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Nitrogen Deposition Modulates Litter Decomposition and Enhances Water Retention in Subtropical Forests

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Abstract: Nitrogen (N) deposition influences litter decomposition and its water-holding capacity in forest ecosystems. Water conservation remains a priority, so understanding these interactions is vital for managing forests, especially in the Yunnan Plateau region. This study aimed to investigate the effects of simulated N deposition on litter decomposition and water-holding capacity in the Evergreen broad-leaf and *Quercus aquifolioides* forest in the central Yunnan Plateau. Indoor flooding experiments were performed alongside varied nitrogen deposition treatments. Litter decomposition rates under these treatments were evaluated using the Olson model. In the decomposition study, the N treatments in the Evergreen broad-leaved forest increased the remaining mass by 4.75%–17.50% and 2.09%–16.36% compared with the control (20.97 ± 0.44% and 42.43 ± 0.47%), while in the *Quercus aquifolioides* forest, the remaining mass of leaves and twigs decreased by 5.00% and 0.70% in the LN treatment compared with the control (35.47 ± 0.39% and 44.10 ± 1.18%) and the MN and HN treatments increased by 2.55%–8.13% and 5.61%–11.28%, respectively. Effects of increased N deposition on litter decomposition changed from promoting to inhibiting, as low N sped up decomposition but higher levels inhibited it. Additionally, N boosted the water-holding capacity of litter, especially in leaves. The litter from both forests displayed a notable ability to absorb water. Nitrogen deposition modulates litter decomposition and water retention properties. Specifically, high nitrogen deposition increases litter water-holding capacity by inhibiting the rate of litter decomposition, which in turn alters its mass remaining rate, lignin, and cellulose remaining rates. Efficient management of the studied forests leveraging nitrogen deposition can boost their water conservation potential, aiding in atmospheric precipitation absorption and surface runoff regulation.

Keywords: nitrogen effects; litter decomposition; water retention; Yunnan Plateau forests; atmospheric precipitation

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1. Introduction

In 2018, China emitted a total of 24.6 $Tg{\cdot}N{\cdot}yr^{-1}$ of ammonia and nitrate nitrogen, with 14.8 $Tg{\cdot}N{\cdot}yr^{-1}$ being ammonia nitrogen and 9.8 Tg N yr^{-1} being nitrate nitrogen. These emissions accounted for 55% (65 $Tg{\cdot}N{\cdot}yr^{-1}$) and 45% (52 $Tg{\cdot}N{\cdot}yr^{-1}$) of total inorganic N emissions, respectively [1]. Although atmospheric nitrogen deposition is mainly composed of ammonia and nitrate nitrogen, it is predicted that global nitrogen deposition rates will increase by 2.5 times in the next century [2]. Nitrogen is a limiting factor for the net primary productivity of terrestrial plants. The continuous accumulation of nitrogen alters the quality of litter and affects various ecological processes, such as the magnitude of litter decomposition rate, nutrient release processes, and decomposition by soil microorganisms. These changes affect the stand productivity and carbon cycling processes of forest ecosystems [3–5]. Litter is an essential component of forest ecosystems and plays a significant role in material cycling. It improves soil and microclimate conditions, enhances soil quality, increases soil enzyme activity, and maintains nutrient cycling in vegetation ecosystems. The eco-hydrological effects of litter have received widespread attention in forest ecosystems [6–10]. Current research on nitrogen deposition in the Central Yunnan Plateau primarily examines the impact of simulated nitrogen deposition on litter decomposition, nutrient release, soil organic carbon components, soil enzyme activity, and microbial community structure [11–14]. Globally, studies have also investigated litter decomposition rates [15,16], soil animals, soil microorganisms, enzyme activities [17,18], soil respiration [19,20], plant growth, biodiversity [21], greenhouse gas fluxes in forests, and the influence on soil carbon budget and nitrogen mineralization [22–24]. However, there is a relative lack of studies on the water-holding properties of litters under nitrogen deposition. This limits our understanding of litter decomposition. Therefore, it is important to study the water-holding properties of litters under nitrogen deposition to provide a theoretical basis for water conservation and forest management in forest ecosystems [25].

The maximum water-holding capacity of the litter layer in forest ecosystems can reach up to 200.0%–448.9%, allowing it to intercept 10%–20% of precipitation. The litter layer plays a crucial role in soil and water conservation [26–28]. Differences in its water-holding characteristics have been the focus of research. Currently, there is limited research on the water-holding characteristics of litter under N deposition. Most studies focus on the accumulation of litter and its water-holding characteristics in different forest types across various regions. For instance, Zhou et al. (2018) found that the semi-decomposed litter's effective water-retention capacity was approximately four times higher for the coniferous (17.3 $t \cdot ha^{-1}$) and mixed forests (17.6 $t \cdot ha^{-1}$) than for the broadleaved forest (4.4 $t \cdot ha^{-1}$) [29]. Similarly, Bai et al. (2021) reported that the thickness and quantity of the undecomposed layer in mixed forests with coniferous and broad-leaved trees ranged from 21.86% to 46.05% and −44.91% to −18.91%, while the thickness and quantity of the semi-decomposed layer ranged from 82.61% to 136.23% and 11.75% to 63.49%, respectively [30]. The maximum water-holding capacity of the undecomposed layer (23.68% to 93.70%) exceeded that of the semi-decomposed layer (23.67% to 87.63%) according to Bai et al. (2021) [30]. The water-holding capacity of litter is influenced by various factors, namely the composition of tree species, the types of litter, the thickness of litter layers, the degree of litter decomposition [8–10], and the local climate conditions [29].

The Mopan Mountain in Central Yunnan connects the subtropical regions of northern and southern Yunnan Province. This study focuses on the Evergreen broad-leaf forest and *Quercus aquifolioides* forest in this area, which has abundant litterfall. The mid-mountain, semi-humid Evergreen broad-leaf forest is crucial in soil and water conservation, while the sparse *Quercus aquifolioides* forest has low stand density. At specific altitudes (2208–2373 m) and under a subtropical climate, a unique dwarf forest forms, with an average breast height diameter of 9.9 cm and a tree height of 4.2 m. This phenomenon has significant scientific research value. Hence, this study integrates field simulations of nitrogen deposition with the indoor water immersion method to explore the two forest stands' litter decomposition rates and water-holding characteristics. The nitrogen deposition is varied across the following gradients: control (CK, 0 $g \cdot m^{-2} \cdot a^{-1}$), low nitrogen (LN, 10 $g \cdot m^{-2} \cdot a^{-1}$), medium nitrogen (MN, 20 $g \cdot m^{-2} \cdot a^{-1}$), and high nitrogen (HN, 25 $g \cdot m^{-2} \cdot a^{-1}$). The hypotheses for this study are as follows: (1) The process of litter decomposition is contingent upon the composition of forest stands, with the application of HN treatment being observed to impede this process.; (2) The water-holding capacity of litter can be either increased or decreased by N deposition depending on its impact on the degree of litter decomposition; and (3) There exists a definite correlation between the rate of litter retention and the maximum water-holding capacity in the presence of nitrogen (N) deposition. The objective of this study is to comprehensively comprehend the water and soil conservation functions of forest ecosystems, as well as the productivity of forest land and the conservation of litter water. It also aims to establish a scientific foundation for water and soil conservation forests on the central Yunnan Plateau.

