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Effect of Soil Fauna on Home-Field Advantages of Litter Mass Loss and Nutrient Release in Different Temperate Broad-Leaved Forests

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Abstract: The home-field advantage (HFA) of litter decomposition dynamics has been investigated intensively in different ecosystems with a wide variety of plant types. HFA mainly occurs due to the specialization of a soil organism. However, for the HFA, the linkages between litter mass loss, nutrient release, and soil faunal community are not fully understood. Thus, in this study, we performed a reciprocal litter transplant experiment using coarse and fine mesh litterbags in a *Quercus mongolica* Fisch. ex Ledeb. forest dominated by *Q. mongolica* (QM) and *Acer pseudosieboldianum* (Pax) Komarov (AP) and miscellaneous wood forests dominated by *Juglans mandshurica* Maxim. (JM) and *Ulmus laciniat*a (Trautv.) Mayr. (UL). Results showed that the *A. pseudosieboldianum* litter displayed a significantly higher total abundance of Oribatida, Tomoceridae, and Entomobryidae at home than away from home after 7 months. However, all litters showed no significant difference in the HFA between the coarse mesh and fine mesh sizes during the 12-month experiment. *A. pseudosieboldianum* and *J. mandshurica* litters showed a significantly higher positive HFA for the C release in the coarse mesh than in the fine mesh litterbags after 7 months. *Q. mongolica* and *J. mandshurica* litters showed a significantly higher positive HFA for N release in the coarse mesh than in the fine mesh litterbags after 7 months. The *A. pseudosieboldianum* litter showed a significantly higher positive HFA for N release in the coarse mesh than in the fine mesh litterbags after 12 months. *Q. mongolica* and *A. pseudosieboldianum* litters showed a significantly higher positive HFA for S release in the coarse mesh than in the fine mesh litterbags after 7 and 12 months, respectively. However, *A. pseudosieboldianum* and *Q. mongolica* litters showed a significantly higher negative HFA for S release in the coarse mesh than in the fine mesh litterbags after 7 and 12 months, respectively. Our results illustrated that soil faunal specialization was found in the *A. pseudosieboldianum* litter only at home after 7 months. Soil fauna had a weak effect on the HFA of the litter mass losses during the 12-month experiment. Soil fauna drove the positive HFA for the N release of both the high- and low-quality litters. Soil fauna have a positive and negative HFA for S release in the low-quality litter.

Keywords: home-field advantage (HFA); litter mass loss; nutrient release; soil fauna; temperate broad-leaved forest

1. Introduction

Litter decomposition is one of the most important pathways in the energy transformation and material cycles of terrestrial ecosystems [1]. Recent studies suggest that leaf litters tend to decompose more rapidly in the habitats from which they were derived (i.e., home) than in other habitats (i.e., away from home). This phenomenon has been termed the home-field advantage (HFA) of litter

decomposition [2]. The HFA of litter decomposition dynamics has been investigated intensively in different ecosystems with a wide variety of plant types [3–5].

Numerous studies have shown the widespread persistence of positive HFAs on litter decomposition [2,6–8]. In contrast, there is a lack of a home-field advantage in the decomposition of leaf litters in the Atlantic rainforest of Brazil [9]. Previous studies documented that the lack of an HFA may cause rapid shifts in the composition of local microbial communities in response to the local litter quality. No 'home' versus 'away' effects for decomposition were found in the grassland–forest reciprocal litter transplant study [10]. It is believed that decomposition is positively related to litter quality (grass > tree) and habitat microclimates. Overall, it has been suggested that the complexity of the drivers of the environment, litter quality, and soil organisms affect the HFA for litter decomposition. More experiments are needed to elucidate the driving mechanism for the HFA of litter decomposition, especially research on the negative effects of HFA.

Soil fauna play an important role in the process of litter decomposition, as they not only break down, consume, and digest the litter [11–15], but also stimulate microbial activity [16]. Soil fauna decompose more litter in the same habitat than in other habitats. This is called the specialization of soil fauna. The observed effects of the HFA mainly occur due to the specialization of a soil organism when the decomposition of the litter results at the origin of that litter [2,17]. For instance, the adjustability of soil microorganisms may have weakening effects on the HFA, and the late entry of soil fauna can potentially lead to different HFA intensities [18]. In addition, the specialization of soil fauna require favorable environmental factors, such as illumination, temperature, and moisture, which lead to differences in the HFA. Water, rather than temperature, impacts the effects of fauna on the carbon and nitrogen release from fresh litters during early litter decomposition [19]. For the HFA, the linkages between litter mass loss, nutrient release, and the soil's faunal community are not fully understood in temperate forest ecosystems.

In order to better understand the dynamic changes of the HFA and the specialization of soil fauna during decomposition in temperate broad-leaved forest ecosystems, a litterbag decomposition experiment in a *Quercus mongolica* forest and a miscellaneous wood forest of Longwan National Nature Reserve was conducted. We hypothesized that: (1) If the soil fauna have specialization in the decomposition of their litters, they come from different tree species, and (2) home vs. away can affect litter mass loss and nutrient release due to soil fauna activity.

2. Materials and Methods

2.1. Site Description

The experiment was carried out in the Longwan National Nature Reserve, located in the middle of the Longgang Mountains, which is the northern foot of Changbai Mountain (42°16′20″ N–42°26′57″ N, 126°13′55″ E–126°32′02″ E), Jilin province, China. The elevation of the study area was 770 m above sea level. The climate was a northern temperate continental monsoon, with a mean annual temperature of 4.1 °C and averaging −18 °C in January and 22.4 °C in July. The mean number of snow-cover days was 110–120 per year. The mean annual precipitation was approximately 700 mm. The low mountains and hills are covered by a *Quercus mongolica* forest (771 m above sea level) and miscellaneous wood forests (770 m above sea level). The dominant tree species of the *Q. mongolica* forest site was found to be *Q. mongolica* (coverage 70%), whereas the remainder was dominated by the shrub species *Acer pseudosieboldianum* (coverage 60%). The dominant tree species of the miscellaneous wood forest site were found to be *Juglans mandshurica* (coverage 50%) and *Ulmus laciniat*a (coverage 30%). The soil was dark brown forest soil. The topsoil (0–10 cm) contained approximately 88.19 g/kg C and with a pH of 6.39 in the *Q. mongolica* forest, and 170.85 g/kg C and with a pH of 5.94 in the miscellaneous wood forest.

