

Article



Vegetation Type and Soil Moisture Drive Variations in Leaf Litter Decomposition Following Secondary Forest Succession

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Abstract: Soil moisture was an important factor affecting litter decomposition. However, less attention has been given to the complete succession ecosystem after farmland abandonment. To better understand the effect of moisture on leaf litter decomposition after farmland abandonment, in this study, we used three water gradients (10%, 25% and 50%) of field moisture capacity for succession vegetation. Furthermore, we used the typical species leaf litter decomposition of four succession stages—grassland (GL), shrubland (SL), pioneer forest (PF), and climax forest (CF) from the Loess Plateau of China. The results showed that leaves decomposition rate exhibited an increasing pattern with increasing moisture contents. The decomposition trend was shown as GL > SL > PF > CF. During the decomposition process, the leaf carbon concentration (LC) and leaf nitrogen concentration (LN) changed, but non-significantly. The effects of LC, LN, and LC: LN on leaf decomposition varied with vegetation type. Soil properties such as NH_4^+ , NO_3^- , dissolved organic nitrogen (DON), and leaf quality parameters such as leaf cellulose, lignin, lignin: LN, and lignin: LC played an important role in driving leaf litter decomposition. Overall, the results provide evidence that litter decomposition in secondary forest succession system was linked to leaf and soil nutrient dynamics, and was limited by soil moisture.

Keywords: cellulose; lignin; leaf litter decomposition; soil nutrients; soil moisture; vegetation type

1. Introduction

Litter decomposition is one of the most important ecological processes that controls the conversion of carbon and nutrients in terrestrial ecosystems [1,2]. It is also an important link between material circulation and energy flow [3,4]. Soil moisture is an important environmental factor that regulates the decomposition of litter in terrestrial ecosystems [5]. Therefore, understanding how litter decomposition responds to changes in water will help to better understand ecosystem carbon and nutrient cycles.

In arid and semi-arid ecosystems, litter decomposition rate is largely limited by the availability of soil moisture [6]. Changes in soil moisture availability will affect soil microorganisms abundance and community [7], which will have a considerable impact on litter decomposition rate. Studies have found that litter decomposition rate is positively correlated with soil moisture [6], and the influence of soil moisture changes on litter decomposition rate varies with litter quality [8]. However, the effect of soil moisture on litter decomposition in different vegetation is still unclear.

Litter decomposition, can increase soil fertility, mainly by transporting organic matter to the soil [9]. Many factors affect litter decomposition, such as litter quality (e.g., N, P, lignin, cellulose, C: N ratio, N: P ratio, lignin: N ratio) [10], environmental variables (e.g., soil moisture, soil temperature, vegetation, soil fertility, dominant tree species) [10,11], and decomposers [12–14]. However, Castro, Fortunel and Freitas [13] found no significant



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). correlation between litter lignin concentration, C: N ratio, lignin: N ratio and litter decomposition rate. Wang, et al. [15] found that the initial litter C and P concentrations were significantly correlated with litter decomposition rates. In short, under different environmental conditions, the indicators that can predict the decomposition of litter are uncertain.

On the Loess Plateau, some studies have been carried out on the effects of litter decomposition after returning farmland to forest and grassland [16]. More litter is returned to the soil following the ongoing practice of returning farmland to forest and grassland [16]. Most studies have focused on litter increasing soil water holding capacity [17], improvements in soil quality [2,18], contributions to soil respiration [19], soil microbial composition [20,21], and carbon sequestration [16,22]. However, the dynamics of litter decomposition following vegetation restoration on the Loess Plateau are not clear, especially in the long-term process of forest succession. Litter decomposition is a complex process that is related to soil nutrient dynamics and vegetation restoration age, and it is mainly restricted by matrix quality and environmental conditions [23,24]. For example, soil moisture drives the activities of soil microorganisms, which can promote the decomposition of litter and accelerate the release of nutrients [24]; additionally, nutrient release from litter could provide most of the nutritional requirements for plant growth [25]. Although these studies have provided valuable recommendations for understanding the effect of substrate quality on litter decomposition, many studies have focused only on single vegetation species or on two species of vegetation [20,26–28]. There are few reports on different kinds of plant litter decomposition of during the complete succession of the Loess Plateau. Therefore, it is necessary to reveal the dynamics of litter decomposition under the influence of different water contents during long-term forest succession.