2. Materials and Methods

2.1. Study

This study was conducted at Mopan Mountain in Xinping County, Yunnan Province, within the Yuxi Forest Ecosystem National Positioning Observation and Research Station (23°46′18″–23°54′34″ N, 101°16′06″–101°16′12″ E). The study area experiences a mid-subtropical plateau monsoon climate with an altitude ranging from 1260.0 m to 2614.4 m. The average annual rainfall in this area is 1050 mm, classifying it as a mid-subtropical climate zone. The mean annual temperature measures 15 °C, with distinct wet and dry seasons (the dry season from November to April of the following year and the rainy season spanning from May to October). The soil composition consists mainly of Argi-udic Ferrosols and Hapli-udic argosols (Soil Taxonomy data from the United States Department of Agriculture). The area exhibits a rich variety of forest plant types with a forest coverage rate of 86% or more. The vegetation is distributed vertically with changes in altitude. The zonal plant community consists of subtropical Evergreen broad-leaved forests, and the understory is characterized by shrubs, such as *Pinus armandii*, *Pinus yunnanensis*, *Quercus aquifolioides*, *Keteleeria evelyniane*, etc. The locations of the study area and sample plots in Figure 1.

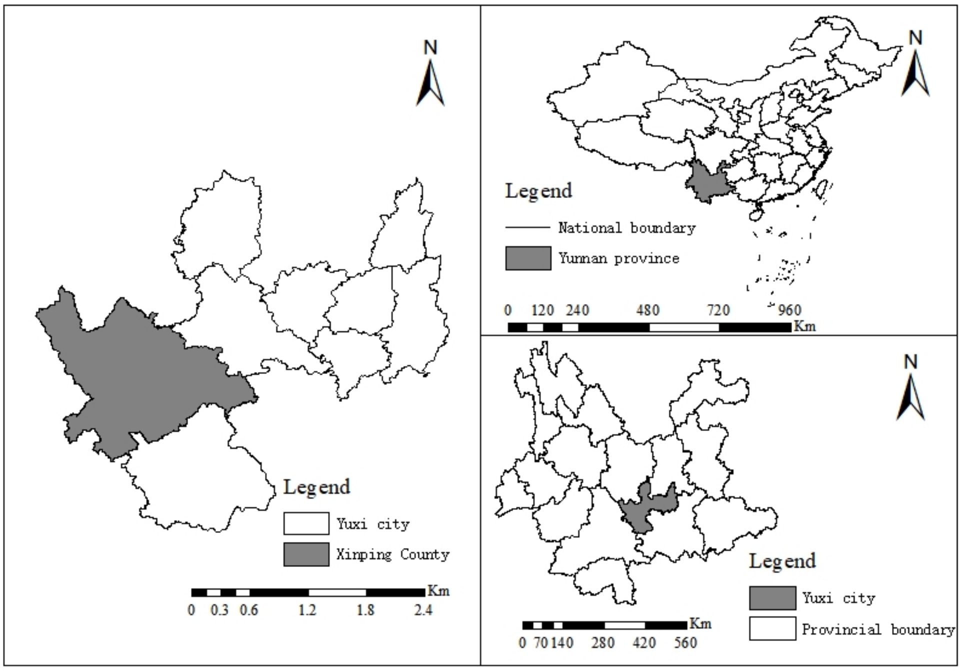

Figure 1. Location of the study area and sample plots.

2.2. Litter Collection and Simulated N Deposition Experiment

In the study area, we identified three standardized plots measuring 20 m × 20 m in the Evergreen broad-leaved and *Quercus aquifolioides* forests. Each forest type consisted of four subplots measuring 3 m × 3 m, with a minimum distance of 10 m between subplots. In these subplots, we collected recently fallen leaves and twigs (with a twig diameter of 3–5 mm). The dominant tree species in the Evergreen broad-leaved forest were *Castanopsis carlesii*, *Lithocarpus mairei*, and *Betula utilis*. The collected litter was then transported to the laboratory and naturally air-dried. Ten grams of desiccated leaves and twigs were carefully weighed before being packed into nylon mesh bags (20 cm × 20 cm) with a mesh size of 1 mm × 1 mm. Subsequently, plant roots and surface litter were removed from each subplot, and the litter bags were methodically distributed randomly and evenly across the soil surface. There were 36 bags allocated for leaves and an additional 36 for twigs, resulting in 432 bags for leaf and twig samples throughout 12 months

(4 treatments × 3 subplots × 3 bags). A minimum distance of 2 cm was maintained between adjacent litter bags to prevent potential overlap and interference during decomposition.

Based on the fluxes, characteristic variation, and potential sources of the atmospheric wet nitrogen deposition in southwestern China [31–33], in addition to the annual nitrogen (N) deposition level observed in our study area [3.84 $g \cdot m^{-2} \cdot a^{-1}$], different N deposition treatments (0, 5, 15, 30 $g \cdot m^{-2} \cdot a^{-1}$) have been set up in previous studies. Combined with the annual increase in nitrogen deposition (0.05 $g \cdot m^{-2} \cdot a^{-1}$), and wet N deposition rates of NO_2, NH_3, and HNO_3 in southwest China (0.6–5.46 $g \cdot m^{-2} \cdot a^{-1}$) [34], we implemented four nitrogen deposition treatments: control (CK) [0 $g \cdot m^{-2} \cdot a^{-1}$], low nitrogen (LN) [10 $g \cdot m^{-2} \cdot a^{-1}$], medium nitrogen (MN) [20 $g \cdot m^{-2} \cdot a^{-1}$], and high nitrogen (HN) [25 $g \cdot m^{-2} \cdot a^{-1}$]. Starting in June 2021, we prepared a solution of $CO\ (NH_2)_2$ in 1 L of deionized water as the nitrogen source and applied it evenly to subplots after each month using a sprayer. The basic characteristics of the Evergreen broad-leaf forest and *Quercus aquifolioides* forest sampled plots as shown in Table 1.

Table 1. Basic characteristics of Evergreen broad-leaf forest and *Quercus aquifolioides* forest sampled plots.

