⁻¹, 100 kg N ha⁻¹ yr⁻¹ and 200 kg N ha⁻¹ yr⁻¹ resulted in decreases in SOCD by 10.57%, 22.22% and 13.66%, respectively, compared to 0 kg N ha⁻¹ yr⁻¹. In the *Pinus thunbergii* Parl. forest, the N addition levels of 50 kg N ha⁻¹ yr⁻¹, 100 kg N ha⁻¹ yr⁻¹ and 200 kg N ha⁻¹ yr⁻¹ led to increases in SOCD by 49.53%, 43.36% and 60.87%, respectively, compared to 0 kg N ha⁻¹ yr⁻¹. Overall, N addition decreases the SOCD of *Quercus acutissima* Carruth., but it increases the SOCD of *Pinus thunbergii* Parl., attributed to the alteration in soil enzyme stoichiometry and nutrient cycling by N addition. This study fills a theoretical gap concerning leaf litter decomposition and SOC sequestration in arid and barren rocky mountainous regions under global climate change.

Keywords: nitrogen deposition; leaf litter decomposition; enzyme stoichiometry; soil organic carbon density



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1. Introduction

The emission of reactive nitrogen (Nr) into the atmosphere has experienced a significant increase due to the industrial revolution and economic development [1,2]. Nr emissions can enter ecosystems through dry and wet deposition, leading to issues, such as soil acidification and lake eutrophication [3]. Increased nitrogen (N) deposition promotes plant growth and enhances ecosystem productivity because N is a limiting nutrient for vegetation and soil microorganisms [4]. However, excessive Nr can reduce ecosystem

biodiversity and disrupt geo-biochemical cycles [5]. Atmospheric N deposition has undergone significant changes in the last four decades, primarily attributable to the regulation of NO_y emissions through the Clean Air Act [6]. While total atmospheric N deposition has decreased in Europe and North America, it remains 3–4 times higher in China compared to these regions. This disparity is attributed to the absence of effective NH_x emission management policies in China, leading to an increase in NH_x that offsets the reduction in NO_y [7]. Studies have indicated that certain regions in China are still experiencing increasing or excessive N deposition, surpassing critical thresholds [8]. This emphasizes the ongoing ecological significance of artificial N additions in high N deposition regions of China, aiding in the prediction of future environmental impacts associated with N deposition.

Forest soils play a crucial role as a carbon (C) pool, containing more than 40% of the total soil organic carbon (SOC) in terrestrial ecosystems [9]. Leaf litter decomposition is a crucial process for enhancing SOC levels within forest soils. A meta-analysis of SOC inputs to temperate forest soils revealed that more than 41% of the annual SOC increase was contributed by leaf litter [10]. The main pathways of SOC formation from leaf litter are (1) the conversion of leaf litter into complex compounds on the forest floor and (2) the transfer of leaf litter and humus to mineral soils. They can become part of aggregates and clay minerals, thereby contributing to their stabilization [11]. These pathways are mainly influenced by the natural environment, biological factors and the inherent characteristics of leaf litter [12]. Among them, N deposition plays a significant role in leaf litter decomposition. Studies have indicated that modest or moderate levels of N deposition can enhance leaf litter decomposition, but beyond a certain threshold, N deposition can impede this process [13]. The extent of N limitation within the local ecosystem determines this threshold. Song et al. observed that low levels of N addition significantly accelerated leaf litter decomposition [14]. He et al. demonstrated that N addition alleviated N limitation in soil microorganisms and enhanced enzyme activity, thereby promoting leaf litter decomposition [15]. However, prolonged or excessive N addition generally exhibited negative effects on litter decomposition [16]. N addition induces soil acidification and elevates the osmotic pressure of the soil solution, which has detrimental effects on microbial growth [17]. Ramirez et al. discovered that prolonged N addition caused a 35% reduction in total soil microbial biomass and an 11% decline in microbial respiration rate [18]. Consequently, the response of leaf litter decomposition to N deposition may lead to different results depending on the extent of N limitation within the ecosystem.

Most research on the impacts of N deposition on litter decomposition and SOC pool has concentrated on forest and grassland ecosystems within temperate and subtropical zones [19–21]. However, this response has been neglected in some arid and barren rocky mountainous regions with higher N limitation. The Yimeng Mountain region, located in the central-eastern region of China, experiences high levels of N deposition and is characterized by its typical arid and barren rocky mountain terrain. The soils in this region have thin layers and poor physical structure, leading to a low nutrient retention capacity [22,23]. Meanwhile, the rainfall in the region has caused severe soil erosion, resulting in reduced local nutrient effectiveness [24]. N is the most affected nutrient, being lost through leaching and other pathways, resulting in severe limitations for local above-ground vegetation and soil microorganisms [25,26]. This exacerbates the influence of N deposition on local leaf litter decomposition. It is known that nutrient effectiveness modifies the nutrient utilization strategy of microorganisms. Soil microorganisms optimize resource allocation to obtain the most limited resource and modify soil nutrient cycling through the production of various extracellular enzymes [27,28]. This means that soil microorganisms change their C use strategies due to differences in soil N and phosphorus (P) effectiveness, which affects soil C sequestration. Enzyme stoichiometry is a tool for determining microbial nutrient limitation and nutrient utilization strategies. Sinsabaugh et al. found that log-transformed β -1,4-glucosidase (β G), β -1,4-N-acetyl-glucosaminidase (NAG) and acid phosphatase (ACP) activities converge to 1:1:1 [29]. Therefore, the deviation direction of enzyme stoichiometry indicates the microbial demand for a specific nutrient.

Based on the above, we propose the following hypotheses: (1) N addition may enhance leaf litter decomposition in the Yimeng Mountains due to a more substantial local N limitation. (2) N addition may augment SOC sequestration in the Yimeng Mountains by modifying soil nutrient cycling. (3) The effects of N addition on leaf litter decomposition and the SOC pool in the Yimeng Mountains may vary depending on the tree species. The research objectives include investigating leaf litter decomposition and nutrient release, soil nutrient effectiveness, enzyme activity and SOC density (SOC_D) in *Quercus acutissima* Carruth. and *Pinus thunbergii* Parl. forests through N addition experiments.

2. Materials and Methods

2.1. Study Area

The experimental site was selected in Dawa Forestry, Yimeng Mountains (35°32′46″ N, 117°54′47″ E). The local climate corresponds to a monsoon climate of medium latitudes, characterized by an average annual temperature of 13.2 °C, an average annual rainfall of 750 mm and a frost-free period of about 196 days. The mother rocks predominantly consist of granite gneiss and limestone, while the soil is mainly brown and cinnamon soil with a pH of 5.0. The dominant tree species in the study area are *Quercus acutissima* Carruth. and *Pinus thunbergii* Parl. Understory shrubs are mainly represented by *Vitex negundo* L. var. *heterophylla* (Franch.) Rehd. The herbaceous species in the forest understory mainly consist of *Achnatherum pekinense* (Hance) Ohwi and *Ophiopogon bodinieri* Levl. *Quercus acutissima* Carruth. and *Pinus thunbergii* Parl. forests with similar altitudes (470 and 434 m), similar slopes (18 and 22°) and similar forest density (689 and 765 trees ha⁻¹) were selected as experimental sites in Dawa Forestry. The average tree height and diameter at the breast height of *Quercus acutissima* Carruth. were 9.41 m and 18.43 cm, respectively, and those of *Pinus thunbergii* Parl. were 7.71 m and 14.45 cm, respectively.

2.2. Experimental Design

The study employed the multiplicative method to simulate N deposition, incorporating four N addition treatments: no nitrogen addition (0 kg N ha⁻¹ yr⁻¹, CK), low N addition (50 kg N ha⁻¹ yr⁻¹, LN), medium N addition (100 kg N ha⁻¹ yr⁻¹, MN) and high N addition (200 kg N ha⁻¹ yr⁻¹, HN). These treatments were set based on local atmospheric N deposition monitoring values [30]. The orthogonal experiment involved two tree species, namely *Quercus acutissima* Carruth. and *Pinus thunbergii* Parl., and included the four N addition treatments, resulting in a total of eight treatments: PCK, PLN, PMN, PHN, QCK, QLN, QMN and QHN. A total of 3 replications were set up for each treatment, with a total of 24 plots (10 × 10 m², at least 10 m apart). Ammonium nitrate solution (NH₄NO₃) was applied starting in October 2020 and sprayed every two months. Specifically, NH₄NO₃ was uniformly mixed with 10 L of water and sprayed within the corresponding plots using a backpack sprayer. The same volume of deionized water was applied for the CK treatment to maintain consistency and avoid confounding effects from additional precipitation.