2.2. Experimental Set Up

The leaf litters were collected with nets during the peak litter-fall period in September 2016. The litters of *Q. mongolica* (QM) and *A. pseudosieboldianum* (AP) were collected from the *Q. mongolica* forest floor, and *J. mandshurica* (JM) and *U. laciniata* (UL) were collected from the miscellaneous wood forest floor. The litters were freshly fallen and fully intact. All of the litters were cleaned with careful and gentle brushing and then dried at room temperature. According to the cross-sectional diameter of the soil fauna [20], the sizes of the soil macrofauna, mesofauna, and microfauna were all greater than 0.01 mm. Therefore, two mesh sizes of the nylon litterbags (15 cm × 20 cm) were chosen. We used a fine mesh of 0.01 mm in size, which allowed microbial activity only, and a coarse mesh of 4 mm in size, which allowed most soil faunal species to be active in the bags. Each litterbag was filled with 10 g (±0.01 g) of air-dried leaf litter. In order to avoid breakage of the leaf litter during filling, the litter was moistened with distilled water before the bags were sealed. The remaining litter was oven-dried at 60 °C until they reached a consistent mass to measure the initial dry mass and the initial chemical analyses. For the initial chemical analyses, the total carbon (TC), total nitrogen (TN), and total sulfur (TS) were analyzed using an elemental analyzer (Elemental Vario-MACRO Cube, Germany). While TC and TN are common analytes for litter quality, we also chose to measure TS because sulfur has been shown to enhance decomposition rates [21].

In October 2016, three 2 × 2 m plots were randomly selected at the field sites (the *Q. mongolica* forest site and miscellaneous wood forest site), with a 10 m distance separating the plots. The site was relatively flat, with a limited spatial variation in soil moisture content. Within each plot, an evenly spaced 3 row × 4 column sampling grid was erected, and a 0.01 mm and a 4 mm litterbag of each litter type was placed at each sampling point along the grid. Each plot had twelve coarse mesh size litterbags, and twelve fine mesh size litterbags, which contained the 4 litter types. A total of 144 litterbags (4 litter types × 2 mesh sizes × 3 plots × 3 sampling periods × 2 sites) were placed in the *Q. mongolica* forest site and the miscellaneous wood forest site. In each plot, the litterbags were placed on the soil surface. At the same time, one iButton (DS 1923) was putted in a random litterbag to measure the litter decomposition's temperature and moisture.

The 144 litterbags in each of the three rows were sampled 7, 9, and 12 months after field placement. On every sampling date, the litterbags were handled with great care during the removal process, and each bag was carefully transported in a separate plastic bag to minimize the loss of any small litter fragments from the litterbags. At the same time, the litterbag with the iButton (DS 1923) was retrieved from each plot. The contents of the litterbags with a coarse mesh size were placed in Tullgren extractors for 24 hours in order to remove the soil fauna from the bags using the method [22]. All extracted soil fauna were preserved in 75% ethanol and identified at the order or family level. The extracted soil fauna were counted by a stereomicroscope Olymps and their taxonomic groups were identified [23]. All leaves were oven-dried at 60 °C to a constant mass and then weighed. For each of the sampling dates, the total C, N, and S concentrations in the remaining litter material were analyzed, as described above.

2.3. Statistical Analyses

The decomposition rate was expressed as the percentage of litter mass loss, as follows: Decomposition rate (%) = $((W_0 - Wt)/W_0) \times 100$, where W_0 is the initial oven dry mass of the litter and W_t represents the oven dry mass of the decomposed leaf litter at time t.

The amount of nutrient release (%) was calculated as $((C_0M_0 - C_tM_t)/(C_0M_0)) \times 100$, where M_t represents the oven dry mass of the decomposed leaf litter at time t; M_0 is the initial oven dry mass of the litter; C_0 is the initial concentration of the nutrients; and C_t is the concentration of the nutrients at sampling time *t*. Positive values indicate net mineralization, and negative values indicate net immobilization.

Mann–Whitney two-sample *U* tests were employed to determine the differences in the litter temperature and moisture between *Q. mongolica* and the miscellaneous wood forest site for the same

month. Paired *t* tests were used to determine the differences in the ADH of the litter mass loss and the C, N, and S release between the coarse mesh and fine mesh litterbags within the same litter types. Paired *t* tests were conducted again to determine the differences in the abundance of soil fauna between the home and away from home within the same litter types. The effects of litter types, home vs. away, sampling period, and their interactions with the litter mass loss and C, N, and S release were analyzed using a repeated measures ANOVA. A one-way ANOVA and a post-hoc test of least-significant difference (LSD) were employed to determine the significance of the difference in the litter mass loss and C, N, and S release among the home-coarse mesh, home-fine mesh, away-coarse mesh, and away-fine mesh litter bags for the same experimental periods. A one-way ANOVA and a post-hoc test of least-significant difference (LSD) were conducted again, in order to determine the significance of the difference in the ADH of the litter mass loss and the C, N, and S release between the litter types for the same experimental periods. The data were transformed by a natural log and square root, for the purpose of meeting the assumptions of normal distribution and a homogeneity of variance. These statistical analyses were performed using the SPSS software (SPSS 22.0).

The response of the soil faunal community to the litter's physicochemical properties (litter mass losses, release of C, N, and S, C/N ratio, C/S ratio, and N/S ratio) were investigated using the redundancy analysis (RDA) (length of gradient < 3 for soil faunal community variables), which utilized CANOCO for Windows 5.0 [24]. The abundance was transformed (log (X + 1)) in order to ensure the normality and down-weight extreme values. It was observed that there were no obvious outliers, and all data were included in the analyses.