This study focused on the typical vegetation of four succession stages under three water gradients after farmland abandonment in the Ziwuling area; specifically, the study assessed the effect of grassland (GL), shrubland (SL), pioneer forest (PF), and climax forest (CF) on leaf decomposition and nutrient dynamics, evaluate the effect of moisture on litter decomposition, and explore the factors that affecting litter decomposition. We hypothesize that (1) the leaf decomposition rate decreases with the succession of vegetation after the abandonment of farmland and (2) leaf decomposition rate increases with the increasing of soil moisture.

2. Materials and Methods

2.1. Study Site

The study was conducted at the Lianjiabian Forest Farm in the Ziwuling forest region of Gansu Province, China (35°03′–36°37′ N, 108°10′–109°18′ E, 1100–1687 m.a.s.l). The Ziwuling forest area is a well-preserved natural secondary forest area on the Loess Plateau and an important ecological forest in the central part of the Loess Plateau. The zone has a warm temperate continental monsoon climate and a semi-arid mid-latitude climate, with an annual average temperature of 7.4–9.3 $^{\circ}$ C, an average temperature of -5.9–7.4 $^{\circ}$ C in January, an average temperature of 20.7-23.1 °C in July, an extreme maximum temperature of 35.7 $^{\circ}$ C and an extreme minimum temperature of $-22.7 \,^{\circ}$ C; additionally, the annual sunshine duration is 2159.4 h. The annual precipitation is 500–600 mm, and it is mostly concentrated in the 3 months of July, August and September. Loessial soil is the main soil type, developed from the primary or secondary loess parent materials, which are evenly distributed at thicknesses of 50–130 m above red earth consisting of calcareous cinnamon soil. After the abandonment of farmland, grassland (GL), shrubland (SL), pioneer forest (PF) and climax forest (CF) developed one after another, forming a complete succession chronosequence. Among them, the plant communities at the GL stage include Bothriochloa ischaemum (L.) Keng, Carex lanceolata Boott, Artemisia gmelinii Web. ex Stechm., Artemisia sieversiana Ehrhart ex Willd., Artemisia lavandulaefolia DC., Setaria viridis (L.) Beauv.; Hippophae rhamnoides L. and C. lanceolata at the SL stage; PF stage has C. lanceolata, Artemisia campestris Linn. Sp. Pl., Ulmus macrocarpa Hance, Acer ginnala Maxim., Armeniaca sibirica (L.)

Lam, Betula platyphylla Suk; And the CF stage mainly includes C. lanceolata, A. campestris, Populus davidiana Dode, B. platyphylla, Pinus tabuliformis Carr.

2.2. Experimental Design and Sampling

A field survey was undertaken in August 2017, and soil sampling and leaf litter collection were performed at the same time. The sampling areas of each succession stage were determined according to their sizes. There were five $20 \text{ m} \times 20 \text{ m}$ plots chosen in PF and CF communities, five $5 \text{ m} \times 5 \text{ m}$ plots in SL communities, and five $2 \text{ m} \times 2 \text{ m}$ plots in GL communities. The plots were no more than 5 km apart and the largest relative elevation difference was less than 120 m. To minimize the effects of site conditions on experimental results, all selected communities had a similar slope aspect, slope gradient, soil type and land use history.

In each plot, ground litter and fine roots were removed and then soils (0–20 cm) were sampled at the five points and mixed to form one soil sample. Soil samples were taken at five points lying at the four corners and center of the soil sampling sites. All soil samples were sieved through a 5 mm screen and air-dried. In addition, before sampling soil, five $1 \text{ m} \times 1 \text{ m}$ quadrats were set in the five soil sampling points of GL, SL, PF and CF sites. We collected all ground litter in quadrats to determine its physico-chemical properties.