2.3. Leaf Litter Collection and Litter Bag Experiment

Fresh leaf litter (Table 1) was collected from *Quercus acutissima* Carruth. and *Pinus thunbergii* Parl. using a litter trap method at the experimental site in October 2020. The fresh leaf litter was transported to the laboratory and dried to constant weight at 65 °C. Samples weighing 10.00 g were put into litter bags of 20 × 15 cm² (aperture 1 mm). The bags were attached to the soil surface of each plot with a wire so that the bags were in close contact with the soil. Leaf litter bags were spaced at least 5 cm apart to avoid interaction. Litter bags from each treatment were collected at bimonthly intervals. After removing soil adhering to the surface of the leaf litter, the bags were dried at 65 °C for 48 h. The residual mass of leaf litter after decomposition was measured. The carbon (C), nitrogen (N) and phosphorus (P) content of the leaf litter were determined using the potassium dichromate external heating method, Kjeldahl method and Mo-Sb colorimetric method, respectively.

The lignin and cellulose content of the leaf litter was determined using Klason's method and the ice bath digestion-anthrone colorimetric method, respectively [13].

Table 1. Initial leaf litter characteristics.

Tree Species	C (%)	N (%)	P (%)	Lignin (%)	Cellulose (%)	C:N	Lignin:N
<i>Quercus acutissima</i> Carruth.	47.60 ± 2.79 a	0.81 ± 0.02 a	0.12 ± 0.01 b	6.39 ± 0.44 a	14.29 ± 1.59 b	59.17 ± 4.08 b	7.93 ± 0.52 a
<i>Pinus thunbergii</i> Parl.	48.91 ± 2.99 a	0.77 ± 0.01 b	0.13 ± 0.01 a	5.92 ± 0.22 b	18.14 ± 2.08 a	63.75 ± 3.81 a	7.72 ± 0.28 a

Note: The same alphabets of the same list show no significance ($p > 0.05$) and, on the contrary, having significance ($p < 0.05$).

2.4. Soil Sample Collection and Laboratory Analysis

Soil samples were collected in December 2021 using the “S”-shaped sampling method. A total of 9 points were selected within each plot for soil sample collection using a soil drill (8 cm diameter) in the 0–20 cm topsoil layer. All soil samples within each plot were combined and thoroughly mixed to create a representative soil sample. The mixed soil samples were then transported to the laboratory. We divided the samples into two parts after removing roots and stones. One part was stored at $-80\text{ }^{\circ}\text{C}$ to determine enzyme activity and inorganic nitrogen (IN). The other part was dried, crushed and sieved through a 0.15 mm sieve to determine SOC and available phosphorus (AP).

Soil enzyme activity was determined according to Deforest's method [31]. Acetic acid buffer was obtained by mixing sodium acetate with deionized water and adjusting the solution pH to 5 with acetic acid to match the soil pH at the study site. Enzyme activity was determined using three 4-methylumbelliferone (MUB)-based fluorogenic enzyme substrates: 4-MUB- β -D-glucopyranoside for β -1,4-glucosidase (β G), 4-MUB-N-acetyl- β -D-glucosaminide for β -1,4-N-acetyl-glucosaminidase (NAG) and 4-MUB-phosphate for acid phosphatase (ACP). Soil homogenates and substrates were added to 96-well plates incubated in the dark ($25\text{ }^{\circ}\text{C}$, 4 h) and soil enzyme activities were determined using a microplate reader (Synergy HTX, Hudson, MA, USA). Soil IN content was determined by continuous flow injection analyzer (AA3-A001-02E, Bran-Luebbe, Germany) after mixing 25 mL of 1 mol L^{-1} KCl solution and 3 g of fresh soil samples. SOC was determined by the potassium dichromate external heating method. Soil AP was extracted by NaHCO_3 solution and determined by Mo-Sb colorimetric method.

2.5. Statistical Analysis

The mass remaining and the C, N and P remaining are expressed in terms of the relative ratio of the initial litter [32]. The mass remaining (M_r) and the nutrient remaining (N_r) of the litter were calculated using Formulas (1) and (2), respectively.

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

$$N_r(\%) = \frac{M_t \times N_t}{M_0 \times N_0} \times 100\% \quad (2)$$

where M_t (g) is the residual mass at t (d) days; M_0 (g) is the initial mass of litter; N_t (%) is the nutrient element concentration of litter at t (d) days; N_0 (%) is the initial nutrient element concentration of litter.

The leaf litter decomposition coefficient was calculated using the Olson [33] exponential decay model (3).

$$M_t/M_0 = e^{-Kt} \quad (3)$$

where k is the decomposition coefficient (K value); t (d) is the time.

Enzymes C:N, C:P and N:P were calculated by the Formulas (4)–(6), respectively.

$$\text{Enzyme C : N} = \ln \beta G \div \ln \text{NAG} \quad (4)$$

$$\text{Enzyme C : P} = \ln \beta G \div \ln \text{ACP} \quad (5)$$

$$\text{Enzyme N : P} = \ln \text{NAG} \div \ln \text{ACP} \quad (6)$$

SOC density (SOC_D) (kg m⁻²) was calculated using Equation (7):

$$\text{SOC}_D (\text{kg m}^{-2}) = \text{soil bulk density} (\text{g cm}^{-3}) \times \text{soil depth (cm)} \times \text{SOC (g kg}^{-1}) \quad (7)$$

The collected data were assessed for the normal distribution and homogeneity of variances. Independent samples *t*-tests were used to compare the differences in the initial leaf litter chemistry between the two tree species. One-way analysis of variance (ANOVA) and Duncan's multiple analysis ($\alpha = 0.05$) were conducted to determine the impact of N addition on leaf litter decomposition, soil physicochemical properties, soil enzyme activity and enzyme stoichiometry. Pearson correlation analysis was performed to examine the relationships between leaf litter nutrient remaining, soil enzyme activity and soil nutrients. The above operations were performed by the software SPSS 23.0. Figures were made using Origin 2018.

3. Results

3.1. Leaf Litter Decomposition

N addition accelerated the decomposition process of the *Quercus acutissima* Carruth. leaf litter with increasing N addition levels (Figure 1). The Mr of the *Quercus acutissima* Carruth. leaf litter for each treatment after one year showed QCK (68.13%) > QLN (61.63%) > QHN (58.57%) > QMN (55.43%). The Mr of *Pinus thunbergii* Parl. leaf litter decomposition showed PHN (69.5%) > PMN (68.47%) > PCK (63.57%) > PLN (61.37%). Notably, the PLN promoted the decomposition of *Pinus thunbergii* Parl. leaf litter, whereas the PMN and PHN hindered this process.

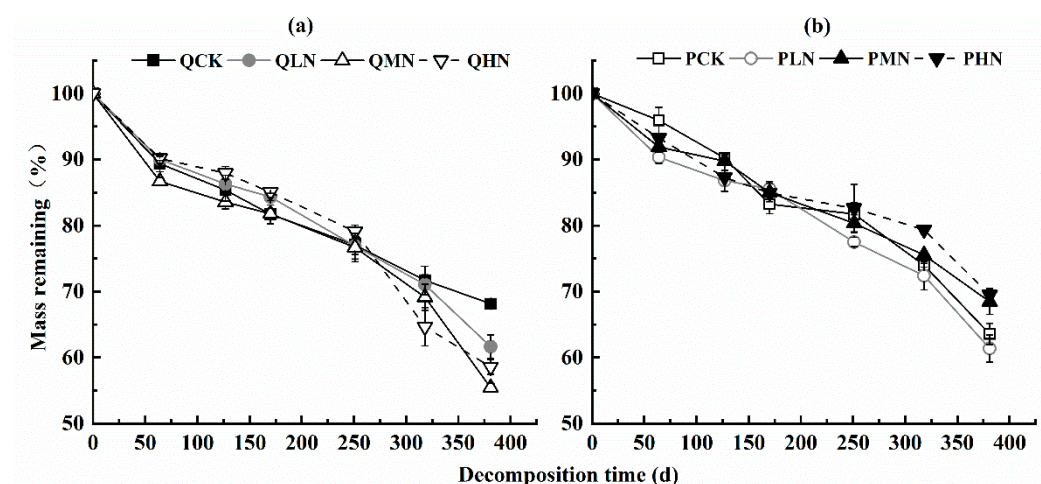


Figure 1. Effect of different treatments on the leaf litter Mr of *Quercus acutissima* Carruth. (a) and *Pinus thunbergii* Parl. (b) The points of different shapes are averaged. The length of the error bars is the standard deviation. QCK, QLN, QMN and QHN: *Quercus acutissima* Carruth. under no N addition, low N addition, medium N addition and high N addition, respectively. PCK, PLN, PMN and PHN: *Pinus thunbergii* Parl. under no N addition, low N addition, medium N addition and high N addition, respectively. Mr: mass remaining.