To quantify litter decomposition's HFA, we used a set of calculations provided by [2,25], which measure the additional decomposition at home (ADH) for each litter type, with a positive value for ADH indicating a HFA (home-field advantage) and a negative value for ADH indicating a HFD (home-field disadvantage (i.e., s negative HFA)):

$$ADH_{a1-1} = \frac{HDD_{a1-1} - ADD_{a1} - H}{N-2} \quad (1)$$

where HDD is the home decomposition difference, ADD is the away decomposition difference, H is the mean home performance for all litter types, and N is the total number of litter types. Lower-case letters indicate different litter types (e.g., a1 = litter types sampled on site A1), and upper-case letters indicate the site on which the litter types are decomposed (e.g., D_{a3A1} = decomposition of litter types a3 on site A1).

$$HDD_{a1\text{-}1} = (D_{a1\text{-}1A1} - D_{a2A1}) + (D_{a1\text{-}1A1} - D_{a3A1}) + \ldots + (D_{a1\text{-}1A1} - D_{f3A1}). \quad (2)$$

HDD is calculated as the sum of the differences between the mass loss and the nutrient release of a certain litter type on its home site and all other litter types on the home site of that certain litter type.

$$ADD_{a1} = (D_{a1A2} - D_{a2A2}) + (D_{a1A3} - D_{a3A3}) + \ldots + (D_{a1F3} - D_{f3F3}). \quad (3)$$

ADD is the sum of the differences between the mass loss and nutrient release of a certain litter type on its away sites and the mass loss and nutrient release of the litter types associated with these sites.

$$H = \frac{HDD_{a1-1} + HDD_{a1-2} + HDD_{a1-3} + \cdots + HDD_{f3-3}}{N-1}. \quad (4)$$

H is calculated as the sum of the HDD for all litter types divided by the number of litter types minus one.

3. Results

3.1. Litter Mass Losses and HFA

The results of the repeated-measures ANOVA indicated that the litter mass loss rates had significantly responded to litter types (LT); mesh sizes (MS); sampling periods (SP); interactions between the litter types (LT) and mesh sizes (MS); and interactions between the litter types (LT) and sampling periods (SP), as detailed in Table 1.

Table 1. Results of a repeated measures ANOVA on the effects of litter types (LT), home vs. away (HA), mesh size (MS), sampling period (SP), their activities in litter mass loss, and C, N, and S release. Statistically significant ($p < 0.05$) results are shown in bold.

Source of Variance	df	Mass Loss		C Release		N Release		S Release	
		F	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Between subjects									
Litter types (LT)	3	49.36	<0.001	95.04	<0.001	40.33	<0.001	33.07	<0.001
Home vs. away (HA)	1	0.20	0.655	0.07	0.801	23.35	<0.001	0.04	0.853
Mesh size (MS)	1	35.84	<0.001	86.53	<0.001	0.57	0.455	5.38	0.027
LT × HA	3	1.21	0.321	1.74	0.178	3.06	0.042	4.60	0.009
LT × MS	3	7.80	<0.001	8.60	<0.001	5.56	0.003	19.44	<0.001
HA × MS	1	0.60	0.808	0.46	0.501	6.12	0.019	8.69	0.006
LT × HA × MS	3	1.24	0.310	0.71	0.554	9.41	<0.001	2.07	0.124
Within subjects									
Sampling period (SP)	2	217.44	<0.001	308.61	<0.001	24.85	<0.001	28.47	<0.001
SP × LT	6	8.19	<0.001	8.72	<0.001	19.83	<0.001	45.26	<0.001
SP × HA	2	1.18	0.304	4.50	0.026	14.87	<0.001	3.46	0.037
SP × MS	2	2.50	0.107	10.52	<0.001	2.65	0.096	6.47	0.003
SP × LT × HA	6	0.63	0.659	3.45	0.013	5.93	<0.001	24.77	<0.001
SP × LT × MS	6	1.67	0.166	1.57	0.193	9.62	<0.001	6.28	<0.001
SP × HA × MS	2	0.85	0.404	2.88	0.081	15.00	<0.001	3.96	0.024
SP × LT × HA × MS	6	0.46	0.780	0.45	0.786	1798	<0.001	17.52	<0.001

It was observed that, whether at home or away, the *U. laciniata* litter displayed significantly higher mass loss in the coarse mesh litterbags during the 12-month experiment ($p = 0.013$; $p = 0.034$; $p = 0.001$); the *J. mandshurica* litter, after 9 months ($p = 0.027$), was compared with the fine mesh litterbags. In addition, the *U. laciniata* litter displayed a significantly higher mass loss in the coarse mesh litterbags at home after 7 months ($p = 0.013$) when compared with the away from home litterbags, as shown in Figure 1.

The changes in the ADH of litter mass loss over the 12 months experiment are presented in Figure 2. A positive ADH was observed in the *Q. mongolica* litter in the fine mesh litterbags, the *A. pseudosieboldianum* litter in the coarse mesh litterbags, and in the *U. laciniata* litter for both mesh sizes after 7 and 12 months. After 9 months, however, a weakly positive ADH was only found in *Q. mongolica* in the fine mesh litterbags and the *A. pseudosieboldianum* litter in the coarse mesh litterbags. The positive ADH of the litter mass loss indicated HFA. Additionally, the *A. pseudosieboldianum* and *U. laciniata* litters displayed a significantly higher ADH than the *Q. mongolica* and *J. mandshurica* litters in the coarse mesh litterbags after 7 months ($p = 0.042$). However, all litters showed no significant difference on their ADH between the coarse mesh and fine mesh litterbags during the 12-month experiment (Figure 2).