2.3. Indoor Controlled Experiment

According to field leaf litter biomasses at every stage of vegetation succession, an indoor dark experiment with a constant temperature (25 °C) was used to simulate leaf litter decomposition. The added amount of litter was proportionally converted according to the area of the basin mouth and the area of the sample land per unit area in the field, and the added amount was consistent with the amount of litter in the same soil area in the field. The dry weight of soil in the basin was set at 300 g, and the maximum field moisture capacity of the four cultivated coverings was 157.6 g for GL, 181.6 g for SL, 192.4 g for PF and 190.6 g for CF, respectively. The water holding capacity was set to three water gradients in each vegetation stage: 10% (lower), 25% (medium) and 50% (higher) of field moisture capacity. Eighteen repeated treatments were set for each water gradient, and samples were taken six times. Three pots were assessed for each measurement. After leaf litter was added, water was replenished once every two days according to the weighing method. Samples were taken at the 1st, 3rd, 6th, 9th, 12th and 15th months after the addition of leaf litters. During sampling, the leaf litters were removed from the pot, and the soil on the surface was gently swept, dried and weighed to determine the related components of the leaves and soil.

2.4. Litter and Soil Property Assay

Litter carbon (LC) and nitrogen (LN) concentrations were determined by $K_2Cr_2O_7$ oxidation and the Kjeldahl method, respectively [29]. The contents of lignin and cellulose were determined by the acid washing fiber method [30]. Soil organic carbon (SOC) and total nitrogen (TN) concentrations were determined by the same method as litter. Ammonium (NH_4^+) and nitrate (NO_3^-) concentrations were assayed using Nessler's reagent and the phenol disulfonic acid colorimetric method, respectively [31]. The chloroform fumigation extraction protocol with K_2SO_4 extraction was employed to determine the soil microbial biomass carbon (MBC) and nitrogen (MBN) using 10 g of oven-dried equivalent field-moist soil [29]. Soil dissolved organic carbon (DOC) and nitrogen (DON) were extracted with K_2SO_4 [32]. A PHS-3G digital pH meter was used to determine the pH of the soil (with a water to soil ratio of 5:1).

2.5. Data Analysis

The mass remaining (*MR*) was calculated as follows [33]:

$$MR = \frac{M_t}{M_0} \times 100\%$$

where ' M_t ' is the mass of a leaf at time *t* (g); and ' M_0 ' is the initial dry mass of a leaf (g). The leaf mass loss rate was calculated as follows [33]:

$$L_t = \frac{M_0 - M_t}{M_0} \times 100\%$$

where ' L_t ' is the mass loss rate of a leaf at time t; ' M_0 ' is the initial weight of a leaf; and ' M_t ' is the mass residual amount at time *t*.

Statistical analysis was carried out using IBM SPSS statistics 24.0 software (IBM Corp., Armonk, NY, USA). After the homogeneity and normal distribution tests were passed, the difference in mass loss of leaves in different species at different decomposition times was tested by two-way analysis of variance (p < 0.05). Redundancy analysis (RDA) was drawn using Canoco 5.0 (Microcomputer Power, Ithaca, NY, USA), and the line chart was plotted using SigmaPlot 12.0 (Systat Software Inc., San Jose, CA, USA).

3. Results

3.1. Dynamics of Leaf Litter Biomass Loss and Leaf Litter Decomposition Rate

The mass residual rate of litters in these four recovery stages of GL, SL, PF and CF all showed decreasing trends (Figure 1A–C). The soil water content determined the speed and the slow decomposition rate (Figure 1A–C). The residual rate changed slowly with time under the lower water conditions, while it changed rapidly under the higher water conditions (Figure 1A–C). Regardless of the water content, the lowest dry mass remaining was in the GL in the four recovery stages (Figure 1A–C).



Figure 1. Dynamics of litter biomass loss and decomposition rate changed with decomposing time (months) in different restoration stages. Lower, medium, higher represent three different water gradients, respectively. GL, grassland; SL, shrubland; PF, pioneer forests; CF, climax forests. (A–C) represent the dry mass remaining under lower water, medium water and higher water treatment, respectively; (D–F) represent the mass loss rate under lower water, medium water and higher water treatment, respectively. All bars represent the mean \pm standard error.