Forest Type	Stand	Altitude (m)	Age (a)	Mean Height (m)	DBH (cm)	Canopy Density	Slope (°)	Aspect	Soil Category
Evergreen broad-leaf forest	1	2130	17	9.6	14.5	0.87	23	NE	Argi-udic Ferrosols
	2	2132	15	12.1	20.7	0.90	28	NE	Argi-udic Ferrosols
	3	2133	17	10.8	18.3	0.85	30	NE	Argi-udic Ferrosols
Quercus aquifolioides	1	2490	15	3.4	12.1	0.90	10	SE	Hapli-udic argosols
	2	2489	16	2.5	9.4	0.88	12	SE	Hapli-udic argosols
	3	2490	17	3.1	8.6	0.92	13	SE	Hapli-udic argosols

2.3. Sample Measurements

The sampling period ran from July 2021 to September 2022 (25–36 months after nitrogen application). However, sampling was impossible between January and March 2022 due to the COVID-19 pandemic. As a result, the sampling was postponed, and the actual sampling periods occurred from July to December 2021 and April to September 2022. In total, there were 12 sampling events. The specific sampling process involved selecting three bags of litter and three bags of twigs from each treatment plot in the latter half of each month. These samples were carefully placed in self-sealing bags and transported to the laboratory. In the laboratory, the collected samples were cleared of roots and sediments and dried at a constant temperature of 65 °C until a stable mass was reached.

Litter lignin and cellulose content were determined using the acid detergent fibre method [35]. The water-holding capacity of the litter was assessed using the indoor soaking method described by Bai and Li [30,36]. Five grams of desiccated litter of leaves and twigs were enclosed in nylon mesh bags with 1 mm × 1 mm pore sizes. Each bag was carefully labeled and submerged in containers filled with water, ensuring complete immersion of the litter samples. At intervals of 0.5, 1, 2, 4, 6, 8, 12, and 24 h, the nylon mesh bags were retrieved from the water and allowed to drain until no further water dripped. The change in mass was then measured at each soaking duration to determine the water-holding capacity, water-holding rate, and water-absorption rate of the litter. The maximum water-holding capacity was identified after 24 h of soaking, corresponding to the maximum water-holding rate.

2.4. Statistical Analyses

The calculation methods for litter water-holding properties are as follows: litter water-holding capacity (in grams) is obtained by subtracting the initial weight (m_0) from the final weight (m_t), denoted as M [8]

$$M = m_t - m_0 \tag{1}$$

The litter water-holding rate (as a percentage) is calculated by dividing the difference between the final and initial weights by the initial weight (m_0) and then multiplying by 100%, expressed as L [8]

$$L = \left({}^{m_t - m_0}/_{m_0} \right) \times 100\% \tag{2}$$

In the equation, M represents the litter's water-holding capacity (in grams), L denotes the litter's water-holding rate (as a percentage), mt represents the wet weight of the litter after a specific soaking time, m0 refers to the initial mass of the litter (5.00 g), and t represents the duration of the soaking process (in hours).

The litter decomposition rate (k) was calculated using the Olson exponential decay model [37]:

$$y = ae^{-kt} \tag{3}$$

Here, a is a fitting parameter, k ($kg \cdot kg^{-1} \cdot a^{-1}$) is the litter decomposition coefficient, and t (years) represents decomposition time. The remaining litter mass (M_R) and lignin (cellulose) content were computed as M_R and L_R, respectively [4].

$$M_R = \frac{M_t}{M_0} \times 100\% \tag{4}$$

$$L_R = (C_t \times M_t)/(C_0 \times M_0) \times 100\% \tag{5}$$

In these equations, M_t (g) is the mass of the dried sample at time t, M_0 (10 g) is the initial air-dried sample mass, C_t ($mg \cdot g^{-1}$) is the lignin (cellulose) content at time t, and C0 ($mg \cdot g^{-1}$) is the initial lignin (cellulose) content. Notably, the calculation method for cellulose is identical to that of lignin. The impacts of N deposition and decomposition time on litter decomposition were compared using repeated measures ANOVA ($p < 0.05$) in SPSS 22.0. Additionally, linear regression analysis was performed to examine the relationship between mass loss and water-holding characteristics under various nitrogen treatments. Data were organized and graphed using Excel 2010 and Origin 2023. The map of the study area in China was generated with ARCGIS (version 10.2, ESRI, Redlands, CA, USA, http://desktop.arcgis.com/en/arcmap (28 February 2024)).

3. Results

3.1. Decomposition Rate and Loss of Leaf Litter Mass

The mass of leaf litter and twigs in both forest types decreased over time (Figure 2). The decomposition rates of litter in the Evergreen broad-leaved forest and *Quercus aquifolioides* forest ranged from 0.242 to 0.355 $kg \cdot kg^{-1} \cdot a^{-1}$ and 0.246 to 0.303 $kg \cdot kg^{-1} \cdot a^{-1}$, respectively (Table 2). After 36 months of decomposition, the N treatments in the Evergreen broad-leaved forest increased the remaining mass by 4.75% to 17.50% compared to the control (20.97 $\pm$ 0.44%). In the *Quercus aquifolioides* forest, the LN treatment decreased the remaining mass by 5.00% compared to the control (35.47 $\pm$ 0.39%), while the MN and HN treatments increased it by 2.55% to 8.13%.