The Olson exponential decay model was determined to be a more appropriate description for the leaf litter decomposition process of the two tree species (Table 2). The larger the

K value, the faster the leaf litter mass loss. Comparing the two tree species, the *Quercus acutissima* Carruth. leaf litter exhibited higher K values than the *Pinus thunbergii* Parl. leaf litter, indicating a more rapid decomposition rate for *Quercus acutissima* Carruth.

Table 2. Decomposition constants (K value) and decomposition age of *Quercus acutissima* Carruth. and *Pinus thunbergii* Parl.

Treatment	Decomposition Equation	Decomposition Constant (K Value)	50% Decomposition Age (a)	95% Decomposition Age (a)	Correlation Coefficient
QCK	$y = e^{-0.386x}$	0.386	1.796	7.761	0.967
QLN	$y = e^{-0.421x}$	0.421	1.646	7.116	0.968
QMN	$y = e^{-0.484x}$	0.484	1.432	6.190	0.913
QHN	$y = e^{-0.46x}$	0.460	1.507	6.512	0.931
PCK	$y = e^{-0.367x}$	0.367	1.889	8.163	0.937
PLN	$y = e^{-0.416x}$	0.416	1.666	7.201	0.958
PMN	$y = e^{-0.34x}$	0.340	2.039	8.811	0.982
PHN	$y = e^{-0.315x}$	0.315	2.200	9.510	0.940

Note: QCK, QLN, QMN and QHN: *Quercus acutissima* Carruth. under no N addition, low N addition, medium N addition and high N addition, respectively. PCK, PLN, PMN and PHN: *Pinus thunbergii* Parl. under no N addition, low N addition, medium N addition and high N addition, respectively.

3.2. Nutrients Remaining in Leaf Litter

N addition had a facilitative effect on the C release from the *Quercus acutissima* Carruth. leaf litter (Figure 2a). The C remaining after one year showed QCK (50.09%) > QLN (42.15%) > QMN (38.57%) > QHN (38.04%). Conversely, high N addition inhibited C release from *Pinus thunbergii* Parl. leaf litter, while low N addition promoted C release from it. The C remaining of *Pinus thunbergii* Parl. leaf litter after one year exhibited PMN (69.79%) > PHN (63.49%) > PCK (58.25%) > PLN (55.28%) (Figure 2d). N addition had an inhibitory effect on the N release from both species of leaf litter (Figure 2b,e). For *Quercus acutissima* Carruth., high N treatments began to inhibit the N release from the leaf litter on day 127, while the other N addition treatments showed inhibitory effects after day 170. For *Pinus thunbergii* Parl. leaf litter, the inhibition started between days 170 and 251. On average, the leaf litter N remaining of *Pinus thunbergii* Parl. after one year was 11.02% lower than that of *Quercus acutissima* Carruth. The trends of P remaining in the *Quercus acutissima* Carruth. and *Pinus thunbergii* Parl. leaf litter were similar to those of the N remaining (Figure 2c,f). On average, N addition reduced the P remaining from the *Quercus acutissima* Carruth. leaf litter by 16.42% and increased that from the *Pinus thunbergii* Parl. leaf litter by 4.22%. This indicates that N addition showed a facilitative effect on P release from *Quercus acutissima* Carruth. leaf litter and an inhibitory effect on *Pinus thunbergii* Parl. leaf litter.

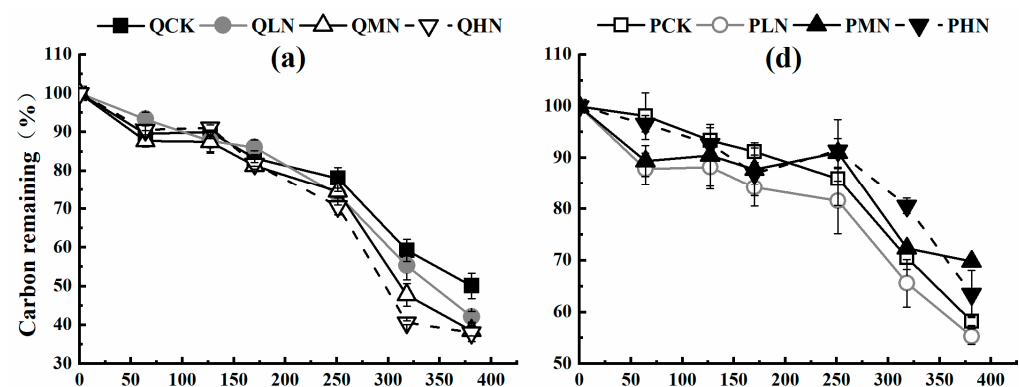


Figure 2. Cont.

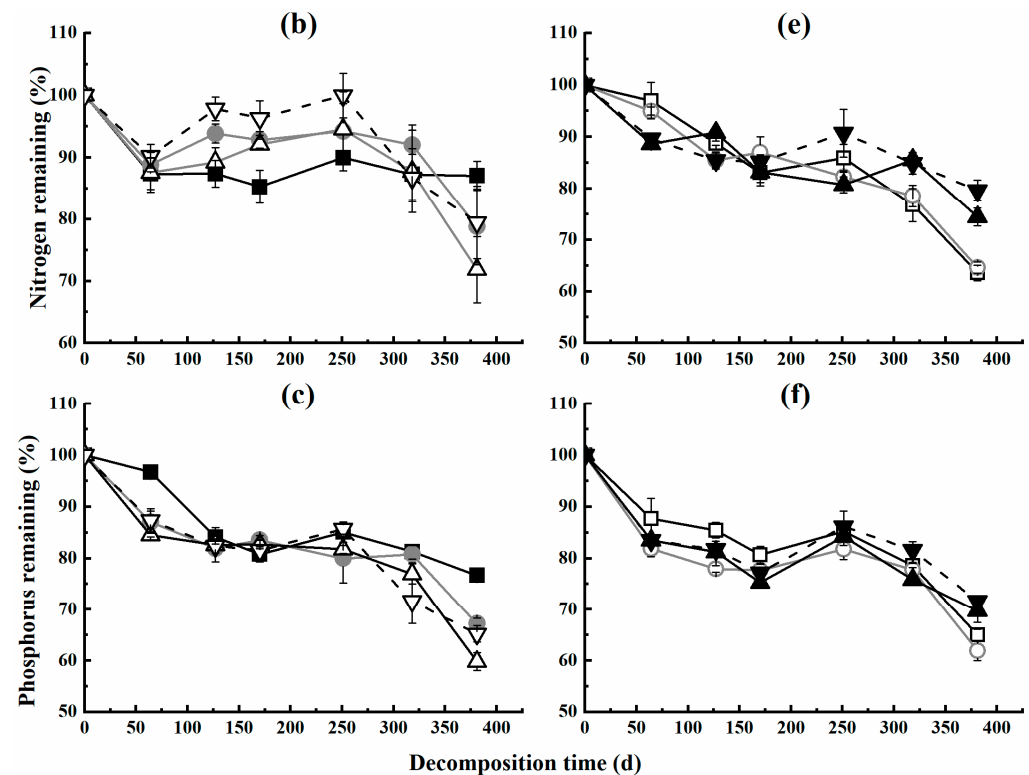


Figure 2. Effect of different treatments on C, N and P remaining in the leaf litter of *Quercus acutissima* Carruth. (a–c) and *Pinus thunbergii* Parl. (d–f). The points of different shapes are averaged. The length of the error bars is the standard deviation. QCK, QLN, QMN and QHN: *Quercus acutissima* Carruth. under no N addition, low N addition, medium N addition and high N addition, respectively. PCK, PLN, PMN and PHN: *Pinus thunbergii* Parl. under no N addition, low N addition, medium N addition and high N addition, respectively. C: carbon. N: nitrogen. P: phosphorus.

3.3. Soil Available Nutrient and Carbon Density

N addition led to a decrease in the SOC content of *Quercus acutissima* Carruth. forest (Figure 3). The SOC content of QLN, QMN and QHN decreased by 10.57%, 22.22% and 13.66%, respectively, compared to QCK. In contrast, N addition increased the SOC content in the *Pinus thunbergii* Parl. forest. PLN, PMN and PHN increased the SOC content by 49.53%, 43.36% and 60.86%, respectively, compared to PCK. The effect of N addition on soil IN content was not significant in both the *Quercus acutissima* Carruth. and *Pinus thunbergii* Parl. forests. Among all N addition treatments, PMN and PHN increased the soil IN content more, by 61.88% and 38.00%, respectively, compared to PCK. The effect of N addition on soil AP content was not significantly different. However, the soil AP content was higher in the *Quercus acutissima* Carruth. forest than that of the *Pinus thunbergii* Parl. forest. For SOCD (Figure 4), the *Quercus acutissima* Carruth. and *Pinus thunbergii* Parl. forests showed different results. N addition decreased the SOCD in the *Quercus acutissima* Carruth. forest but increased the SOCD in the black pine forest, although the differences among the treatments were not significant.