Regardless of the water content, litters decomposition rate in the four recovery stages showed an increasing trend with time. However, the decomposition rate changes with soil water levels were as follows: higher > medium > lower. The fastest decomposition rates were all in the GL (Figure 1D–F). With the increase of water, litters decomposition rate was increasingly manifested as follows: GL > SL > PF > CF (Figure 1D–F). The LC changed regularly in the lower water stage, and the SL and CF showed an increasing trend, while the GL and PF showed an increasing trend and then a decreasing trend (Figure 2). However, in the medium water and higher water, except for the steady change in PF, the LC showed irregular changes and that of the SL had the largest change range (Figure 2A–C). The overall variation trend of LN was stable during decomposition (Figure 2D–F). The LC: LN of GL was the highest among the four stages, followed by that of CF. The LC: LN of SL and PF changed steadily and had similar ratios (Figure 2G–I). Overall, the cellulose content decreased (Figure 2J–L; Table 1), and the lignin first increased and then stabilized (Figure 2M–O; Table 1). The cellulose content in grassland was higher, and the lignin content was the lowest (Figure 2).



Figure 2. Chemical properties of litter changed with decomposing time (months) in different restoration stages. Lower, medium, higher represent three different water gradients, respectively. LC: LN indicates the ratio of litter organic carbon to total nitrogen. GL, grassland; SL, shrubland; PF, pioneer forests; CF, climax forests. (A–C) represent the dynamics of litter organic carbon under lower water, medium water and higher water treatment, respectively; (D–F) represent the dynamics of litter total nitrogen under lower water, medium water and higher water treatment, respectively; (G–I) represent the dynamics of the ratio of litter organic carbon (LC) to litter total nitrogen (LN) under lower water, medium water and higher water treatment, respectively; (J–L) represent the dynamics of cellulose content under lower water, medium water and higher water treatment, respectively. (M–O) represent the dynamics of lignin content under lower water, medium water and higher water treatment, respectively. (M–O) represent the dynamics of lignin content under lower water, medium water and higher water treatment, respectively. (M–O) represent the dynamics of lignin content under lower water, medium water and higher water treatment, respectively. (M–O) represent the dynamics of lignin content under lower water, medium water and higher water treatment, respectively. All bars represent the mean \pm standard error.

Forests 2021 , 12, 1195	
10,0000 2021 , 12, 11,0	Table 1 Stepwise regression analysis of litter decomposition rate with litter properties

Vegetation Type	Equation	R^2	F
GL	$LC = 334.108 + 9.0460X - 0.6632X^2$	0.3189 ***	11.9390
SL	$LC = 264.2299 + 13.4820X - 0.4378X^2$	0.3877 ***	16.1432
PF	$LC = 326.8054 + 2.515X - 0.1620X^2$	0.02	0.5216
CF	$LC = 382.8769 - 6.7872X + 0.3938X^2$	0.1646 *	5.0227
GL	$LN = 1.0444 - 0.0473X + 0.004X^2$	0.4652 ***	22.1829
SL	$LN = 2.1413 - 0.0542X + 0.0027X^2$	0.0747	2.0582
PF	LN = 1.6307 + 0.0109X	0.0565	3.1158
CF	LN = 1.1645 + 0.0123X	0.0936 *	5.3700
GL	$LC:LN = 319.8364 + 27.9883X - 2.1552X^2$	0.4298 ***	19.2200
SL	LC:LN = 140.6932 + 4.4725X	0.2343 ***	15.9100
PF	LC:LN = 209.1411 - 1.5415X	0.0667	3.7163
CF	$LC:LN = 366.5378 - 19.9371X + 0.9920X^2$	0.3207 ***	12.0394
GL	$Cellulose = 246.1229 - 1.5756X - 0.1910X^2$	0.2342 ***	5.3508
SL	Cellulose = 253.3808 - 5.4886X	0.3415 ***	24.8911
PF	$Cellulose = 252.1429 - 7.7153X + 0.1690X^2$	0.3371 ***	12.7149
CF	$Cellulose = 252.1429 - 3.6091X - 0.0903X^2$	0.2906 ***	10.2428
GL	Lignin = 159.9363 + 7.3713X	0.4216 ***	26.2382
SL	$Lignin = 159.7506 + 17.1866X - 0.5830X^2$	0.4489 ***	19.1421
PF	$Lignin = 130.5952 + 26.8986X - 1.2207X^2$	0.5156 ***	26.6058
CF	$Lignin = 116.9031 + 26.8906X - 1.0978X^2$	0.6808 ***	53.3160

X: decomposition time (month), LC: litter carbon, LN: litter nitrogen. * p < 0.05; *** p < 0.001. GL, grassland; SL, shrubland; PF, pioneer forests; CF, climax forests.