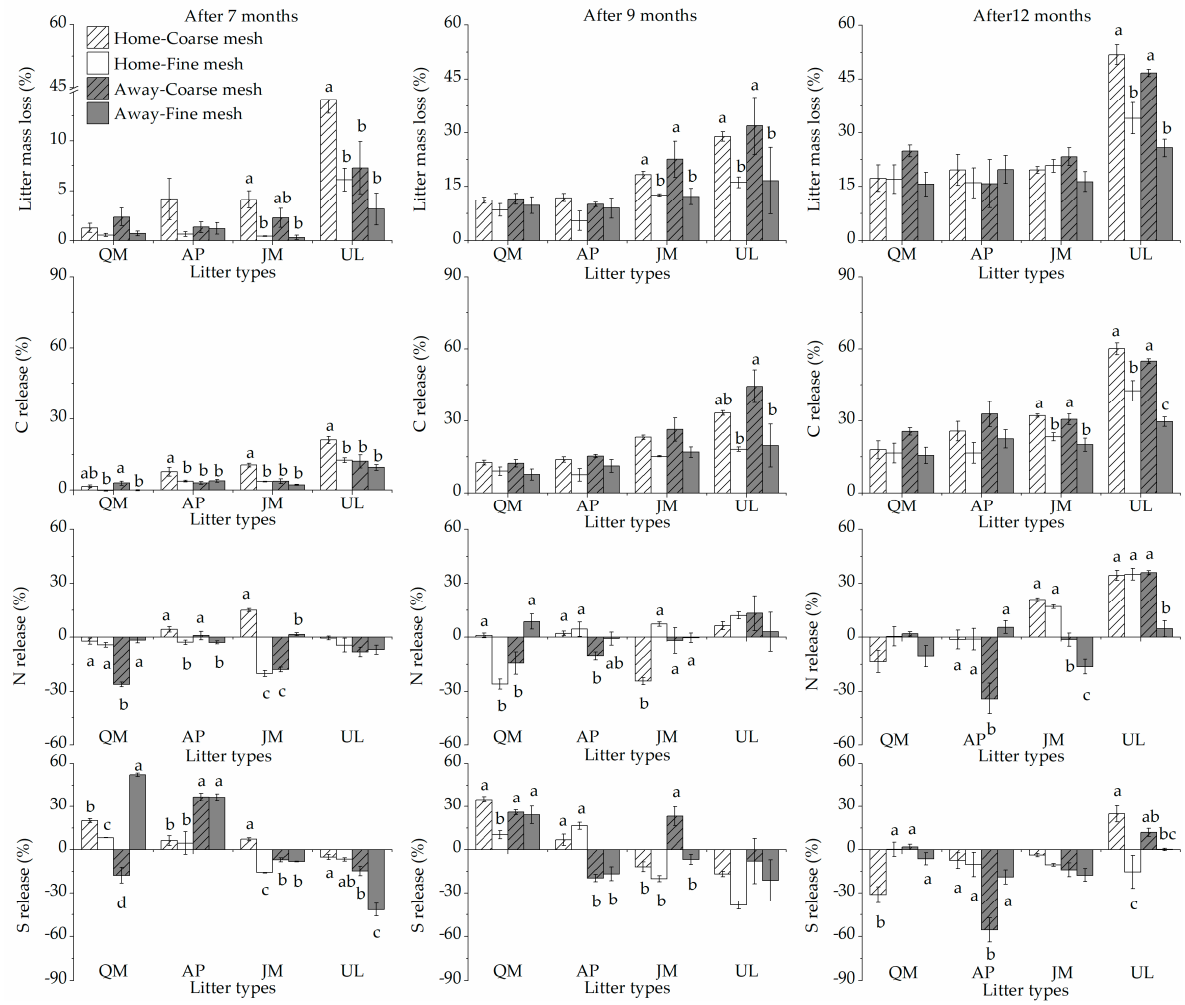

Figure 1. Mean litter mass loss and nutrient release of different litter types during the experimental period. Values are the mean ± SE (n = 3). Lowercase letters indicate significant differences among the home-coarse mesh, home-fine mesh, away-coarse mesh, and away-fine mesh litterbags within the same litter types in the same experimental periods.

3.2. Litter Nutrient Release and HFA

The results of the repeated ANOVA indicated that the release C, N, and S significantly responded to litter types; sampling periods; interactions between the litter types and mesh sizes; interactions between the sampling periods and litter types; sampling periods and home vs. away; and the interactions among the sampling periods, litter types, and home vs. away, as detailed in Table 1. It could also be seen from the repeated ANOVA results that the releases of N and S significantly responded to interactions between the litter types and home vs. away; the interactions among the sampling periods, litter types, and mesh sizes; sampling periods, home versus away, and mesh sizes; and interactions among the sampling periods, litter types, home versus away, and mesh sizes (Table 1).

The changes in the release (or mineralization) of C, N, and S over the 12-month experiment, in comparison with the initial values, are presented in Figure 1. It was determined that whether at home or away, C release was found in all litters during the 12-month experiment. It was observed that, whether at home or away, the *J. mandshurica* and *U. laciniata* litters had a significantly higher C release in their coarse mesh litterbags after 12 months (p = 0.007; p = 0.001), when compared with the fine meshlitterbags. It was determined that the *A. pseudosieboldianum*, *J. mandshurica*, and *U. laciniata* litters had a significantly higher C release in their coarse mesh litterbags under at home than away from home by the seventh month of the experiment (p = 0.048; p = 0.001; p = 0.008), as shown in Figure 1.