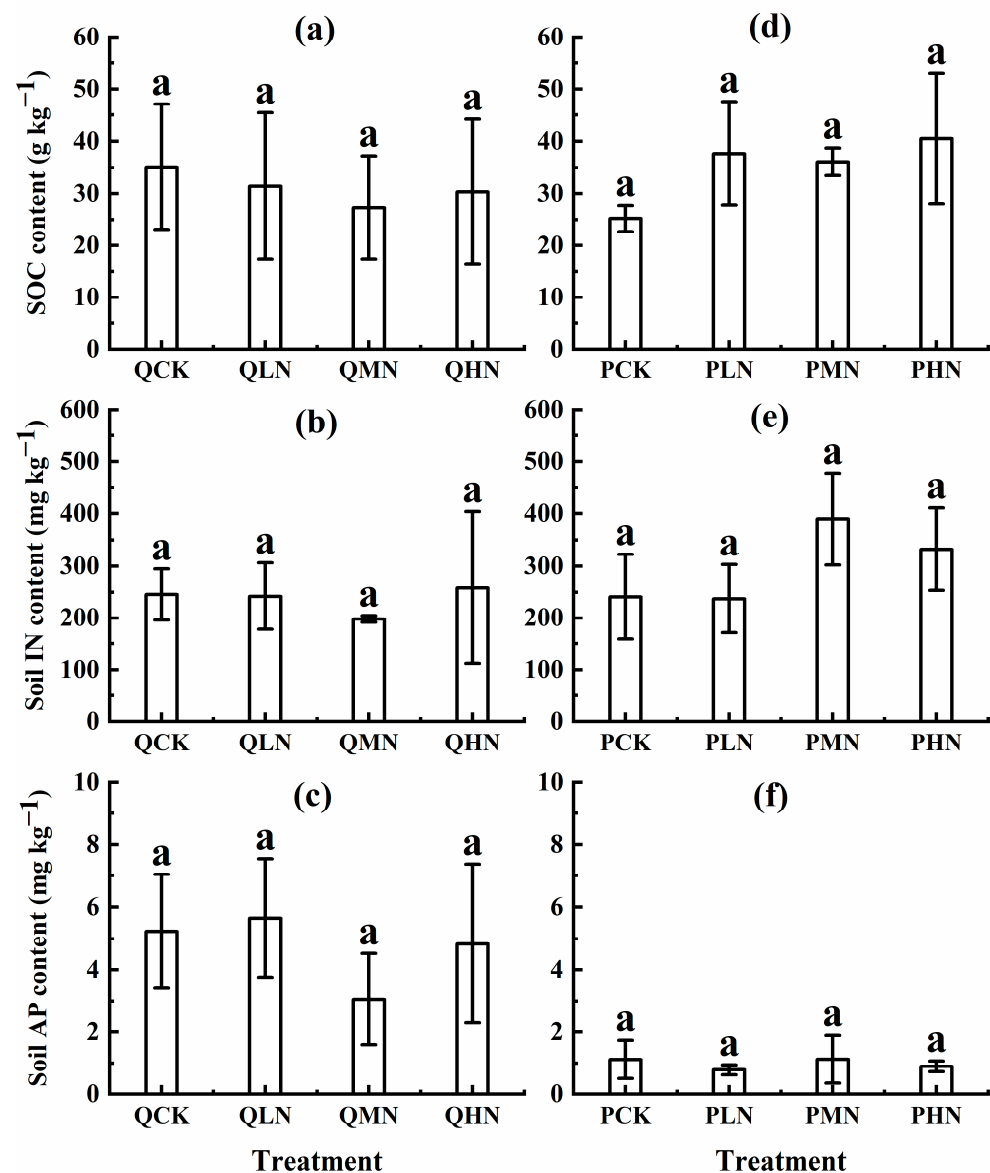


Figure 3. Effect of different treatments on SOC, IN and AP content of *Quercus acutissima* Carruth. (a–c) and *Pinus thunbergii* Parl. forests (d–f) soil. The length of the error bars is the standard deviation. Different letters indicate significant differences between different treatments ($p < 0.05$) for the same tree species. QCK, QLN, QMN and QHN: *Quercus acutissima* Carruth. forest under no N addition, low N addition, medium N addition and high N addition, respectively. PCK, PLN, PMN and PHN: *Pinus thunbergii* Parl. forest under no N addition, low N addition, medium N addition and high N addition, respectively. SOC: soil organic carbon. IN: inorganic nitrogen. AP: available phosphorus.

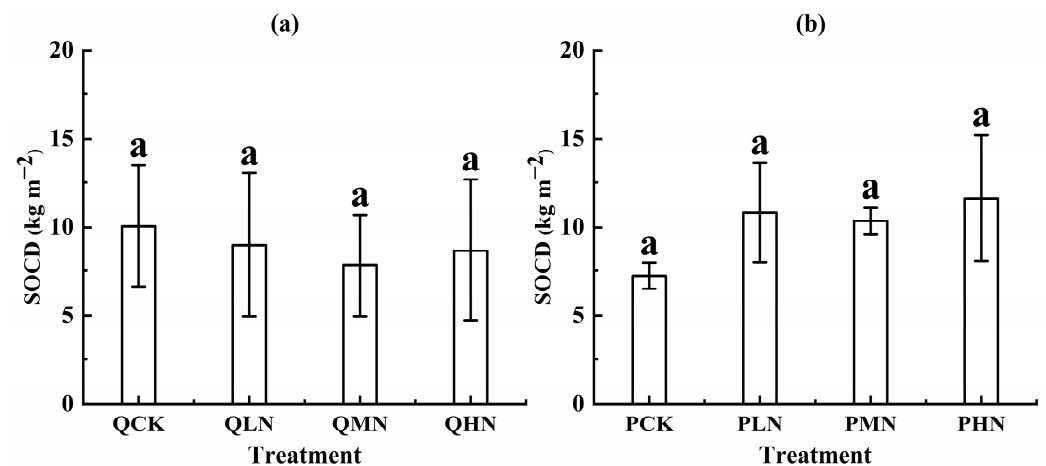


Figure 4. Effect of different treatments on SOCD of *Quercus acutissima* Carruth. (a) and *Pinus thunbergii* Parl. forests (b). The length of the error bars is the standard deviation. Different letters indicate significant differences between different treatments ($p < 0.05$) for the same tree species. QCK, QLN, QMN and QHN: *Quercus acutissima* Carruth. forest under no N addition, low N addition, medium N addition and high N addition, respectively. PCK, PLN, PMN and PHN: *Pinus thunbergii* Parl. forest under no N addition, low N addition, medium N addition and high N addition, respectively. SOCD: soil organic carbon density.

3.4. Enzyme Activity and Enzyme Stoichiometry

Both low and high N additions significantly increased the soil βG enzyme activity in the *Quercus acutissima* Carruth. forest (Figure 5). However, our study revealed no significant variations in the soil NAG enzyme activity among all N addition levels. The effect of N addition on soil ACP enzyme activity in the *Quercus acutissima* Carruth. forest showed inhibition at low N addition, promotion at medium N addition and no significant difference at high N addition. In the *Pinus thunbergii* Parl. forest, all N addition levels significantly increased the soil βG enzyme activity. The soil NAG enzyme activity increased with an increasing N addition level. PLN, PMN and PHN increased the NAG enzyme activity by 16.98%, 39.54% and 86.41%, respectively, compared to PCK. All N addition levels inhibited the soil ACP enzyme activity in the *Pinus thunbergii* Parl. forest, with significant differences for PLN and PHN compared to PCK.

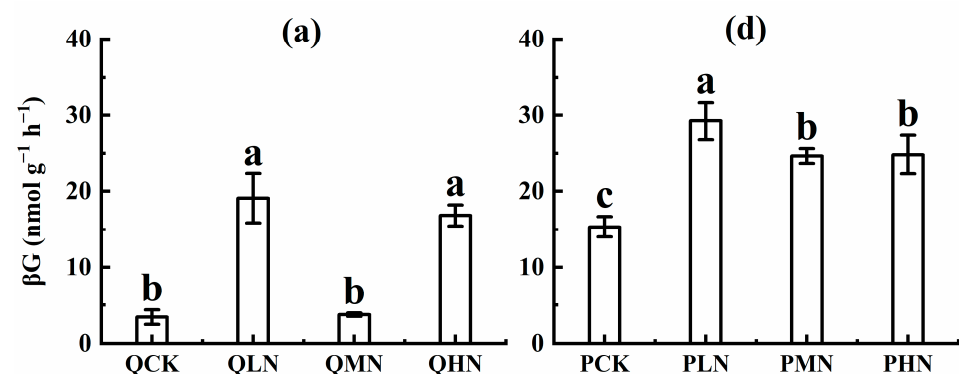


Figure 5. Cont.