3.3. Effects of Factors on Leaf Litter Decomposition

Two-way ANOVA showed that vegetation type and soil moisture had significant effects on LC, LN, cellulose: LN, and lignin: LN (p < 0.001). However, the combination of the type of vegetation and soil water content had a significant effect on only LC (Table 2, p < 0.001). From the RDA results, the interpretation rate of GL and PF was higher in comparison, and all four vegetation succession stages are positively correlated with lignin and lignin: LC under the influences of different soil moisture (Figure 3, p < 0.01).

Table 2. Multivariate analysis of variance of vegetation type and soil moisture and litter characteristics.

Treatments df	LC		LN		LC:LN		Cellulose: LC		Lignin: LC		Cellulose: LN		Lignin: LN		
	df	Mean Square	F	Mean Square	F	Mean Square	F	Mean Square	F	Mean Square	F	Mean Square	F	Mean Square	F
Vegetation type	3	28,929.99	30.20 ***	17.04	397.24 ***	747,116.66	266.27 ***	0.14	5.74 ***	0.16	5.12 **	108,014.26	48.98 ***	62,473.48	24.25 ***
Soil moisture	2	9067.13	9.47 ***	0.56	12.96 ***	30,009.85	10.70 ***	0.03	1.11	0.01	0.16	8775.18	3.98 *	27,263.86	10.58 ***
Vegetation type × Soil moisture	6	6077.91	6.35 ***	0.01	0.30	1210.64	0.43	0.05	2.02	0.03	0.81	1967.88	0.89	3938.45	1.53

LC: litter carbon, LN: litter nitrogen; * *p* < 0.05; ** *p* < 0.01; *** *p* < 0.001.



Figure 3. Redundancy analysis of vegetation litter decomposition rate and related factors of vegetation and soil under different soil water. (**A–D**) represent the relationship between litter decomposition rate and plant, soil physicochemical properties under lower water (W1), medium water (W2) and higher water (W3) treatments of the four types vegetation (GL, SL, PF and CF), respectively. SOC: soil organic carbon, TN: total nitrogen, MBN: microbial biomass nitrogen, MBC: microbial biomass carbon, DOC: dissolved organic carbon, DON: dissolved organic nitrogen, NH₄⁺: ammonium nitrogen, NO₃⁻: nitrate nitrogen, LC: litter carbon, LN: litter nitrogen. GL, grassland; SL, shrubland; PF, pioneer forests; CF, climax forests.

4. Discussion

4.1. Interactions of Vegetation Type and Soil Moisture on Leaf Litter Quality

Soil moisture could regulate litters quality loss [34]. In this study, the LC concentration decreased slightly with increasing soil water content (Figure 2A–C), and the most obvious reduction was in the stage of SL. Among them, in a water-deficient environment, and litter decomposes slowly [35,36]. With the increase in water content, insoluble substances will decompose accordingly, which will result in a higher litter decomposition rate, leading to the accelerated decomposition of LC and the decrease in LC concentration [36–38].

The vegetation community structure and composition changed significantly during the succession process [39], and changes in litter properties showed diverse patterns [9]. For example, although our results showed that the LC concentrations decreased with decomposition, the LN concentrations of GL, SL, PF, and CF tended to be stable during decomposition, and the concentrations of different recovery stages were as follows: SL > PF > CF > GL (Figure 2D–F). The difference between them did not change with the change in soil water content, which was contrary to the results of Montané, et al. [40] and Zhang, et al. [41]. The leaf litter of SL usually contained a high N concentration (Figure 2D–F), which is a nutrient resource that is easily accessible by microorganisms [42] and litter decomposition rate may be faster than other vegetation types. It shows that litter nutrient conditions, GL litter decomposed faster than the litter of forest restoration stages (Figure 1), which may be because secondary compounds (such as lignin) are less abundant in the litter of GL [44]. Compared to other recovery stages, the GL had the highest LC: LN (Figure 2G–I) and the fastest decomposition, which was consistent with the results of

other studies; that is, the unstable C source in the litter may accelerate quality loss [45]. SL had a higher N concentration and a lower LC: LN ratio; thus, the decomposition rate was slower (Figure 1D–F and Figure 2G–I). In addition, the results indicated that cellulose and lignin material affected litters decomposition through quick leaching from litter as the soil water content increased (Figure 2M–O) [46]. This may be due to a corresponding increase in microbial decomposition activity as soil moisture increases, promoting the uptake and conversion of nutrients from litter [46,47].