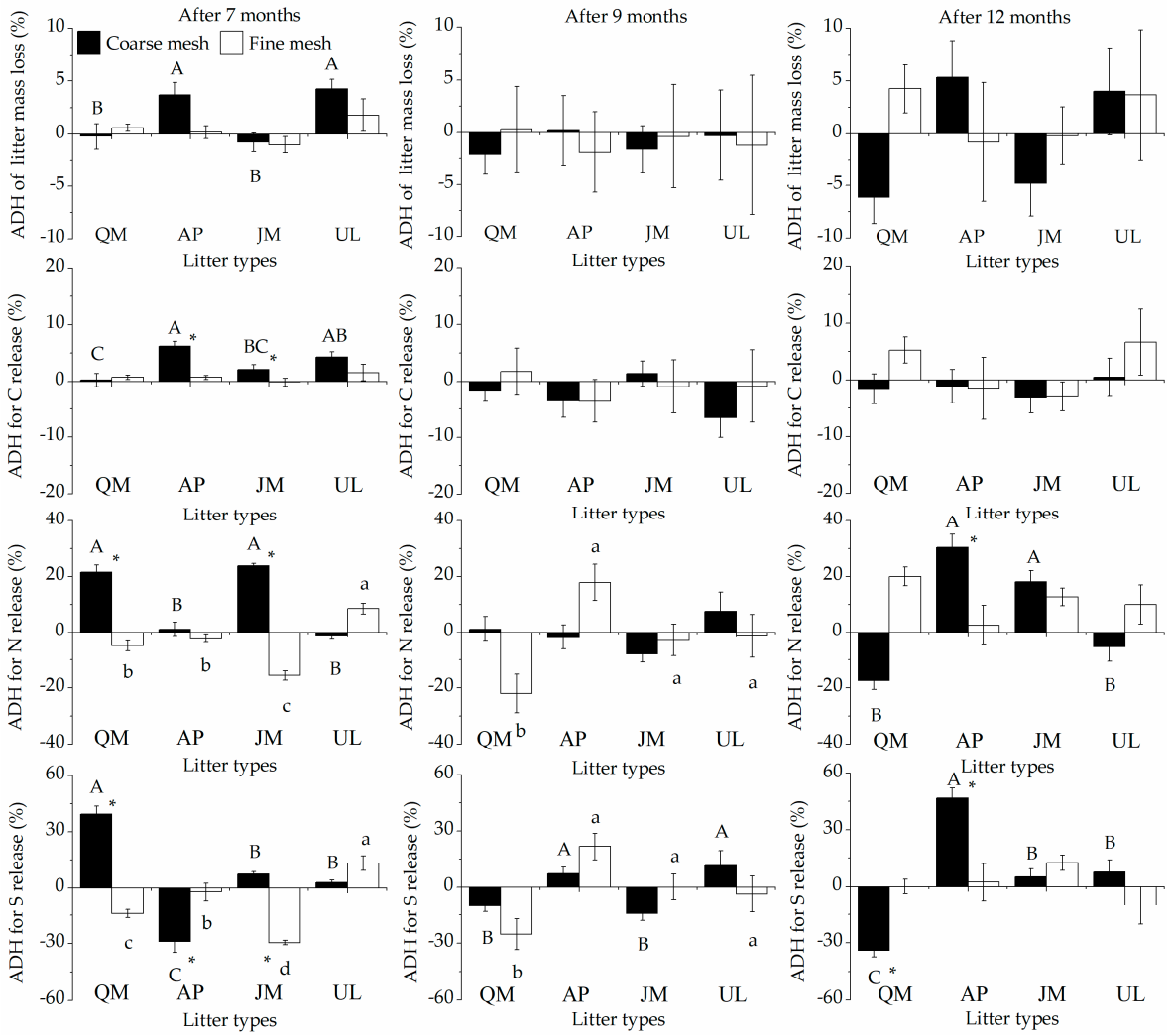

Figure 2. Mean additional decomposition at home (ADH) of different litter types during the experimental period. Values are the mean ± SE (n = 3). The asterisk indicates significant differences between the coarse mesh and fine mesh sizes within the same litter types. Different uppercase letters indicate significant differences among litter types in the coarse mesh litterbags within the same experimental period ($p < 0.05$). Different lowercase letters indicate significant differences among the litter types in the fine mesh litterbags within the same experimental period ($p < 0.05$).

Whether home or away from home, N accumulation (or immobilization) was found in *Q. mongolica* and *U. laciniata* litters for both mesh sizes after 7 months. However, N release was found in *U. laciniata* litter, for both mesh sizes, after 9 and 12 months, as shown in Figure 1. In addition, the *J. mandshurica* litter showed significantly higher N accumulations in its coarse mesh litterbags at home than away from home at month 9 of the experiment (p = 0.003). However, the *Q. mongolica* litter showed significantly lower N accumulations in its coarse mesh litterbags at home at month 7 of the experiment (p = 0.001), the *A. pseudosieboldianum* litter at month 12 of the experiment (p = 0.008), when compared with the away from home litter, as shown in Figure 1.

S accumulation (or immobilization) was found in the *U. laciniata* litter after 7 and 9 months and in the *A. pseudosieboldianum* and *J. mandshurica* litters after 12 months, for both the at home and away from home groups. However, S release was found in the *A. pseudosieboldianum* litter after 7 months and in the *Q. mongolica* litter after 9 months, as shown in Figure 1. The *U. laciniata* litter displayed significantly lower S accumulations in its coarse mesh litterbags at home after 7 months (p = 0.001) and in the *A. pseudosieboldianum* litter after 12 months (p = 0.004), when compared to the away from home

group. In addition, the *A. pseudosieboldianum* litter showed significantly lower S release in its coarse mesh litterbags at home than away from home after 7 months ($p = 0.001$), as shown in Figure 1.

The changes in the ADH of the litter nutrient release over the 12 months of the experiment are presented in Figure 2. The *A. pseudosieboldianum* and *U. laciniata* litters showed a significantly positive ADH for C release than the *Q. mongolica* litter in the coarse mesh litterbags after 7 months ($p = 0.012$). In addition, the *A. pseudosieboldianum* and *J. mandshurica* litters showed significantly higher ADH for the C release in their coarse mesh than fine mesh litterbags after 7 months ($p = 0.038$; $p = 0.021$). After 9 and 12 months, all litters showed no significant difference in the ADH between their coarse mesh and fine mesh sizes (Figure 2).

The *Q. mongolica* and *J. mandshurica* litters showed a significantly positive ADH for N release than *A. pseudosieboldianum* and *U. laciniata* litters in the coarse mesh litterbags after 7 months ($p < 0.001$). In addition, the *Q. mongolica* and *J. mandshurica* litters showed a significantly higher ADH for N release in their coarse mesh than fine mesh litterbags after 7 months ($p = 0.029$; $p = 0.001$). However, the *Q. mongolica* and *U. laciniata* litters showed a significantly negative ADH for N release than the *A. pseudosieboldianum* and *J. mandshurica* litters in their coarse mesh litterbags after 12 months ($p < 0.001$). The negative ADH of the litter mass loss indicated a negative HFA. Moreover, the *Q. mongolica* and *A. pseudosieboldianum* litters had a significantly lower and higher ADH for the N release in their coarse mesh than fine mesh litterbags after 12 months ($p = 0.026$; $p = 0.037$) (Figure 2).

The *Q. mongolica* litter showed significantly positive and negative ADH for S release in the coarse mesh litterbags after 7 and 12 months, respectively ($p < 0.001$; $p < 0.001$). However, the *A. pseudosieboldianum* litter showed a negative and positive ADH for S release in the coarse mesh litterbags after 7 and 12 months, respectively ($p = 0.003$; $p < 0.001$). In addition, the *Q. mongolica* and *A. pseudosieboldianum* litters showed a significant difference in the ADH for S release between the coarse mesh and fine mesh litterbags after 7 and 12 months ($p = 0.003$; $p = 0.037$) (Figure 2).