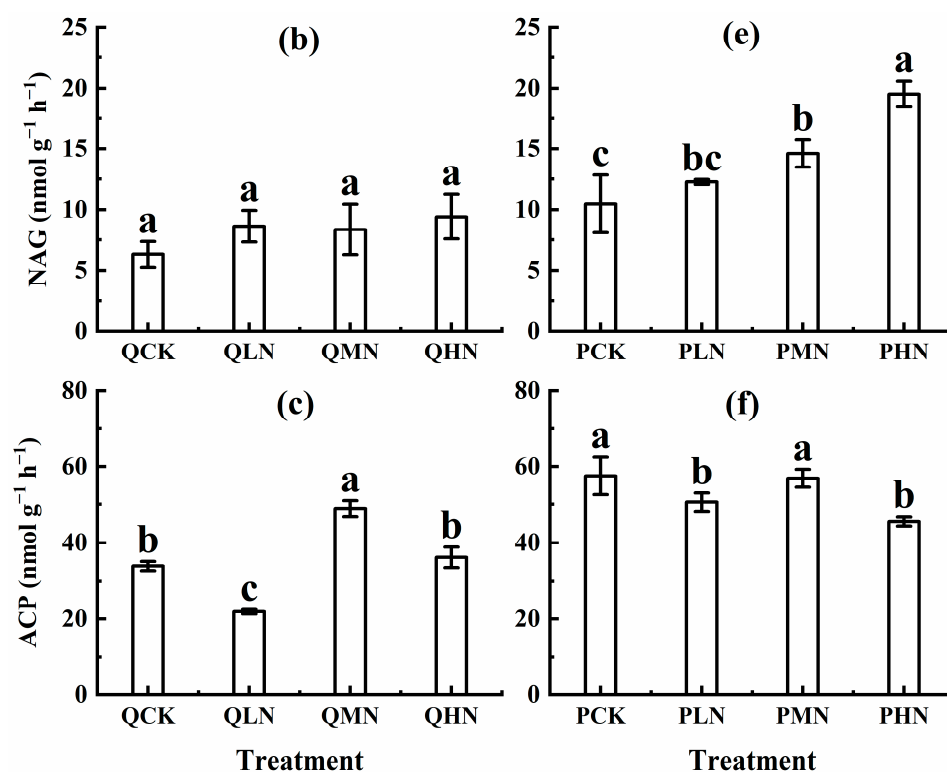


Figure 5. Effect of different treatments on soil enzyme activities of *Quercus acutissima* Carruth. (a–c) and *Pinus thunbergii* Parl. forests (b–f). The length of the error bars is the standard deviation. Different letters indicate significant differences between different treatments ($p < 0.05$) for the same tree species. QCK, QLN, QMN and QHN: *Quercus acutissima* Carruth. forest under no N addition, low N addition, medium N addition and high N addition, respectively. PCK, PLN, PMN and PHN: *Pinus thunbergii* Parl. forest under no N addition, low N addition, medium N addition and high N addition, respectively. β G: β -1,4-glucosidase. NAG: β -1,4-N-acetyl-glucosaminidase. ACP: acid phosphatase.

The enzyme stoichiometry closer to one indicates that soil microorganisms are less nutrient limited (Table 3). In the *Quercus acutissima* Carruth. forest, QHN changed the microbial limiting nutrient from N to C compared to QCK. However, QHN brought the soil enzyme C:N ratio closer to one. Soil microorganisms exhibited P limitation in all treatments of the *Quercus acutissima* Carruth. forest because the enzyme C:P and N:P ratios were less than one. In the *Pinus thunbergii* Parl. forest, the soil enzyme C:N ratio was greater than one, while the enzyme C:P and N:P ratios were less than one in all treatments, indicating that the soil microbial nutrients limitations were C and P. Among them, high N addition brought the soil enzyme C:N, C:P and N:P ratios closer to one, which alleviated the C and P limitation of soil microorganisms.

3.5. The Correlation between Leaf Litter, Soil Nutrients and Enzyme Activity

In the *Quercus acutissima* Carruth. forest, a significantly positive correlation was observed between SOC content and AP content. Conversely, β G enzyme activity and ACP enzyme activity exhibited a significant negative correlation (Figure 6). The C and N remaining from the *Quercus acutissima* Carruth. leaf litter were highly significantly and positively correlated with the P remaining. Meanwhile, this leaf litter N remaining was also highly significantly positively correlated with soil AP content. In the *Pinus thunbergii* Parl. leaf litter, there were significant or highly significant positive correlations among the C, N and P remaining. Meanwhile, they all showed significant positive correlations with the soil IN content. The SOC content of the *Pinus thunbergii* Parl. forest was only significantly positively correlated with β G activity.

Table 3. Soil enzyme stoichiometry of *Quercus acutissima* Carruth. and *Pinus thunbergii* Parl. forests.

Treatment	Enzyme C:N Ratio	Enzyme C:P Ratio	Enzyme N:P Ratio
QCK	0.67 ± 0.22 b	0.34 ± 0.09 c	0.52 ± 0.05 b
QLN	1.37 ± 0.03 a	0.95 ± 0.06 a	0.70 ± 0.05 a
QMN	0.63 ± 0.09 b	0.34 ± 0.01 c	0.54 ± 0.06 b
QHN	1.27 ± 0.10 a	0.79 ± 0.02 b	0.62 ± 0.06 ab
PCK	1.18 ± 0.11 b	0.67 ± 0.01 c	0.58 ± 0.05 c
PLN	1.35 ± 0.03 a	0.86 ± 0.02 a	0.64 ± 0.01 b
PMN	1.20 ± 0.02 b	0.79 ± 0.02 b	0.66 ± 0.02 b
PHN	1.08 ± 0.04 b	0.84 ± 0.03 a	0.78 ± 0.02 a

Note: Data are expressed as mean ± standard deviation. Different letters indicate significant differences between different treatments ($p < 0.05$) for the same tree species. QCK, QLN, QMN and QHN: *Quercus acutissima* Carruth. forest under no N addition, low N addition, medium N addition and high N addition, respectively. PCK, PLN, PMN and PHN: *Pinus thunbergii* Parl. forest under no N addition, low N addition, medium N addition and high N addition, respectively. C: carbon. N: nitrogen. P: phosphorus.

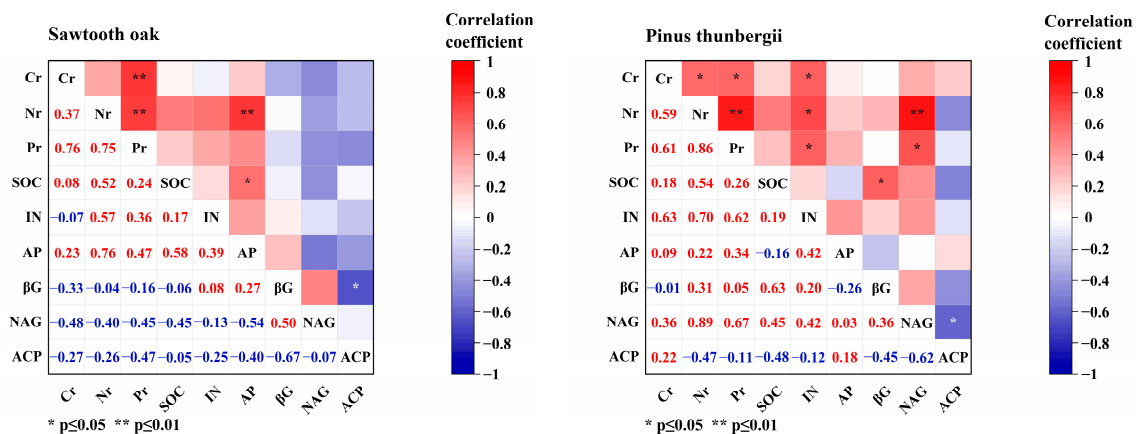


Figure 6. The heatmap of Pearson's correlation coefficients between leaf litter, soil nutrients and enzymatic activity in *Quercus acutissima* Carruth. and *Pinus thunbergii* Parl. Cr, Nr and Pr indicate the nutrient remaining of carbon, nitrogen and phosphorus in leaf litter, respectively. SOC, IN and AP indicate the organic carbon, inorganic nitrogen and available phosphorus content of the soil, respectively. βG: β-1,4-glucosidase. NAG: β-1,4-N-acetyl-glucosaminidase. ACP: acid phosphatase.