4.2. Interactions of Vegetation Type and Soil Moisture on Leaf Litter Decomposition

The early stages of litter decomposition were primarily rapid physical leaching processes [48], in which water soluble components and a small amount of unstable organic components were degraded [49,50]. In the later stages, the organic components (lignin and cellulose) were degraded [51]. The increase in soil moisture promoted the decomposition of litter (Figure 1D–F). Moreover, with the increase in soil moisture, the litter in early succession was faster than the litter in later vegetation (Figure 1) [52,53]. With the increase in soil moisture, the litter decomposition rate was increasingly manifested as follows: GL > SL > PF > CF (Figure 1D–F). This was consistent with the law of succession of vegetation. The higher the succession stage of vegetation, the more difficult litters are to decompose [38,54]. However, the mass loss of the two types of PF and CF litter were not affected by the soil moisture, indicating that the vegetation restoration stage itself may be the main controlling factor of decomposition (Table 2), and the different vegetation restoration stages and the related litter characteristics were significantly related [54].

Litters with lower LC: LN ratios decompose faster than litters with higher LC: LN ratios [24,55]. In this study, the LN of the SL litter was almost twice that of the GL and CF litter; however, the litter decomposition rate of SL was the lowest in the lower soil moisture treatment, and the rate rapidly increased in the late stage of the medium soil moisture and higher soil moisture treatments. This result may be related to the fact that SL itself is a nitrogen-fixing plant with high nitrogen-related properties [56], and the significant difference in the litter decomposition rates between different stages can be attributed to differences in litter quality [42,43]. Therefore, the variation in litter decomposition and its influencing factors during vegetation development was diverse and complex [11]. The differences between different vegetation may be due to the responsiveness and interaction with biotic or abiotic factors caused by vegetation succession [38].

4.3. Effect of Leaf Litter Quality on Litter Decomposition Rate under Vegetation Type and Soil Moisture

In this study, the fluctuations of LN and LC: LN during decomposition (Figure 2) did not have a significant effect on litter decomposition (Figure 4G–I), which showed that the rate of litter decomposition was independent of vegetation type and seemed to suggest that it was affected by the chemical properties of the litters rather than by the microscopic environment and determined the observed difference in decomposition rates [43,57]. A similar result was obtained at the same sites, it shows that litter decomposition rate was closely related to its own quality [58]. In addition, there was no significant difference in the litter decomposition rates between PF and CF (Figure 1). Wang, Yang, Yang, Xin, Qu, Zhao and Gao [15] provided evidence that a higher N concentration in the soil accelerated the first stage of decomposition but negatively affected the rate of decomposition of insoluble compounds; therefore, the difference in decomposition between PF and CF was small.



Figure 4. Correlation between LC, LN, LC: LN and litter decomposition rate. LC: litter carbon, LN: litter nitrogen. Lines not shown in the figure indicate no correlation (p > 0.05). GL, grassland; SL, shrubland; PF, pioneer forests; CF, climax forests. (**A–C**) represent the correlation between litter decomposition rate and LC under lower water, medium water, and higher water treatments, respectively; (**D–F**) represent the correlation between litter decomposition rate and LN under lower water, medium water, and higher water treatments, respectively; (**G–I**) represent the correlation between litter decomposition rate and LC: LN under lower water, medium water, and higher water treatments, respectively; (**G–I**) represent the correlation between litter decomposition rate and LC: LN under lower water, medium water, and higher water treatments, respectively.

Except for LC and LN, cellulose and lignin were more strongly related to litter decomposition (Figure 5), because cellulose and lignin content directly affect litter decay rate [59]. The litter decomposition could also be affected by affecting the biomass accumulation and the activity of extracellular enzymes of decomposers [60,61]. In addition, the decomposition rate of woody plant leaves was lower than that of herbs (Figure 1). Because herbs contain less lignin content (Figure 2M–O) [60,62]. It would limit decomposers growth and inhibit litter lignin degradation by microorganisms [12]. The difference in litter decomposition from different vegetation was driven by microorganisms that specialize in decomposing litter cellulose and lignin, and had the ability to degrade litter resources [59].