3.3. Soil Fauna Community Composition and Diversity

During the experiment, a total of 27 groups of soil fauna were collected and identified, as shown in Table S2. Entomobryidae, Tomoceridae, and Oribatida were the most dominant groups in all litter types whether at home or away from home. Sminthuridae and Onychiuridae were dominant as well in the *A. pseudosieboldianum* and *J. mandshurica* litters at home, respectively. The dominant groups accounted for 62.54%–92.26% of the total abundance of soil fauna across all litter types. The total abundance of soil fauna was higher at home when compared with those away from home in the *Q. mongolica*, *A. pseudosieboldianum*, and *J. mandshurica* litters.

The *A. pseudosieboldianum* litter displayed a significantly higher total abundance ($p = 0.011$) of Oribatida ($p = 0.032$), Tomoceridae ($p = 0.003$), and Entomobryidae ($p = 0.021$) at home, when compared with the values away from home at month 7 of the experiment (Figure 3). However, an exception was noted in that the abundance of the Oribatida of the *J. mandshurica* ($p = 0.040$) and *U. laciniata* ($p = 0.013$) litters at month 7 of the experiment. In addition, the *A. pseudosieboldianum* litter showed a higher abundance of soil fauna abundance of Oribatida ($p = 0.047$), Tomoceridae ($p = 0.008$), and Entomobryidae ($p = 0.002$) than that of other litter types at home at month 7 of the experiment. Whether home or away from home, the abundance of Tomoceridae and Entomobryidae increased significantly in all litters after 9 months of the experiment (Figure 3). The abundance of Onychiuridae increased significantly in the *J. mandshurica* litter at home at month 12 of the experiment (Figure 3).

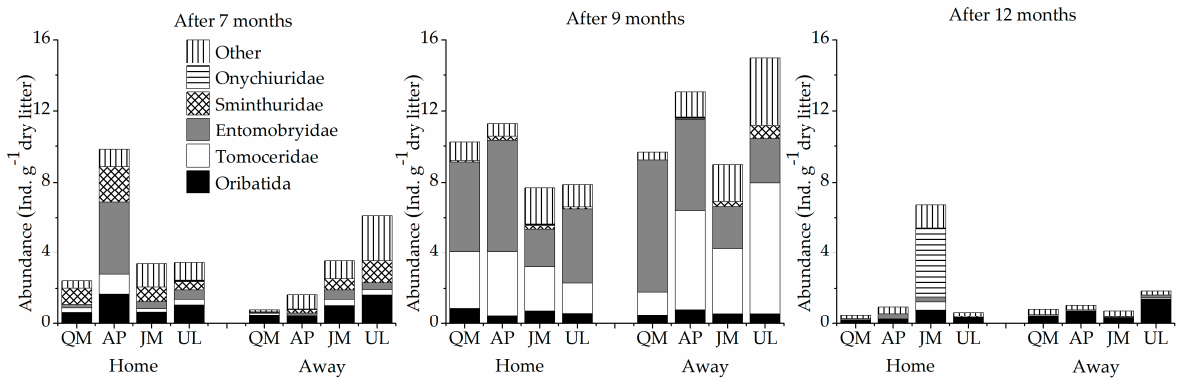

Figure 3. Abundance dynamics of soil fauna of different litter types during the experimental period.

3.4. Relationships between Soil Fauna, Litter Mass Loss, and Nutrient Release

The redundancy analysis (RDA) showed that in the *Q. mongolica* forest, the first two axes captured 88.98% of the variability of the soil faunal communities, whereas RDA1 (the x-axis) and RDA2 (the y-axis) accounted for 36.95% and 12.24% of the variation, respectively (Figure 4a). After 9 months, a positive relationship was observed between the soil fauna assemblage and S release in the *Q. mongolica* litter. A positive relationship also was observed between the soil fauna assemblage and C release in the *U. laciniata* litters after 7 months. A positive relationship was observed between the soil fauna assemblage and the C/N ratio in the *Q. mongolica* and *A. pseudosieboldianum* litters after 7 months. Entomobryidae correlated positively with litter S release whereas Araneae and Sminthuridae positively correlated with litter C release and the C/N ratios, respectively. According to the RDA analysis, the S release, C/N ratio, and C release significantly affected the distribution of soil faunal communities (Figure 4a).

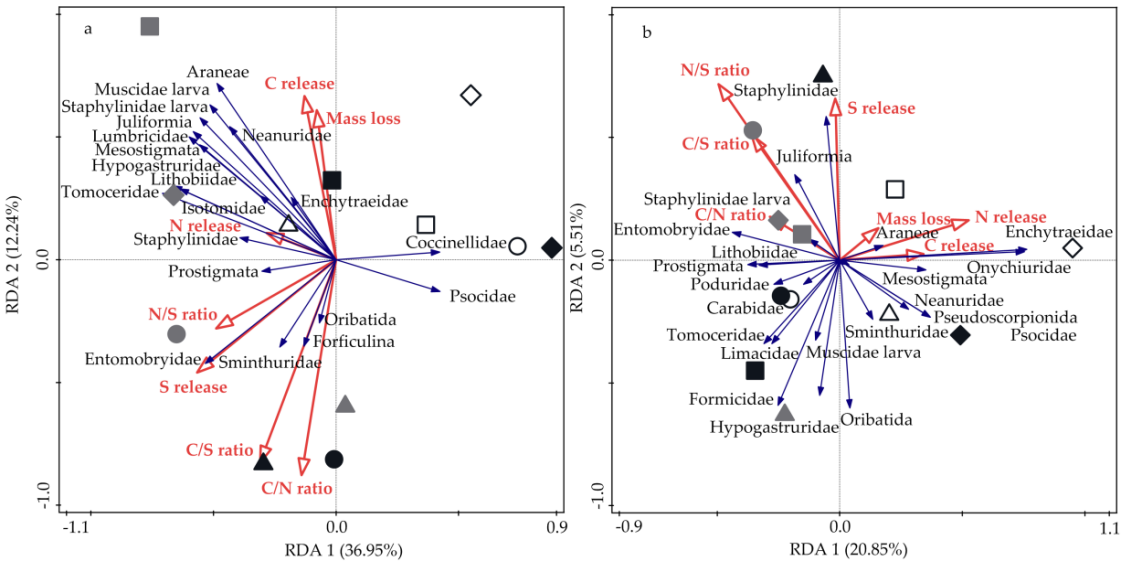

Figure 4. Redundancy analysis (RDA) results of the soil fauna community in association with litter physicochemical properties during the experimental period. Values are the means of different plots within the same experimental period (n = 3). a: *Quercus mongolica* forest habitat; b: miscellaneous wood forest habitat. The circle: *Q. mongolica* (QM); up triangle: *Acer pseudosieboldianum* (AP); diamond: *Juglans mandshurica* (JM); square: *Ulmus laciniata* (UL). Black: after 7 months; Gray: after 9 months; White: after 12 months.