4. Discussion

4.1. Response of Leaf Litter Decomposition to N Addition

According to references [34–37], the impact of N addition on leaf litter decomposition can be categorized into three main conclusions: promotion, inhibition or no significant effect. In our study, N addition promoted the decomposition of *Quercus acutissima* Carruth. leaf litter. This can be attributed to the relatively low lignin content of *Quercus acutissima* Carruth. litter, which made it less susceptible to the inhibitory effects of N addition. When the exogenous N was added to the system, N could combine with lignin and its degradation intermediates, inhibiting lignin decomposition [38]. N addition altered the C:N ratio of leaf litter, thus promoting the decomposition of *Quercus acutissima* Carruth. leaf litter [39]. For *Pinus thunbergii* Parl. leaf litter, low N addition promoted decomposition, while medium and high N inhibited decomposition. High N addition can limit the growth of white rot fungi, which play a crucial role in lignin degradation [40]. Additionally, high N levels can inhibit the secretion of ligninolytic enzymes, further hindering the decomposition of *Pinus thunbergii* Parl. leaf litter [41]. The results of our study align with previous research, specifically a worldwide meta-analysis by Knorr et al. This indicated that leaf litter decomposition patterns exhibit consistency in areas with high N limitation and globally, albeit with increased levels of extremity and significance. Knorr et al. found that high N addition inhibited the decomposition of leaf litter with high lignin content but promoted the decomposition of leaf litter with low lignin content [42]. In summary, the

impact of N addition on leaf litter decomposition in the Yimeng Mountains was influenced by both N levels and the inherent lignin content of the leaf litter.

4.2. Response of Soil Nutrient Cycling to N Addition

Research has shown that the impacts of N addition on SOC content are consistent with the trend of leaf litter decomposition and C release. This is because the subsurface C input is mainly from the mass loss of leaf litter [43]. However, the opposite result was observed in this study, i.e., N addition caused varying decreases in SOC content and SOCD in the *Quercus acutissima* Carruth. forest. In contrast, SOC content and SOCD in the *Pinus thunbergii* Parl. forest increased with increasing N addition. We considered that SOC accumulation was mainly influenced by both or a combination of increased SOC supply and decreased SOC mineralization. *Quercus acutissima* Carruth. leaf litter is a high-quality C source with high cellulose content, which can be easily decomposed and utilized by microorganisms [44]. Meanwhile, N addition was observed to enhance soil microbial activity and respiration, leading to increased SOC mineralization. The effect of N addition on SOC mineralization became more pronounced with higher N addition levels [45]. Our findings also supported the view that the soil microbial nutrient utilization strategy of the *Quercus acutissima* Carruth. forest changed from N to C with the increased N addition level. This indicated that SOC mineralization was enhanced in the *Quercus acutissima* Carruth. forest with increasing N effectiveness, resulting in lower SOC sequestration. Conversely, *Pinus thunbergii* Parl. leaf litter has lower cellulose content and higher lignin content, which is difficult for soil microorganisms to utilize [46]. This caused the *Pinus thunbergii* Parl. leaf litter to be stored in the soil for a long time. The SOC input exceeded the SOC output in the *Pinus thunbergii* Parl. forest, which increased subsurface SOC sequestration [47].

N addition reduced the microbial demand for N from leaf litter, resulting in higher N remaining in the leaf litter compared to the treatment without N addition [48]. Chomel et al. observed that N addition changed the microbial community structure to fungal dominated and reduced the microbial demand for N in leaf litter [49]. This is consistent with this study that the increased N addition enhanced the inhibition of N release from leaf litter. Furthermore, N addition significantly alleviated N limitation by soil microorganisms in the *Quercus acutissima* Carruth. and *Pinus thunbergii* Parl. forests. The microbial nutrient use strategy shifted from N to P due to N addition, alleviating the soil microbial N limitation. This change in nutrient limitation strategy led to a greater emphasis on P utilization by microorganisms, resulting in enhanced P release from leaf litter [50,51]. The promotion of P release from leaf litter became more significant with higher levels of N addition. The soil enzyme C: P and N: P ratios, which were less than one, further support the idea that P was a limiting nutrient for soil microorganisms in these ecosystems [52].

4.3. Response of SOCD to N Addition

SOCD is an important indicator to measure the SOC pool. This study indicated that the effect of N addition on SOCD was influenced by the tree species and leaf litter characteristics. This is because the tree species and leaf litter characteristics significantly influence soil C, N and P cycling, which alters the SOC content and stability [53]. In the *Quercus acutissima* Carruth. forest, SOC content was significantly positively correlated with soil AP content, suggesting that P availability plays an important role in influencing SOC content. However, increasing soil AP content may not be an effective strategy for increasing the local SOC pool in the context of N addition. This is because increasing soil AP content can lead microorganisms to invest more resources in acquiring C [54]. Li et al. showed that P increased soil microbial activity, accelerated SOC turnover and reduced SOC stability in the N addition context [55]. In the *Pinus thunbergii* Parl. forest, the SOC content was significantly positively correlated with soil β G enzyme activity. N addition alleviated soil microbial N limitation, leading to increased β G enzyme activity and accelerated cellulose decomposition in leaf litter. The lignin in the *Pinus thunbergii* Parl. leaf litter was transferred to the soil with leaf litter decomposition, leading to an

increase in SOCD and SOC stability [56]. Therefore, the response of SOCD to N addition in the Yimeng Mountains can depend on the tree species and the characteristics of their leaf litter. N addition decreases the SOCD of tree species with high cellulose content and low lignin content in leaf litter. Meanwhile, it increases the SOCD of tree species with low cellulose content and high lignin content in leaf litter. Overall, these findings highlight the complex interactions between N deposition, tree species, leaf litter characteristics and soil nutrient cycling in influencing SOCD and SOC stability. Further research is needed to fully understand the underlying mechanisms behind these responses to maintain or enhance the SOC pool in forest ecosystems.

5. Conclusions

The results highlight the importance of considering tree species and leaf litter characteristics when studying the effects of N addition on leaf litter decomposition and SOCD in arid and barren rocky mountainous regions, such as the Yimeng Mountains. The different responses of *Quercus acutissima* Carruth. and *Pinus thunbergii* Parl. leaf litter to N addition reflect the influence of leaf litter lignin content. The N addition promoted the decomposition of *Quercus acutissima* Carruth. leaf litter with high cellulose content and low lignin content. It also accelerated SOC turnover, leading to significant C loss and SOCD reduction. In addition, N addition showed a different effect on *Pinus thunbergii* Parl. leaf litter with low cellulose content and high lignin content. It promoted cellulose decomposition and facilitated the transfer of lignin to the soil, contributing to increased SOCD. Furthermore, N addition had contrasting effects on N and P release from leaf litter. The N addition alleviated the N limitation by soil microorganisms, which inhibited the N release from the leaf litter of both tree species. The N addition promoted P release from the leaf litter due to the microorganisms exhibiting P limitation. Overall, the findings demonstrate that N addition alters leaf litter decomposition, nutrient cycling and SOCD in the Yimeng Mountains, with the response depending on the tree species and leaf litter characteristics. This emphasizes the importance of considering these factors in understanding and managing nutrient dynamics and SOC sequestration in forest ecosystems.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/f14071351/s1>.