4.4. Effect of Soil Properties on Litter Decomposition Rate under Different Vegetation Types and Soil Moisture

Soil physico-chemistry properties play an important role in litter decomposition [63]. Among them, at the lower water level, soil NO₃⁻ had a significant positive effect on litter decomposition (Figure 3, Table 3, p < 0.01). This result indicated that there was nitrogen conversion between litter and soil, and litter decomposition was strongly correlated with the increase in NO₃⁻ [64,65]. The MBC and MBN had significant effects on litter decomposition only in the PF (Table 3, p < 0.05), but not in the GL and CF. This may be because specific microbial communities drive litter decomposition at different stages of recovery [21,66], because nutrients in litter are closely related to the soil microbial community [14,20]. The decomposition rate of SL was positively correlated with NH₄⁺ and NO₃⁻ only at the lower water level (Table 3, p < 0.01). It shows that both soil moisture and NH₄⁺, NO₃⁻ affect the litter decomposition and nutrient release [67,68]. The LC: LN of the SL was the lowest (Figure 2G–I), which may have been due to the biological nitrogen fixation of SL [56]. This



process can increase TN, and the related nitrogen-fixing enzyme activity will affect the reduction of LN [69].

Figure 5. Correlation between cellulose, lignin and litter decomposition rate. LC: litter carbon, LN: litter nitrogen. Lines not shown in the figure indicate no correlation (*p* > 0.05). GL, grassland; SL, shrubland; PF, pioneer forests; CF, climax forests. (**A–C**) represent the correlation between litter decomposition rate and cellulose under lower water, medium water, and higher water treatments, respectively; (**D–F**) represent the correlation between litter decomposition rate and lignin under lower water, medium water, and higher water, and higher water treatments, respectively; (**G–I**) represent the correlation between litter decomposition rate and cellulose: LC under lower water, medium water, and higher water treatments, respectively; (**M–O**) represent the correlation between litter decomposition rate and cellulose: LN under lower water, medium water, and higher water treatments, respectively; (**M–O**) represent the correlation between litter decomposition rate and lignin: LC under lower water, medium water, and higher water treatments, respectively; (**P–R**) represent the correlation between litter decomposition rate and lignin: LC under lower water, medium water, and higher water treatments, respectively; (**P–R**) represent the correlation between litter decomposition rate and lignin: LN under lower water, and higher water treatments, respectively.

Soil Moisture	Vegetation Types	Soil Properties									
Son Moisture		SOC	TN	NH_4^+	NO ₃ -	pН	MBC	MBN	DOC	DON	
Lower	GL	0.338	-0.153	0.527 *	0.684 **	0.453	0.082	0.014	0.714 **	0.324	
	SL	-0.304	-0.205	0.589 *	0.828 **	0.099	-0.026	0.224	0.411	0.563 *	
	PF	0.214	-0.297	0.197	0.913 **	0.521 *	0.789 **	0.661 **	-0.070	0.374	
	CF	0.040	-0.275	-0.204	0.872 **	0.072	0.315	0.405	0.575 *	0.784 **	
Medium	GL	-0.265	-0.303	0.681 **	0.860 **	0.431	-0.291	0.439	0.615 **	0.795 **	
	SL	-0.461	$^{-0.494}_{*}$	0.007	0.274	-0.232	-0.284	0.621 **	-0.118	0.312	
	PF	-0.170	-0.050	0.281	0.713 **	0.429	0.614 **	0.644 **	0.580 *	0.763 **	
	CF	0.155	0.078	-0.341	0.662 **	0.456	0.405	0.686 **	0.245	0.353	
Higher	GL	-0.783 **	-0.603 **	0.667 **	0.797 **	0.361	-0.386	0.467	0.730 **	0.767 **	
	SL	-0.477 *	-0.088	0.121	0.449	-0.293	-0.180	0.633 **	-0.056	0.475 *	
	PF	0.172	-0.651	0.460	0.644 **	0.388	0.179	0.560 *	0.180	0.743 **	
	CF	-0.234	0.286	-0.402	0.489 *	0.291	0.101	0.343	0.299	0.660 **	

Table 3. Correlation coefficient between litter decomposition rate and soil physico-chemical properties under the influence of vegetation type and soil moisture.