In the miscellaneous wood forest, the first two axes captured 80.41% of the variability of the soil faunal communities, with 72.12% and 8.19% of the variation explained by RDA1 and RDA2, respectively

(Figure 4b). A positive relationship also was observed between the soil fauna assemblage and N/S ratio in the *Q. mongolica* litter after 9 months. A positive relationship was also observed between the soil fauna assemblage and N release in the *J. mandshurica* litter after 12 months. Staphylinidae correlated positively with litter N/S ratio, whereas Enchytraeidae and Onychiuridae correlated positively with litter N release. According to the RDA analysis, the N/S ratio and N release significantly affected the distribution of soil faunal communities (Figure 4b).

4. Discussion

4.1. Effects of Soil Fauna on the HFA of Litter Mass Losses

According to their C/N ratios and S concentrations, *Q. mongolica* and *A. pseudosieboldianum* were considered to be low quality litters (higher C/N ratios and less S), while *J. mandshurica* and *U. laciniata* were determined to be high quality litters (lower C/N ratios and greater S) (Table S1). It is suggested that a high-quality litter (lower C/N ratios) can be decomposed by almost all known decomposers, because no specific adaptations are necessary, and, therefore, HFA is unlikely under such circumstances. In contrast, a low-quality litter potentially contains recalcitrant or toxic compounds known to constrain decomposition; thus, HFA is likely under such circumstances [9,26]. In addition, the observed effects of the HFA mainly occur due to the specialization of the soil fauna when decomposition of the litter has occurred from its origin [2,18].

Indeed, the *A. pseudosieboldianum* litter showed a significantly higher total abundance in Entomobryidae, Sminthuridae, and Oribatida at home than away from home at month 7 of the experiment (Figure 3). Consequently, soil fauna showed a positive HFA for the litter mass losses. However, the *A. pseudosieboldianum* litter showed no significant difference for the ADH between the coarse mesh and fine mesh sizes after 7 months (Figure 2). For the same quantity of litter, the volume of the *A. pseudosieboldianum* litter is larger than that of the other litter. The litter only provides a better hiding place for soil fauna and then attracts more soil fauna than other litters. The food web of the soil fauna plays a fundamental role in the process of litter decomposition. Entomobryidae, Sminthuridae, and Oribatida were the dominant groups in the *A. pseudosieboldianum* litter (Figure 3). The functional groups of Collembola and Oribatida are fungivores and omnivores, respectively. This functional diversity influenced the litter mass loss in a variety of direct and indirect ways [27]. Decomposer communities are specialized to break down litter from the plants they associate with [25]. This specialization may be related to differences in the abundance of some faunal functional groups or may be the species-specific trophic behavior of soil fauna [28].

The positive effects of soil fauna on litter mass loss have been found to be the highest for the N rich and C poor litter samples [29]. It was determined that, whether home or away from home, the *U. laciniata* litter decomposed the fastest, and soil fauna had positive effects on litter mass losses during the 12 months experimental period, as illustrated in Figure 1. However, a higher mass loss does not indicate a significant HFA for the litter mass losses (Figure 2). All of the above analytical results indicate that soil fauna had a weak effect on the HFA of litter mass losses during the 12-month experiment.

Within such a small-scale perspective, we propose to focus on the surrounding environment of litter decomposition. Low quality litter placed in a non-native plant community may decompose more rapidly than in its home habitat due to the positive effect of the surrounding environment [10]. This would explain the negative HFA of the low-quality litter of *Q. mongolica* in the coarse mesh during the 12 months experiment (Figure 2). In the current study, a significantly higher abundance of soil fauna was evident in the miscellaneous wood forest than in the *Q. mongolica* forest [30]. Moreover, soil organic carbon of the topsoil (0–10 cm) was higher in the miscellaneous wood forest (188.91 g/kg, 171.74 g/kg, and 151.90 g/kg) than in the *Q. mongolica* forest (90.27 g/kg, 95.20 g/kg, and 79.09 g/kg) after 7, 9, and 12 months. However, it was found that litter temperature and moisture were higher in the *Q. mongolica* forest than in the miscellaneous wood forest after 7, 9, and 12 months, with the exception of the litter moisture in May 2017 (after 7 months), as illustrated in Figure S1. We infer that

the weak HFA effect was mainly due to an imbalance of the soil faunal community and the soil and litter's physical and chemical properties between the home and away from home habitats. Therefore, the complexity of the relationship was evident between the soil faunal specialization and HFA effect. In addition, we agree that the magnitude of the HFA's effect on litter mass loss may be underestimated, since litterbags restrict the removal of litter from litterbags by soil fauna [2,31,32].

4.2. Effects of Soil Fauna on the HFA of Litter Nutrient Release

Soil fauna accelerate litter nutrient release and show a significantly positive HFA (Figure 2). For high quality litter, the *J. mandshurica* litter showed a significantly more positive ADH for N release in the coarse mesh than in the fine mesh litterbags after 7 months ($p = 0.001$). For the low quality litter, the *A. pseudosieboldianum* litter showed a significantly more positive ADH for C release in the coarse mesh than in the fine mesh litterbags after 7 months ($p = 0.029$). A strong specialization of the soil fauna community on C release in *A. pseudosieboldianum* litter at home was only found at month 7 of the experiment (Figure 3). Moreover, the *Q. mongolica* and *A. pseudosieboldianum* litters showed a significantly more positive ADH for N and S release in the coarse mesh than in the fine mesh litterbags after 7 and 12 months, respectively ($p = 0.029$; $p = 0.003$; $p = 0.047$; $p = 0.037$), as illustrated in Figure 2. Our results suggest that soil fauna drive positive HFA effects for the N release of both high- and low-quality litters. Similarly, soil fungi participate actively in driving HFA effects for both high- and low-quality litters [33]. Litter quality appears to have no effect on the HFA [25].