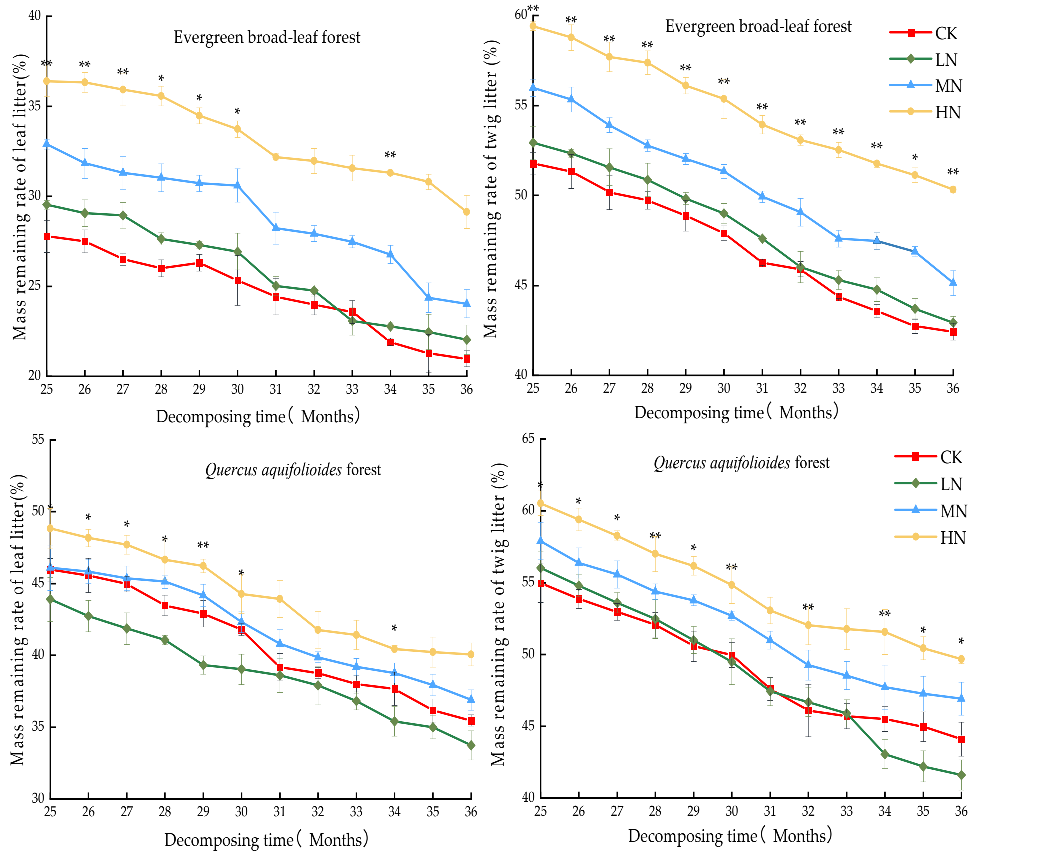

Figure 2. Changes in mass remaining of leaf litter and twigs during decomposition. Control, low N, medium N, and high N are 0, 10, 20, and 25 g·m^{-2}·a^{-1}, respectively. The same is below. * represents high statistical significance ($p < 0.05$). ** represents high statistical significance ($p < 0.01$).

Table 2. Models (y = ae^{-kt}) for the relationship between mass remaining (y, %) of leaf litter and time (t, a).

Forest Type	Litter Type	Treatment	Regression Equation	Determination Coefficient R^2	Decomposition Coefficient (k, kg·kg^{-1}·a^{-1})	Time of Half Decomposition ($T_{50\%}$, a)	Time of 95% Decomposition ($T_{95\%}$, a)
Evergreen broad-leaf forest	Leaf litter	CK	$y = 29.105\ e^{-0.316\,t}$	0.959 **	0.316	2.194	9.480
		LN	$y = 31.101\ e^{-0.355\,t}$	0.969 **	0.355	1.953	8.439
		MN	$y = 34.475\ e^{-0.333\,t}$	0.935 **	0.332	2.088	9.023
		HN	$y = 37.844\ e^{-0.242\,t}$	0.964 **	0.242	2.864	12.379
	Twig litter	CK	$y = 53.376\ e^{-0.236\,t}$	0.989 **	0.236	2.937	12.694
		LN	$y = 54.664\ e^{-0.242\,t}$	0.990 **	0.242	2.864	12.379
		MN	$y = 57.190\ e^{-0.229\,t}$	0.992 **	0.229	3.027	13.082
		HN	$y = 60.557\ e^{-0.187\,t}$	0.994 **	0.187	3.707	16.020
Quercus aquifolioides	Leaf litter	CK	$y = 47.913\ e^{-0.303\,t}$	0.981 **	0.303	2.288	9.887
		LN	$y = 44.852\ e^{-0.274\,t}$	0.988 **	0.274	2.530	10.933
		MN	$y = 48.168\ e^{-0.264\,t}$	0.972 **	0.264	2.626	11.347
		HN	$y = 50.304\ e^{-0.246\,t}$	0.972 **	0.246	2.818	12.178
	Twig litter	CK	$y = 56.156\ e^{-0.256\,t}$	0.973 **	0.256	2.708	11.702
		LN	$y = 58.294\ e^{-0.341\,t}$	0.990 **	0.341	2.033	8.785
		MN	$y = 58.962\ e^{-0.244\,t}$	0.984 **	0.244	2.841	12.278
		HN	$y = 61.345\ e^{-0.220\,t}$	0.982 **	0.220	3.151	13.617

** represents high statistical significance ($p < 0.01$).

Twigs in the Evergreen broad-leaved forest decomposed at rates ranging from 0.187 to 0.242 kg·kg^{-1}·a^{-1}, while those in the *Quercus aquifolioides* forest decomposed at rates ranging from 0.220 to 0.341 kg·kg^{-1}·a^{-1}. The decomposition rates for all treatments were in the order LN > CK > MN > HN (Table 2). After 36 months, the Evergreen broad-leaved forest treatments showed a mass increase of 2.09% to 16.36% compared to the control (42.43 ± 0.47%). In the *Quercus aquifolioides* forest, the LN treatment decreased the remaining mass by 0.70% compared to the control (44.10 ± 1.18%), while the MN and HN treatments increased it by 5.61% and 11.28%, respectively. LN stimulated litter decomposition in the *Quercus aquifolioides* forest, while MN and HN treatments hindered it compared to the control. All treatments in the Evergreen broad-leaved forest suppressed litter decomposition.

3.2. Decomposition Rate of Lignin and Cellulose in Litter

The remaining lignin and cellulose rates in both forest types generally decrease as decomposition time increases, (Figure 3). In Evergreen broad-leaved forest, the order of cellulose remaining rate for leaf litter is HN > MN > LN > CK, while for other forest types, it is HN > MN > CK > LN. After 36 months of decomposition, the average lignin and cellulose remaining rates for leaf litter in Evergreen broad-leaved forest range from 34.77% to 45.41% and 26.76% to 36.94%, respectively, and for *Quercus aquifolioides* the ranges are 33.28% to 40.09% and 35.58% to 42.22%, respectively. In Evergreen broad-leaved forest, the lignin remaining rate is 2.15% lower than CK (26.50 ± 0.44%) in the LN treatment, while the MN and HN treatments result in rates that are 21.14% to 30.60% higher than CK. The cellulose remaining rate in all N treatments is 6.88% to 38.04% higher than CK (19.42 ± 0.53%). For *Quercus aquifolioides*, the lignin remaining rate (29.37 ± 0.44%) and cellulose remaining rate (31.94 ± 0.49%) are 1.85% and 0.62% lower than CK, respectively, while the MN and HN treatments lead to rates that are 12.54% to 20.46% and 7.71% to 17.93% higher than CK.