SOC: soil organic carbon, TN: total nitrogen, MBN: microbial biomass nitrogen, MBC: microbial biomass carbon, DOC: dissolved organic carbon, DON: dissolved organic nitrogen, NH_4^+ : ammonium nitrogen, NO_3^- : nitrate nitrogen. * p < 0.05; ** p < 0.01. GL, grassland; SL, shrubland; PF, pioneer forests; CF, climax forests.

At the medium water level, NO_3^- , DON and MBN (Table 3), which play a major role in litter decomposition, indicated that the turnover of N concentration and microbial biomass was closely related to the rate of litter decomposition [70,71]. Moreover, the suitability of water improved the availability of soil nutrients and provided sufficient nutrients for the growth of microorganisms, which in turn stimulated the growth of microorganisms and accelerated litter decomposition [64]. At the high water level, DON was the common factor affecting litter decomposition (Tables 3 and 4). Moreover, there was a significant positive correlation between DON concentration in soil and litter decomposition rate (Figure 3), indicating that DON concentration was the controlling factor of litters decomposition (Table 4) [72].

Table 4. Stepwise regression analysis of litter decomposition rate with litter and soil physico-chemical properties.

Soil Moisture	Vegetation Type	Equation	R^2
Lower	GL	Mass loss = $0.856Cellulose:LC - 0.041$	0.733 ***
	SL	Mass loss = $0.819NO_3^ 0.041$	0.631 ***
	PF	Mass loss = $0.907NO_3^- + 0.057$	0.827 ***
	CF	Mass loss = $0.817MBC + 0.923DON - 0.356pH + 0.471$	0.958 ***
Medium	GL	Mass loss = $-0.305Cellulose + 0.774NO_3^{-} + 0.302$	0.927 ***
	SL	Mass loss = $-0.332SOC + 0.744DON + 0.653$	0.738 ***
	PF	Mass loss = 0.744DON + 0.345Lignin:LC + 0.343pH - 2.152	0.870 ***
	CF	Mass loss = $0.306MBN - 0.334NH_4^+ + 0.736Cellulose:LC - 0.142$	0.942 ***
Higher	GL	$Mass loss = -0.254SOC + 0.415DON + 0.562NO_3^{-} + 0.575$	0.967 ***
	SL	Mass loss = -0.18SOC + 0.277MBN - 0.246TN + 0.773DON + 1.884	0.948 ***
	PF	Mass loss = $0.645DON - 0.532TN + 0.802$	0.826 ***
	CF	Mass loss = $0.508DON + 0.511Lignin - 0.06$	0.674 ***

LC: litter carbon, NH₄⁺: ammonium nitrogen, NO₃⁻: nitrate nitrogen, MBN: microbial biomass nitrogen, MBC: microbial biomass carbon, DON: dissolved organic nitrogen, SOC: soil organic carbon, TN: total nitrogen. *** p < 0.001. GL, grassland; SL, shrubland; PF, pioneer forests; CF, climax forests.

In this study, litter decomposition of leaf was not affected by the SOC concentration (Table 3). These results were consistent with those of previous studies, which showed that the SOC concentration did not alter litter chemical changes [73,74]. Therefore, changes in litter decomposition were not very sensitive to changes in soil carbon pools because SOC was not a direct factor affecting litter decomposition. In summary, litter decomposition was more strongly correlated with the nitrogen NO_3^- , NH_4^+ , DON and MBN concentration, while it was weakly correlated with the carbon component [73,75]. In our study, the soil N element was the main factor that affected litters decomposition. With the increase in

soil moisture, nitrogen will promote the change of litter composition mechanism, and then transform to the direction of rapid decomposition [47,72].

5. Conclusions

Both soil moisture and vegetation types in different succession stages affect litter decomposition rate. And litter chemical properties regulate litter decomposition. Among them, the cellulose content is negatively correlated with litter decomposition, which inhibits litter decomposition; While lignin, lignin: LC, lignin: LN, soil NO₃⁻, DON and MBN can promote it. This indicates that vegetation types affect litter chemistry properties, which in turn affect litter decomposition rate.

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