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References

1. Sun, K.; Gao, Y.; Guo, X.; Zhang, J.; Zeng, X.; Ma, M.; Chen, Y.; Luo, K.; Yao, X.; Gao, H. The enhanced role of atmospheric reduced nitrogen deposition in future over East Asia–Northwest Pacific. *Sci. Total Environ.* **2022**, *833*, 155146. [CrossRef]
2. Galloway, J.N.; Townsend, A.R.; Erismann, J.W.; Bekunda, M.; Cai, Z.; Freney, J.R.; Martinelli, L.A.; Seitzinger, S.P.; Sutton, M.A.J.S. Transformation of the Nitrogen Cycle: Recent Trends, Questions, and Potential Solutions. *Science* **2008**, *320*, 889–892. [CrossRef]

3. Li, Y.; Schichtel, B.A.; Walker, J.T.; Schwede, D.B.; Chen, X.; Lehmann, C.M.B.; Puchalski, M.A.; Gay, D.A.; Collett, J.L. Increasing importance of deposition of reduced nitrogen in the United States. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 5874–5879. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Fleischer, K.; Rebel, K.T.; Van Der Molen, M.K.; Erisman, J.W.; Wassen, M.J.; Van Loon, E.E.; Montagnani, L.; Gough, C.M.; Herbst, M.; Janssens, I.A.; et al. The contribution of nitrogen deposition to the photosynthetic capacity of forests. *Glob. Biogeochem. Cycles* **2013**, *27*, 187–199. [\[CrossRef\]](#)
5. Walter, C.A.; Adams, M.B.; Gilliam, F.S.; Peterjohn, W.T. Non-random species loss in a forest herbaceous layer following nitrogen addition. *Ecology* **2017**, *98*, 2322–2332. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Gilliam, F.S.; Burns, D.A.; Driscoll, C.T.; Frey, S.D.; Lovett, G.M.; Watmough, S.A. Decreased atmospheric nitrogen deposition in eastern North America: Predicted responses of forest ecosystems. *Environ. Pollut.* **2019**, *244*, 560–574. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Liu, L.; Zhang, X.; Xu, W.; Liu, X.; Zhang, Y.; Li, Y.; Wei, J.; Lu, X.; Wang, S.; Zhang, W.; et al. Fall of oxidized while rise of reduced reactive nitrogen deposition in China. *J. Clean. Prod.* **2020**, *272*, 122875. [\[CrossRef\]](#)
8. Zhao, Y.H.; Zhang, L.; Chen, Y.F.; Liu, X.J.; Xu, W.; Pan, Y.P.; Duan, L. Atmospheric nitrogen deposition to China: A model analysis on nitrogen budget and critical load exceedance. *Atmos. Environ.* **2017**, *153*, 32–40. [\[CrossRef\]](#)
9. IPCC. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2007.
10. Freschet, G.T.; Cornwell, W.K.; Wardle, D.A.; Elumeeva, T.G.; Liu, W.; Jackson, B.G.; Onipchenko, V.G.; Soudzilovskaia, N.A.; Tao, J.; Cornelissen, J.H. Linking litter decomposition of above- and below-ground organs to plant-soil feedbacks worldwide. *J. Ecol.* **2013**, *101*, 943–952. [\[CrossRef\]](#)
11. Prescott, C.E. Litter decomposition: What controls it and how can we alter it to sequester more carbon in forest soils? *Biogeochemistry* **2010**, *101*, 133–149. [\[CrossRef\]](#)
12. Laiho, R.; Laine, J.; Trettin, C.C.; Finér, L. Scots pine litter decomposition along drainage succession and soil nutrient gradients in peatland forests, and the effects of inter-annual weather variation. *Soil Biol. Biochem.* **2004**, *36*, 1095–1109. [\[CrossRef\]](#)
13. Yin, R.; Liu, Q.; Tian, S.; Potapov, A.; Zhu, B.; Yang, K.; Li, Z.; Zhuang, L.; Tan, B.; Zhang, L.; et al. Nitrogen deposition stimulates decomposition via changes in the structure and function of litter food webs—ScienceDirect. *Soil Biol. Biochem.* **2022**, *166*, 108522. [\[CrossRef\]](#)
14. Song, X.Z.; Zhou, G.M.; Gu, H.H.; Qi, L.H. Management practices amplify the effects of N deposition on leaf litter decomposition of the Moso bamboo forest. *Plant Soil* **2015**, *395*, 391–400. [\[CrossRef\]](#)
15. He, Z.M.; Yu, Z.P.; Huang, Z.Q.; Davis, M.; Yang, Y.S. Litter decomposition, residue chemistry and microbial community structure under two subtropical forest plantations: A reciprocal litter transplant study. *Appl. Soil Ecol.* **2016**, *101*, 84–92. [\[CrossRef\]](#)
16. Frey, S.D.; Ollinger, S.; Nadelhoffer, K.E.; Bowden, R.; Brzostek, E.; Burton, A.; Caldwell, B.A.; Crow, S.; Goodale, C.L.; Grandy, A.S.; et al. Chronic nitrogen additions suppress decomposition and sequester soil carbon in temperate forests. *Biogeochemistry* **2014**, *121*, 305–316. [\[CrossRef\]](#)
17. Xia, M.X.; Talhelm, A.F.; Pregitzer, K.S. Chronic nitrogen deposition influences the chemical dynamics of leaf litter and fine roots during decomposition. *Soil Biol. Biochem.* **2017**, *112*, 24–34. [\[CrossRef\]](#)
18. Ramirez, K.S.; Craine, J.M.; Fierer, N. Consistent effects of nitrogen amendments on soil microbial communities and processes across biomes. *Glob. Chang. Biol.* **2012**, *18*, 1918–1927. [\[CrossRef\]](#)
19. Wang, Q.; Kwak, J.H.; Choi, W.J.; Chang, S.X. Decomposition of trembling aspen leaf litter under long-term nitrogen and sulfur deposition: Effects of litter chemistry and forest floor microbial properties. *For. Ecol. Manag.* **2018**, *412*, 53–61. [\[CrossRef\]](#)
20. Peng, Y.; Li, Y.J.; Song, S.Y.; Chen, Y.Q.; Chen, G.T.; Tu, L.H. Nitrogen addition slows litter decomposition accompanied by accelerated manganese release: A five-year experiment in a subtropical evergreen broadleaf forest. *Soil Biol. Biochem.* **2022**, *165*, 108511. [\[CrossRef\]](#)
21. Zhang, Y.J.; Jin, Y.H.; Xu, J.W.; He, H.S.; Tao, Y.; Yang, Z.P.; Bai, Y.Y. Effects of exogenous N and endogenous nutrients on alpine tundra litter decomposition in an area of high nitrogen deposition. *Sci. Total Environ.* **2022**, *805*, 150388. [\[CrossRef\]](#)
22. Liu, X.; Zhang, G.C.; Heathman, G.C.; Wang, Y.Q.; Huang, C.H. Fractal features of soil particle-size distribution as affected by plant communities in the forested region of Mountain Yimeng, China. *Geoderma* **2009**, *154*, 123–130. [\[CrossRef\]](#)
23. Yan, T.T.; Zhao, W.J.; Zhu, Q.K.; Xu, F.J.; Gao, Z.K. Spatial distribution characteristics of the soil thickness on different land use types in the Yimeng Mountain Area, China. *Alex. Eng. J.* **2021**, *60*, 511–520. [\[CrossRef\]](#)
24. Zhang, R.H.; Xia, L.; Heathman, G.C.; Yao, X.Y.; Hu, X.L.; Zhang, G.C. Assessment of soil erosion sensitivity and analysis of sensitivity factors in the Tongbai–Dabie mountainous area of China. *Catena* **2013**, *101*, 92–98. [\[CrossRef\]](#)
25. Lasota, J.; Małek, S.; Jasik, M.; Bońska, E. Effect of planting method on C:N:P stoichiometry in soils, young silver fir (*Abies alba* Mill.) and stone pine (*Pinus cembra* L.) in the upper mountain zone of karpaty mountains. *Ecol. Indic.* **2021**, *129*, 107905. [\[CrossRef\]](#)
26. Qin, Y.Y.; Feng, Q.; Adamowski, J.F.; Zhu, M.; Zhang, X.F. Community level response of leaf stoichiometry to slope aspect in a montane environment: A case study from the Central Qilian Mountains, China. *Glob. Ecol. Conserv.* **2021**, *28*, e01703. [\[CrossRef\]](#)
27. Rosinger, C.; Rousk, J.; Sandén, H. Can enzymatic stoichiometry be used to determine growth-limiting nutrients for microorganisms?—A critical assessment in two subtropical soils. *Soil Biol. Biochem.* **2019**, *128*, 115–126. [\[CrossRef\]](#)
28. Xu, M.P.; Jian, J.N.; Wang, J.Y.; Zhang, Z.J.; Yang, G.H.; Han, X.H.; Ren, C.J. Response of root nutrient resorption strategies to rhizosphere soil microbial nutrient utilization along *Robinia pseudoacacia* plantation chronosequence. *For. Ecol. Manag.* **2021**, *489*, 119053. [\[CrossRef\]](#)
29. Sinsabaugh, R.L.; Lauber, C.L.; Weintraub, M.N.; Ahmed, B.; Zeglin, L.H. Stoichiometry of soil enzyme activity at global scale. *Ecol. Lett.* **2008**, *11*, 1252–1264. [\[CrossRef\]](#)
30. Xu, W.; Luo, X.S.; Pan, Y.P.; Zhang, L.; Tang, A.H.; Shen, J.L.; Zhang, Y.; Li, K.H.; Wu, Q.H.; Yang, D.W.; et al. Quantifying atmospheric nitrogen deposition through a nationwide monitoring network across China. *Atmos. Chem. Phys.* **2015**, *15*, 12345–12360. [\[CrossRef\]](#)