The average rates of remaining lignin and cellulose in twig litter within Evergreen broad-leaved forest range from 40.70% to 47.77% and 48.13% to 57.93%, respectively (Figure 2). For *Quercus aquifolioides* forest, the range is 39.60% to 47.23% for lignin and 42.22% to 52.67% for cellulose. The order of remaining rates for lignin and cellulose in twig litter within Evergreen broad-leaved forests is HN > MN > CK > LN, while for *Quercus aquifolioides*, it is HN > MN > LN > CK. The remaining lignin rate (26.72 ± 0.47%) and cellulose rate (48.08 ± 0.47%) in N treatments within Evergreen broad-leaved forest are lower than CK by 0.42% and 2.32%, respectively, whereas MN and HN treatments surpass CK by 12.47% to 16.88% and 10.49% to 17.57%, respectively. In *Quercus aquifolioides* forest, the lignin remaining rate (24.34 ± 0.47%) and cellulose remaining rate (39.52 ± 0.88%) in N treatments exceed CK by 5.69% to 19.29% and 8.46% to 24.73%, respectively. The response of remaining lignin and cellulose rates to N deposition varies between the forest types, with exogenous N addition inhibiting the decomposition of both litter lignin and cellulose, an effect that intensifies with higher N concentrations.

3.3. Impacts of Modeled Nitrogen Deposition on the Water Retention Ability of Leaf Litters

The maximum water-holding capacity of litter exhibited a parallel decrease with the declining decomposition rate. After 36 months of decomposition (Figure 4), the average range of the maximum water-holding capacity of litter in the Evergreen broad-leaved forest and *Quercus aquifolioides* forest was found to be between 16.06 g and 18.61 g and between 16.32 g and 18.03 g, respectively. The average maximum water-holding capacity for each nitrogen (N) treatment followed the following sequence: high nitrogen (HN) > medium nitrogen (MN) > low nitrogen (LN) > control group (CK). In the Evergreen broad-leaved forest, the maximum water-holding capacity of litter was 318.47% to 359.92% higher, and for each N treatment, it was 1.06 to 1.16 times that of the control group (14.42 ± 0.44 g). Similarly, the maximum water-holding capacity of litter in the *Quercus aquifolioides* forest was 328.28% to 368.78% higher, and for each N treatment, it was 1.04 to 1.10 times that of the control group (13.36 ± 0.38 g).

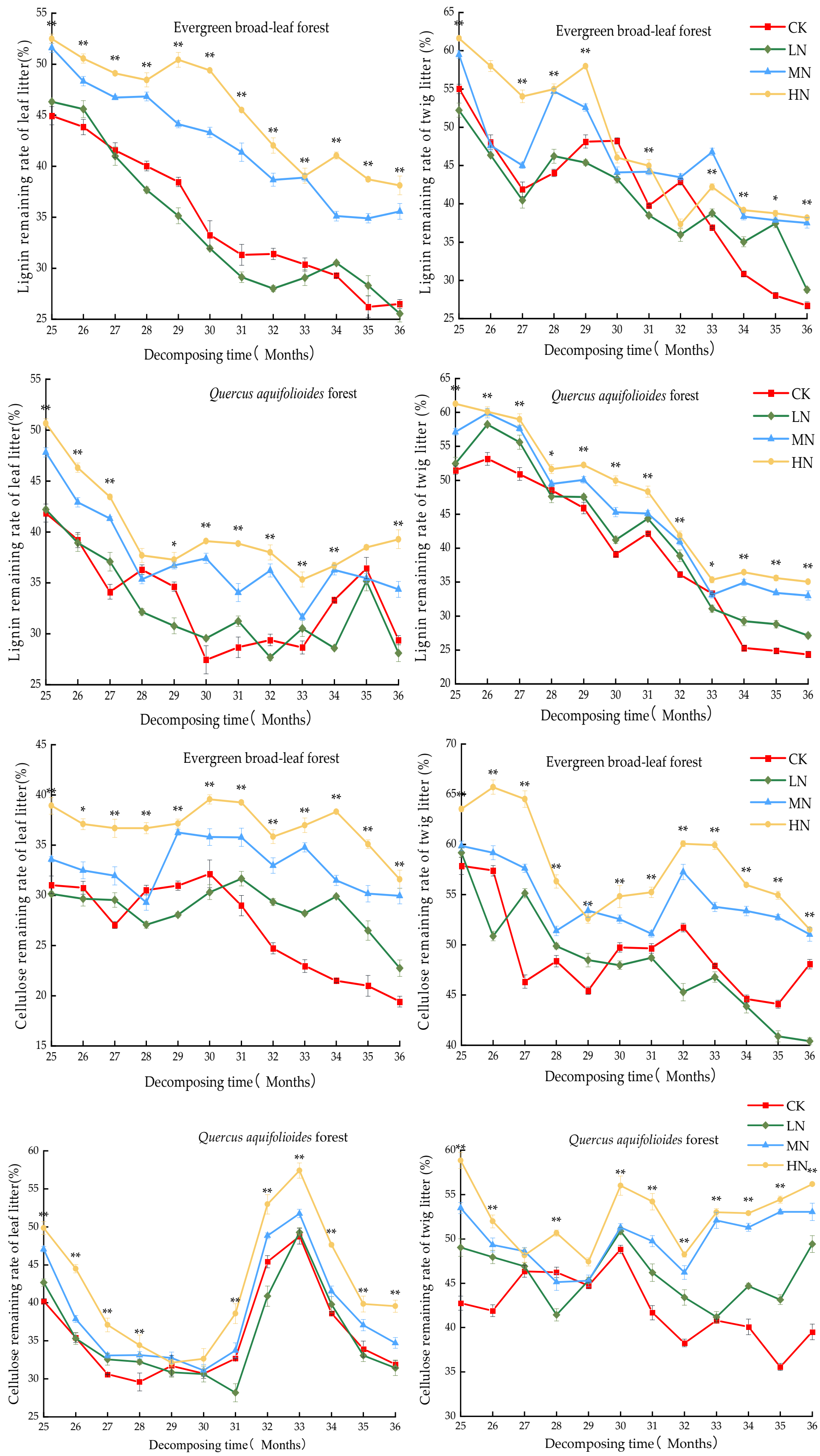

Figure 3. Changes in lignin and cellulose remaining rates during decomposition of litter. * represents high statistical significance ($p < 0.05$). ** represents high statistical significance ($p < 0.01$).