Soil fauna can not only immobilize N from litter but also influence the release of N at an early stage of decomposition [34–36]. Litter decomposition at an away site may immobilize more N after a given amount of time than litter decomposition at home (i.e., a positive HFA). In this study, the *Q. mongolica* and *A. pseudosieboldianum* litters displayed significantly lower N immobilization in the coarse mesh litterbags at home than away from home at months 7 and 12 of the experiment, respectively ($p < 0.001$; $p = 0.035$). Similarly, *A. pseudosieboldianum* litter displayed a significantly lower S immobilization in the coarse mesh litterbags at home than away from home at month 12 of the experiment ($p = 0.004$), as illustrated in Figure 1. In addition, the soil fauna showed a significantly negative HFA for their S release (Figure 2). The *A. pseudosieboldianum* and *Q. mongolica* litters showed a significantly more negative ADH for their S release in their coarse mesh than in their fine mesh litterbags after 7 and 12 months, respectively ($p = 0.037$; $p = 0.003$). N immobilization often increases with mass loss during the earliest stages of decomposition [37]. Litter decomposition at home may immobilize more N after a given amount of time than litter decomposition at an away site (i.e., a negative HFA) [38]. Previous studies have also discovered that S deposition suppressed litter decomposition in a broadleaf forest [39]. Similarly, the *Q. mongolica* litter displayed a significantly higher S immobilization at home than away from home in the coarse mesh litterbags at month 12 of the experiment ($p = 0.002$). However, the *A. pseudosieboldianum* litter displayed significantly lower S mobilization at home than away from home in the coarse mesh litterbags at month 7 of the experiment ($p = 0.001$) (Figure 1). In addition, According to the RDA analysis, S release was more positively and negatively correlated with the *Q. mongolica* litter in *Q. mongolica* forest than in the miscellaneous wood forest after 7 months, respectively. Also, S release was more positively and negatively correlated with the *A. pseudosieboldianum* litter in the *Q. mongolica* forest than in the miscellaneous wood forest after 12 months, respectively. This would explain the positive HFA of S release in the *Q. mongolica* and *A. pseudosieboldianum* litters in the coarse mesh after 7 and 12 months. Our results suggest that soil fauna have positive and negative on the HFA for S release in the low-quality litter.

Unfortunately, all litters showed no significant differences in the HFA of their litter mass losses and nutrient release after 9 months. The litter temperatures were found to be the highest in the *Q. mongolica* forest site and miscellaneous wood forest site at month 9 of the experimental period (July of 2017), and the litter moisture was also higher during this period of time (Figure S1). Further, the abundance of soil fauna was highest in the hot rainy season. Nevertheless, all litters showed no significant difference in the abundance of their soil fauna between the home and away from home group after 9 months

(Figure 3). In addition, stronger eluviation may have weakened the impact of the soil fauna on the HFA of the litter mass losses and nutrient release at month 9 of the experimental period.

We have to admit that an experimental duration of only 12 months is not sufficiently long to examine the long-term links between litter mass losses, the release of litter nutrients, and soil faunal communities, especially in our study area, with long, snowy winters and short summers. In addition, the short duration of this study's litter decomposition experiment may have limited our ability to detect the HFA to some extent [40]. Therefore, for future studies, it may be advisable to shorten the sampling intervals in order to capture more snapshots of faunal activities, especially during the summer seasons.

5. Conclusions

Our study on the *Q. mongolica* forest and miscellaneous wood forest of Longwan National Nature Reserve suggests that the soil fauna had a specialization in the decomposition of the *A. pseudosieboldianum* litter at home at month 7 of the experiment. HFA could affect a litter's mass loss and nutrient release due to the soil's faunal activity. A positive HFA for litter mass loss was observed in the *A. pseudosieboldianum* and *U. laciniata* litters in the coarse fine mesh litterbags after 7 and 12 months. Whether home or away from home, the *U. laciniata* litter decomposed the fastest; however, a higher mass loss does not necessarily indicate a significantly higher HFA for litter mass losses. A positive HFA for litter mass loss was observed in the *A. pseudosieboldianum* and *U. laciniata* litters in the coarse fine mesh litterbags after 7 and 12 months. However, all litters showed no significant difference in the HFA between their coarse mesh and fine mesh sizes during the 12-month experiment. The *A. pseudosieboldianum* and *J. mandshurica* litters showed a significantly higher positive HFA for C release in the coarse mesh than in the fine mesh litterbags after 7 months. The *Q. mongolica* and *J. mandshurica* litters showed a significantly higher positive HFA for N release in the coarse mesh than in the fine mesh litterbags after 7 months. The *A. pseudosieboldianum* litter showed a significantly higher positive HFA for N release in the coarse mesh than in the fine mesh litterbags after 12 months. The *Q. mongolica* and *A. pseudosieboldianum* litters showed a significantly higher positive HFA for S release in the coarse mesh than in the fine mesh litterbags after 7 and 12 months, respectively. However, the *A. pseudosieboldianum* and *Q. mongolica* litters showed a significantly higher negative HFA for S release in the coarse mesh than in the fine mesh litterbags after 7 and 12 months, respectively. To elucidate the mechanisms behind these phenomena, experiments of longer duration may be warranted in order to examine the long-term dynamics of faunal communities and explore the sustained effects of soil fauna on the HFA of litter mass losses and nutrient release in temperate forest ecosystems.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/10/11/1033/s1, Table S1: Litter types and initial quality characteristics of the litters at the start of the experiment (October 2016). Values are the mean ± SE (n = 3). Table S2: The abundance (Ind. g^{-1} dry litter) of the soil faunal communities in all litter types over the 12 months experiment of Longwan National Nature Reserve. Values are means of different plots with total three sampling periods. Figure S1: Litter temperature and moisture in *Quercus mongolica* forest and miscellaneous wood forest.

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