31. Deforest, J.L. The influence of time, storage temperature, and substrate age on potential soil enzyme activity in acidic forest soils using MUB-linked substrates and l-DOPA. *Soil Biol. Biochem.* **2009**, *41*, 1180–1186. [\[CrossRef\]](#)
32. Liu, Q.; Yin, R.; Tan, B.; You, C.M.; Zhang, L.; Zhang, J.; Xu, Z.F.; Schadler, M.; Scheu, S. Nitrogen addition and plant functional type independently modify soil mesofauna effects on litter decomposition. *Soil Biol. Biochem.* **2021**, *160*, 108340. [\[CrossRef\]](#)
33. Olson, J.S. Energy Storage and the Balance of Producers and Decomposers in Ecological Systems. *Ecology* **1963**, *44*, 322–331. [\[CrossRef\]](#)
34. Deforest, J.L. Chronic phosphorus enrichment and elevated pH suppresses *Quercus* spp. leaf litter decomposition in a temperate forest—ScienceDirect. *Soil Biol. Biochem.* **2019**, *135*, 206–212. [\[CrossRef\]](#)
35. Wu, J.P.; Liu, W.F.; Zhang, W.X.; Shao, Y.H.; Duan, H.L.; Chen, B.D.; Wei, X.H.; Fan, H.B. Long-term nitrogen addition changes soil microbial community and litter decomposition rate in a subtropical forest. *Appl. Soil Ecol.* **2019**, *142*, 43–51. [\[CrossRef\]](#)
36. Wu, C.S.; Shu, C.J.; Zhang, Z.J.; Zhang, Y.; Liu, Y.Q. Effect of N deposition on the home-field advantage of wood decomposition in a subtropical forest. *Ecol. Indic.* **2022**, *140*, 109043. [\[CrossRef\]](#)
37. Vivanco, L.; Austin, A.T. Nitrogen addition stimulates forest litter decomposition and disrupts species interactions in Patagonia, Argentina. *Global Chang. Biol.* **2011**, *17*, 1963–1974. [\[CrossRef\]](#)
38. Wu, A.; Yin, R.; Xu, Z.; Zhang, L.; You, C.; Liu, Y.; Li, H.; Wang, L.; Liu, S.; Zhang, Y.; et al. Forest gaps slow lignin and cellulose degradation of fir (*Abies faxoniana*) twig litter in an alpine forest. *Geoderma* **2019**, *424*, 116010. [\[CrossRef\]](#)
39. Pei, G.T.; Liu, J.; Peng, B.; Gao, D.C.; Wang, C.; Dai, W.W.; Jiang, P.; Bai, E. Nitrogen, lignin, C/N as important regulators of gross nitrogen release and immobilization during litter decomposition in a temperate forest ecosystem. *For. Ecol. Manag.* **2019**, *440*, 61–69. [\[CrossRef\]](#)
40. Frey, S.D.; Knorr, M.; Parrent, J.L.; Simpson, R.T. Chronic nitrogen enrichment affects the structure and function of the soil microbial community in temperate hardwood and pine forests. *For. Ecol. Manag.* **2004**, *196*, 159–171. [\[CrossRef\]](#)
41. Micks, P.; Downs, M.R.; Magill, A.H.; Nadelhoffer, K.J.; Aber, J.D. Decomposing litter as a sink for ¹⁵N-enriched additions to an oak forest and a red pine plantation. *For. Ecol. Manag.* **2004**, *196*, 71–87. [\[CrossRef\]](#)
42. Knorr, M.; Frey, S.D.; Curtis, P.S. Nitrogen additions and litter decomposition: A meta-analysis. *Ecology* **2005**, *86*, 3252–3257. [\[CrossRef\]](#)
43. Rubino, M.; Dungait, J.A.J.; Evershed, R.P.; Bertolini, T.; De Angelis, P.; D’Onofrio, A.; Lagomarsino, A.; Lubritto, C.; Merola, A.; Terrasi, F.; et al. Carbon input belowground is the major C flux contributing to leaf litter mass loss: Evidences from a ¹³C labelled-leaf litter experiment. *Soil Biol. Biochem.* **2010**, *42*, 1009–1016. [\[CrossRef\]](#)
44. Lin, H.; He, Z.H.; Hao, J.W.; Tian, K.; Jia, X.Q.; Kong, X.S.; Akbar, S.; Bei, Z.L.; Tian, X.J. Effect of N addition on home-field advantage of litter decomposition in subtropical forests—ScienceDirect. *For. Ecol. Manag.* **2017**, *398*, 216–225. [\[CrossRef\]](#)
45. Duan, P.P.; Xiao, K.C.; Wang, K.L.; Li, D.J. Responses of soil respiration to nitrogen addition are mediated by topography in a subtropical karst forest. *Catena* **2023**, *221*, 106759. [\[CrossRef\]](#)
46. Marshall, J.D.; Peichl, M.; Tarvainen, L.; Lim, H.; Lundmark, T.; Nasholm, T.; Oquist, M.; Linder, S. A carbon-budget approach shows that reduced decomposition causes the nitrogen-induced increase in soil carbon in a boreal forest. *For. Ecol. Manag.* **2021**, *502*, 119750. [\[CrossRef\]](#)
47. Ngaba, M.J.Y.; Uwiragiye, Y.; Bol, R.; Vries, W.D.; Zhou, J.B. Low-level nitrogen and short-term addition increase soil carbon sequestration in Chinese forest ecosystems. *Catena* **2014**, *215*, 106333. [\[CrossRef\]](#)
48. Dias, T.; Oakley, S.; Alarcón-Gutiérrez, E.; Ziarelli, F.; Trindade, H.; Martins, M.A.; Sheppard, L.; Ostle, N.; Cruz, C. N-driven changes in a plant community affect leaf-litter traits and may delay organic matter decomposition in a Mediterranean maquis. *Soil Biol. Biochem.* **2013**, *58*, 163–171. [\[CrossRef\]](#)
49. Chomel, M.; Baldy, V.; Guitttonny-Larchevque, M. Effect of mixing herbaceous litter with tree litters on decomposition and N release in boreal plantations. *Plant Soil* **2016**, *398*, 229–241. [\[CrossRef\]](#)
50. Bai, X.J.; Dippold, M.A.; An, S.S.; Wang, B.R.; Zhang, H.X.; Loeppmann, S. Extracellular enzyme activity and stoichiometry: The effect of soil microbial element limitation during leaf litter decomposition. *Ecol. Indic.* **2021**, *121*, 107200. [\[CrossRef\]](#)
51. Zhang, Y.; Shengzhe, E.; Wang, Y.; Su, S.; Bai, L.; Wu, C.; Zeng, X. Long-term manure application enhances the stability of aggregates and aggregate-associated carbon by regulating soil physicochemical characteristics. *Catena* **2021**, *203*, 105342. [\[CrossRef\]](#)
52. Yang, Y.; Liang, C.; Wang, Y.Q.; Cheng, H.; An, S.S.; Chang, S.X. Soil extracellular enzyme stoichiometry reflects the shift from P- to N-limitation of microorganisms with grassland restoration. *Soil Biol. Biochem.* **2020**, *149*, 107928. [\[CrossRef\]](#)
53. Yang, Y.; Liu, B.R.; An, S.S. Ecological stoichiometry in leaves, roots, litters and soil among different plant communities in a desertified region of Northern China. *Catena* **2018**, *166*, 328–338. [\[CrossRef\]](#)
54. Li, J.W.; Liu, Y.L.; Hai, X.Y.; Shangguan, Z.P.; Deng, L. Dynamics of soil microbial C:N:P stoichiometry and its driving mechanisms following natural vegetation restoration after farmland abandonment. *Sci. Total Environ.* **2019**, *693*, 133613. [\[CrossRef\]](#) [\[PubMed\]](#)
55. Li, H.; Chen, Y.; Lu, Z.; Wang, F.; Lambers, H.; Zhang, J.; Qin, G.; Zhou, J.; Wu, J.; Zhang, L.; et al. Nitrogen deposition in low-phosphorus tropical forests benefits soil C sequestration but not stabilization. *Ecol. Indic.* **2023**, *146*, 109761. [\[CrossRef\]](#)
56. Wang, H.; Liu, S.; Wang, J.; You, Y.; Yang, Y.; Shi, Z.; Huang, X.; Zheng, L.; Li, Z.; Ming, A.; et al. Mixed-species plantation with *Pinus massoniana* and *Castanopsis hystrix* accelerates C loss in recalcitrant coniferous litter but slows C loss in labile broadleaf litter in southern China. *For. Ecol. Manag.* **2018**, *422*, 207–213. [\[CrossRef\]](#)

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