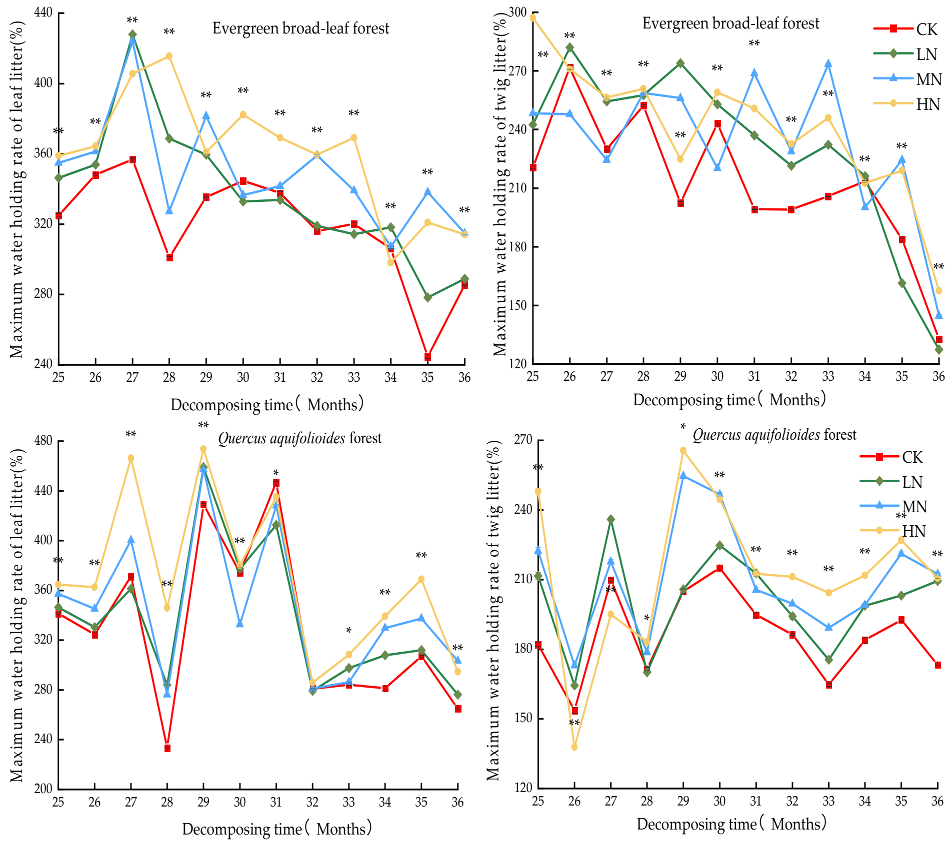

Figure 4. Changes in maximum water-holding rate of leaf and twig litter during decomposition. * represents high statistical significance ($p < 0.05$). ** represents high statistical significance ($p < 0.01$).

The average maximum water-holding capacity range for twigs of Evergreen broad-leaved forest and *Quercus aquifolioides* forest ranged from 10.89 g to 12.42 g and 9.36 g to 10.77 g, respectively. Both forests' average maximum water-holding capacity followed HN > MN > LN > CK. The maximum water-holding capacity of the Evergreen broad-leaved forest was 212.85% to 240.63% higher, and for each treatment, it was 1.09 to 1.14 times greater than CK (6.61 $\pm$ 0.44 g). Similarly, the maximum water-holding capacity of *Quercus aquifolioides* forest was 186.09% to 212.64% higher, and for each treatment, it was 1.07 to 1.15 times greater than CK (8.70 $\pm$ 0.39 g). All four treatments demonstrated a positive effect on enhancing the water-holding capacity of litter, with the HN treatment resulting in a stronger water-holding effect than the LN and MN treatments.

3.4. Analysis of the Correlation between Leaf and Twig Retention Rate and Peak Water Holding Capacity

Based on the fitting analysis (Figures 5 and 6), a positive correlation was observed between the mass remaining rate, lignin remaining rate, and cellulose remaining rate of litter in both Evergreen broad-leaved forest and *Quercus aquifolioides* forest twigs with their respective maximum water-holding capacity ($p < 0.05$). Moreover, it was observed that in the *Quercus aquifolioides* forest twigs, the mass remaining rate of litter displayed a positive correlation with maximum water-holding capacity, while the lignin remaining rate and cellulose remaining rate exhibited a negative correlation with maximum water-holding capacity ($p < 0.05$).

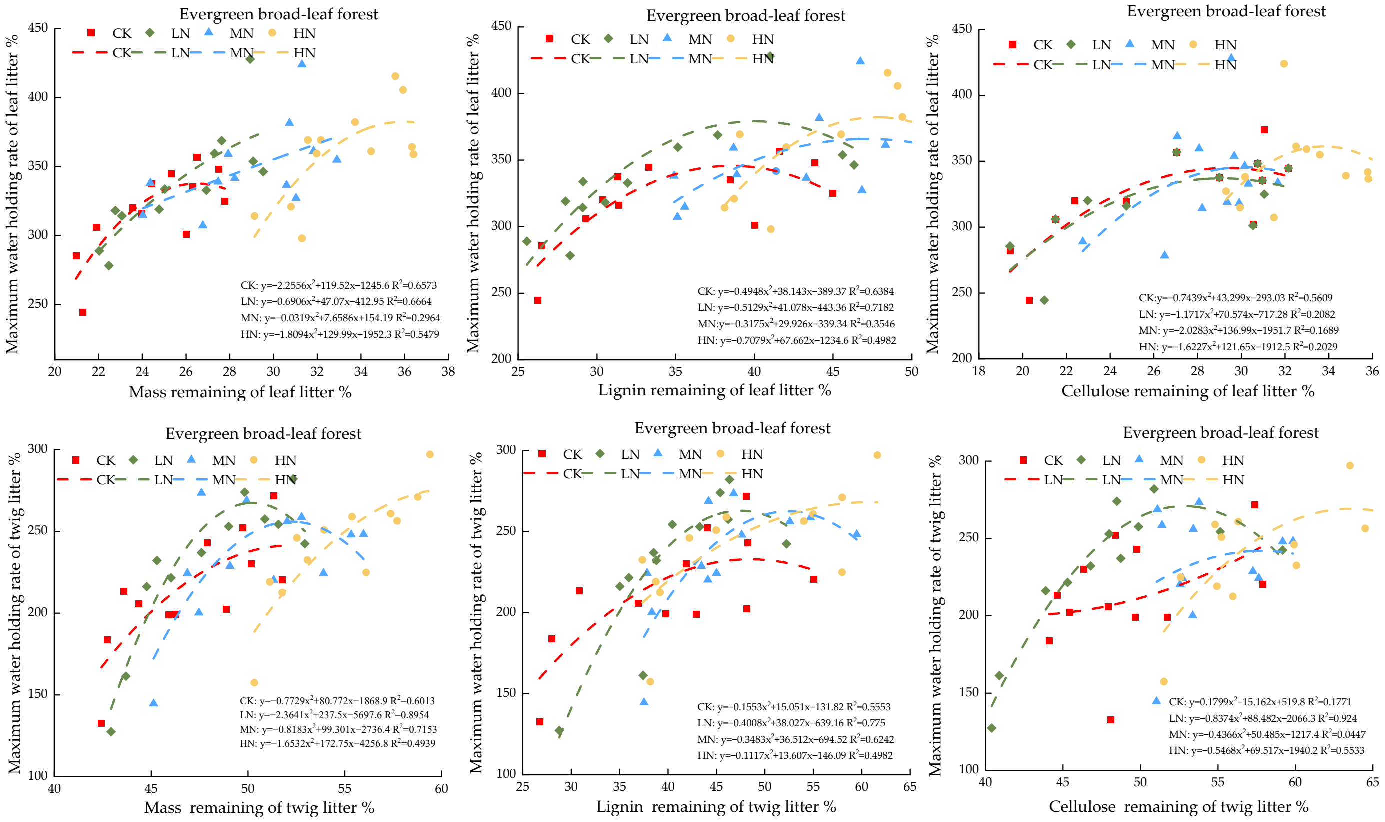

Figure 5. Fitting analysis of withered leaves and twigs remaining rate of Evergreen broad-leaf forest with maximum water-holding rate. The ellipse in the figure represents the 95% confidence interval and is used to predict the extra-elliptical outliers. The same is below.

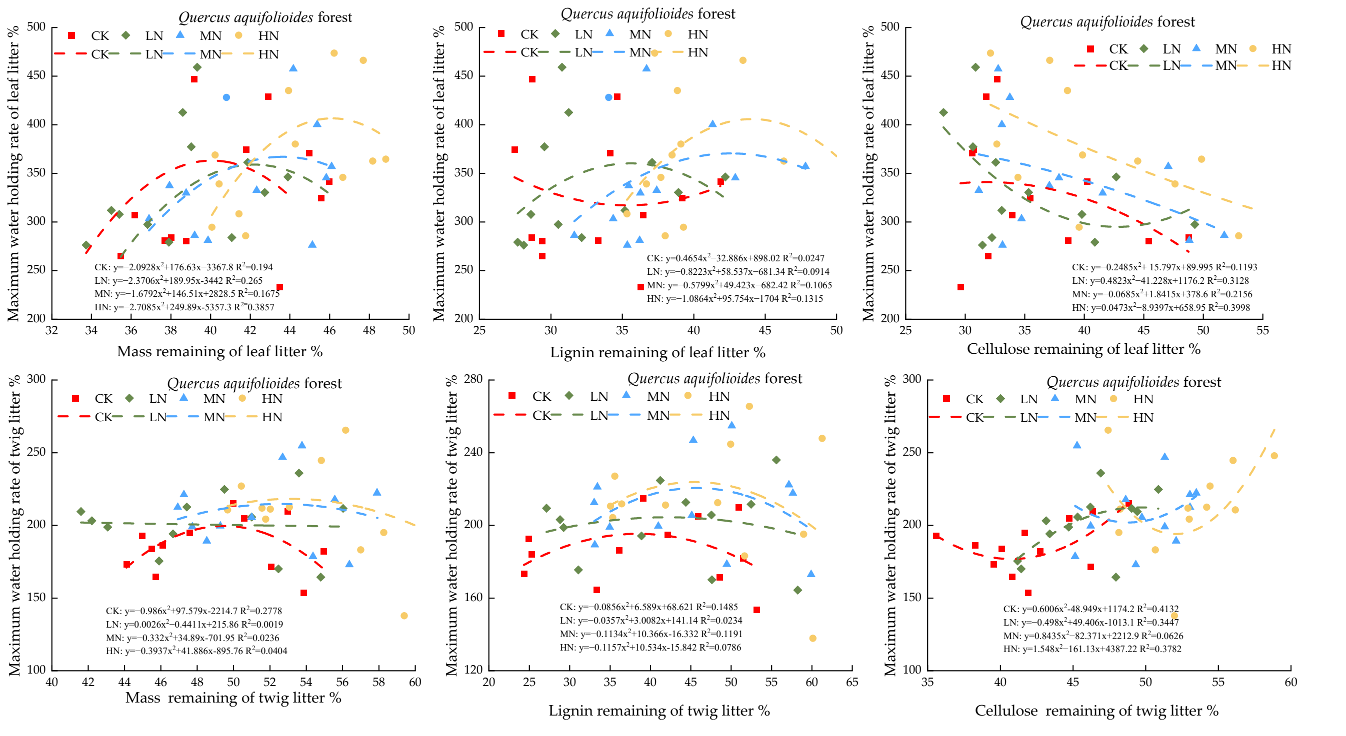

Figure 6. Fitting analysis of withered leaves and twig remaining rate of *Quercus aquifolioides* with maximum water-holding rate.

4. Discussion

4.1. Simulation of the Effect of Nitrogen Deposition on Litter Decomposition

In this investigation, we observed that litter decomposition was influenced by N deposition in both stands, with the decomposition rate decreasing as the N application increased. The LN treatment promoted litter decomposition, whereas the MN and HN treatments hindered litter decomposition. This outcome supports our initial hypothesis but contradicts previous findings that demonstrated the incorporation of N accelerating the litter decomposition rate in *Camptotheca acuminata* in the western areas of the Sichuan Basin [38]. Friedman's long-term experiments in the boreal hardwood forest ecosystem of Michigan aimed to increase atmospheric nitrogen deposition and decrease woodland decay [39]. These inconsistencies in the results can be partially attributed to variations in the level of experimental N addition [40]. Low levels of nitrogen addition significantly accelerated the decomposition of litter [41]. Nitrogen addition reduces the nitrogen limitation of soil microorganisms and enhances enzyme activity, thereby promoting leaf litter decomposition [42]. However, prolonged or excessive N addition generally exhibited negative effects on litter decomposition [43]. Nitrogen addition induces soil acidification, increases the osmotic pressure of the soil solution, and adversely affects microbial growth, which in turn inhibits litter decomposition [44,45].

Secondly, it may also be associated with the litter's natural environment's sufficient nitrogen (N) content [46]. Research has demonstrated that the southern and central regions of China exhibit heightened nitrogen deposition, surpassing 35 $kg \cdot hm^{-2} \cdot a^{-1}$, with a sequential decrease to the northwest, reaching 7.55 $kg \cdot hm^{-2} \cdot a^{-1}$ [7,47]. Owing to abundant precipitation and reactive nitrogen deposition, the atmospheric wet nitrogen deposition in southwest China exceeds the average annual wet nitrogen deposition (NH_4^+-N and nitrate-N) fluxes in the country, measuring 15.8 ± 11.1 $kg \cdot N \cdot hm^{-1} \cdot yr^{-1}$ [47,48]. Hence, disparities in environmental N deposition result in variations in litter decomposition rates, and when atmospheric N deposition surpasses the capacity of forest ecosystems to retain N, N saturation transpires, consequently impeding litter decomposition, and the degree of nitrogen limitation in the local ecosystem determines this threshold [46,49]. To summarize, N addition level and environmental N deposition are two pivotal factors governing litter decomposition [50].

Evaluation utilizing Olson's exponential model demonstrated that the timeframe necessary for 50% and 95% decomposition of twig litter exceeded that of leaf litter in both forest stands. This discrepancy can be attributed to the limited surface area of twig litter in contact with soil fauna and microorganisms, as well as the elevated presence of recalcitrant lignin compounds within twig litter, resulting in a comparatively sluggish decomposition process [3,51].

4.2. Simulation of the Effect of Nitrogen Deposition on Lignin and Cellulose Degradation in Litter

In this study, remaining rates of lignin and cellulose showed an increasing trend in the later stage of the study. Lignin and cellulose are macromolecules known for their inherently slower degradation compared to other constituents of litter [52,53]. The increase in lignin content may be due to the following reasons: firstly, resistant substances are generated and preserved as lignin during decomposition, leading to a considerable absolute increase in lignin content [54]. These recalcitrant lignin-like substances may originate from the recondensation of lignin degradation products or aromatic compounds formed through microbial metabolism [53]. Secondly, the byproducts of lignin degradation may form stable N-containing compounds, reducing nitrogen availability to decomposing organisms and inhibiting lignin degradation [55]. Thirdly, the long-term application of nitrogen alters the soil microbial community structure, shifting from fungal dominance to bacterial dominance and consequently decreasing the population of lignin-degrading microorganisms, thereby inhibiting lignin degradation [52,56,57]. The increase in cellulose may be due, on the one hand, to climate-induced effects on the soil microbial community; this is because the breakdown of cellulose necessitates a diverse and abundant microbial community, and a warm and humid climate creates an optimal microenvironment for soil microbial activities. In such conditions, soil microbes proliferate and produce cellulose-degrading enzymes, thereby expediting the degradation of cellulose. Conversely, a cold and arid climate reduces soil microbial activity, resulting in a decline in the secretion of cellulose-degrading enzymes and, consequently, slower cellulose degradation [46,57]. On the other hand, the accumulation of N elements during litter decomposition leads to more carbon sources that cannot be decomposed, fewer nutrients available for microbial decomposition, and slower degradation of cellulose [58]. Moreover, a study conducted by Zak et al. (2019) in eastern North American forests found that nitrogen addition inhibits ligninolytic enzyme activity, thus promoting cellulolytic activity [59].

Lignin and cellulose exhibited a consistent response to N deposition. This is because the degradation of litter lignin is influenced by the composition of cellulose, hemicellulose, and pectin, which is shielded by hemicellulose and lignin itself, thus hindering both lignin and cellulose degradation. In conclusion, the N dynamics during litter decomposition are closely related to the dynamics of lignin and cellulose contents in litter.

4.3. Simulation of the Effect of Nitrogen Deposition on the Water-Holding Characteristics of Litter

The magnitude of the water-holding capacity of litter serves as a critical parameter for evaluating its water retention abilities, as greater water-holding capacity indicates superior water-holding performance [60]. In this investigation, the overall water-holding litter capacity in both Evergreen broad-leaf and *Quercus aquifolioides* forest exhibited a decline corresponding to the decrease in the remaining decomposition rate. Interestingly, the HN treatment impeded litter decomposition and enhanced its water-holding capacity. This disparity in the holding capacity of litter can be attributed to variations in the decomposition rate among the stands and may contribute to alterations in the hydrological characteristics of the litter layer following an extended decomposition cycle of the experimental materials (36 months) [60]. Although HN treatment inhibited the decomposition of litter and enhanced its water-holding capacity, the reason for this may be affected by the density of the litter. The density of the material can reflect its degree of compactness, with higher density resulting in lower specific surface area and structural voids. The water-holding capacity of litter involves both the adsorption of water molecules on its surface and the storage of water in its inner voids. The degree of compactness of litter in the HN treatment was smaller than in the CK treatment, resulting in a decrease in the maximum water-holding capacity of the litter with an increase in its density. The HN treatment had a higher water-holding capacity due to its lower density [45].

The maximum water-holding capacities of wilted leaves in Evergreen broad-leaved forest and *Quercus aquifolioides* forest ranged from 318.47% to 359.92% and 328.28% to 368.78%, respectively. Similarly, the maximum water-holding capacities of wilted twigs ranged from 212.85% to 240.63% and 186.09% to 212.64%, respectively. These findings imply that these forest types' wilted leaves and twigs can absorb water approximately 3.21 to 3.72 times and 3.26 to 3.61 times their dry weight, respectively. This corresponds with the results reported by Xing and Du [27,28], who found that the litter layer can exhibit a water-holding capacity ranging from 200.0% to 448.9%. The water-holding capacity of the *Quercus aquifolioides* forest slightly surpasses that of the Evergreen broad-leaf forest. Disparities in the rate of litter decomposition can be attributed to the variations in physical and chemical properties of litter among different species, including stand composition, litter type, thickness, storage, water retention capacity, and the degree of litter decomposition [26,28,61].

In general, the water-holding capacity of leaf litter in both stands exhibited a higher value than twig litter. This disparity can likely be attributed to differences in the lignin content, which tends to be relatively higher in twig litter than leaf litter. Lignin contributes to enhanced toughness and resistance to decay, particularly in wood and bark, while also facilitating water transport within plants due to its inherent hydrophobic properties [62]. Thus, leaves, litter, and twigs manifest distinct water-holding attributes. The fitting analysis

(Figures 5 and 6) revealed that the remaining rates of mass, lignin, and cellulose in leaf and twig litter within the Evergreen broadleaf forest, as well as twig litter within the *Quercus aquifolioides* forest, exhibited significant positive correlations with the maximum water-holding rate ($p < 0.05$). Regarding leaf litter in the *Quercus aquifolioides* forest, the mass remaining rate positively correlated with the maximum water-holding rate and negatively correlated with the lignin and cellulose remaining rates ($p < 0.05$). While the maximum water-holding rate contributes to litter's decomposition rate and water-holding capacity, it is crucial to acknowledge that the lignin content also shapes the decomposition rate and water-holding capacity.

5. Conclusions

The litter decomposition rate was influenced by N deposition, with the LN treatment promoting litter decomposition while the MN and HN treatments hindered it. Notably, the continuous addition of N increased the water-holding capacity while suppressing litter decomposition, indicating that N deposition treatments affect both the water-holding capacity and litter decomposition rate in forest ecosystems. The Evergreen broad-leaf forest exhibited a stronger water-holding capacity than the *Quercus aquifolioides* forest, and the water-holding capacity of litter leaves surpassed that of litter twigs across all treatments. Consequently, as N deposition continues to increase, research on plantation ecohydrology should prioritize accelerating the decomposition of litter material while enhancing its water-holding capacity to ensure sustainable forest development. Furthermore, selecting tree species for plantation forests should consider the specific stand types and incorporate suitable soil and water conservation measures and vegetation restoration efforts. Future investigations should emphasize elucidating the impacts of multifactorial interactions on litter decomposition and its capacity for water retention. These endeavors will yield valuable insights into the advantageous role of litter in forest ecosystems, particularly in regard to soil and water conservation as well as its water-holding functionalities.

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