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Seasonal variation in litter decomposition rates: a comparison of spring- and autumn-detached litter in a steppe grassland ecosystem

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Abstract

In grassland ecosystems, many plants gradually senesce in autumn, forming standing dead material (standing litter) that remains through the winter rather than immediately falling to the ground as litter. However, limited research has focused on the decomposition of standing litter during winter and its subsequent effects on decomposition after being shed in the following spring. We conducted a one-year experiment in the typical steppe of Inner Mongolia, China, to investigate the decomposition processes of litter from the dominant plant *Leymus chinensis* and *Stipa grandis* litter in autumn and spring. During the experiment, autumn-shed litter was placed directly on the soil surface, while spring-shed litter remained suspended above the soil surface for the first seven months of winter until it detached and fell to the ground. The results showed that throughout the study, the decomposition rate of spring-shed litter was consistently faster than that of autumn-shed litter. Notably, the lignin content in spring litter decreased significantly during the winter standing period, while no such change was observed in autumn litter. This suggests that photodegradation played a crucial role in lignin decomposition during the winter, facilitating the subsequent breakdown of plant litter. These findings highlight the significant differences in decomposition rates between litter shed in autumn and spring.

Introduction

Litter decomposition is crucial for nutrient cycling, soil fertility, and carbon dynamics, with decomposition rates largely determined by litter quality and microbial communities (Bradford et al. 2016). The state of plant material, whether standing dead or detached on the soil surface, significantly influences decomposition (Lin and King 2014). In grasslands, plants often retain dead material as standing dead for extended periods, exposing it to harsh environmental conditions that inhibit microbial activity (Wang et al. 2017). However, the role of the standing-dead phase in decomposition, especially processes like lignin photodegradation, remains underexplored. Understanding these dynamics is critical for comprehending nutrient cycling, particularly in grazed grasslands, where management practices influence the standing-dead phase.

Microorganisms in soil and vegetation are vital to litter decomposition, but those attached to litter often face drier conditions and greater temperature fluctuations, which reduce their activity and slow decomposition (Lin and King, 2014; Wang et al. 2017). In addition to microbial decomposition, abiotic processes such as leaching, physical fragmentation, and lignin photodegradation also play important roles (Rahman et al. 2013; Yanni et al. 2015). Solar radiation promotes photodegradation, making lignin more accessible to microbes for further decomposition (Lin et al. 2015; Austin et al. 2016). In sunlit areas, photodegradation dominates, while microbial decomposition is more significant in shaded regions (Lin and King 2014). For example, in semi-arid grasslands and alpine meadows, suspended litter decomposes faster than litter on the soil surface (Wang et al. 2021; Lin and King 2014). Although photodegradation is not the only factor, its contribution to litter decomposition is significant.

The natural grasslands of northern China, covering 2.82 million square kilometers, play a crucial role in supporting pastoral activities and maintaining ecological stability (Li et al. 2019). These grasslands are predominantly dominated by species like *Leymus chinensis* and *Stipa grandis*, which have tall, erect stems that persist long after senescence in autumn (Giese et al. 2009; Peng et al. 2014). The region's land use practices include grazing, mowing, and fencing, with grazing, especially rotational and continuous grazing, being the most common management strategy (Li 1989; Baoyin et al. 2014; Zhang et al. 2020). During the non-growing season, grazing and trampling accelerate litter accumulation and shorten the standing-dead phase (Mor-Mussery et al. 2021). Consequently, in grazed grasslands, dead plants bypass the standing-dead phase and fall directly to the soil surface. In contrast, ungrazed grasslands may see dead plants remain standing through the winter and fall in the spring or summer when grazed. This highlights the significant role of trampling in litter decomposition, as it accelerates litter burial and promotes the formation of a soil-litter interface (Liu et al. 2018; Wei et al. 2021).

To explore the effects of the standing-dead phase on litter decomposition, we conducted a one-year experiment in central Inner Mongolia, comparing the decomposition of litter from *Leymus chinensis* and *Stipa grandis* shed in autumn and spring. We hypothesized that: (1) plant residues that undergo the standing-dead phase decompose more slowly during this period than those that fall directly to the soil surface after senescence; and (2) residues that experience the standing-dead phase, due to changes in lignin content, are more readily degradable and decompose more rapidly than fresh litter.

Methods

The study was conducted at the Grassland Ecosystem Research Station of Inner Mongolia University, located 60 km northeast of Xilinhot, Inner Mongolia, China (116°31′E, 44°15′N, elevation 1146 m). The region has a temperate semi-arid climate, with an average annual temperature of 2.8°C and precipitation ranging from 280 to 350 mm, mostly occurring from May to September. The native steppe is dominated by *L. chinensis* and *S.* grandis.

The experiment was conducted in a 50 m × 50 m grassland plot, which had been used for grazing but had remained ungrazed for six years prior to the study in 2018. In November 2017, we collected senescent leaves and stems from two dominant grass species, *L. chinensis* and *S. grandis*. The collected litter was air-dried at room temperature, then portioned into 10 g samples and placed in nylon mesh bags (15 cm × 20 cm, with a 1 mm mesh size). The bags were divided into two groups to simulate the decomposition processes of autumn and spring litter. The first group, termed "surface litter" consisted of material placed directly on the soil surface, representing the decomposition of autumn litter. The second group, referred to as "standing litter," was initially suspended 0.1 meters above the ground for seven months over the winter before being placed on the soil surface to simulate the spring decomposition process, following the standing-dead phase. Litter samples were collected at the 7th and 12th months of decomposition. This study involved placing both autumn and spring litter from all species in five replicates, using a fully random design. This resulted in a total of 40 litterbags, calculated as: 2 plant species (*L. chinensis* and *S. grandis*) × 2 litter types (autumn *vs*. spring) × 2 sampling points（7months and 12 months） × 5 replicates. The concentrations of nitrogen (N%) were quantified using an elemental analyzer (Vario MACRO cube, Elementar, Germany). Neutral detergent fiber content (NDF%) and acid detergent fiber content (ADF%) were measured using an ANKOM 2000 Automated Fiber Analyzer (A2000i, Fiber Analyzer, American). The digestion of acid detergent lignin (ADL%) in 72% H_2SO_4 solution, obtained by the lignin sulfate method, was used to analyze the lignin content of ADF fractions (Trofymow et al. 2002).

Results

Changes in plant litter mass

For both species (*L. chinensis* and *S. grandis*), the mass of both spring and autumn litter decreased significantly during decomposition. In the first 7 months, the remaining mass of spring litter from *L. chinensis* was significantly higher than that of autumn litter (P<0.05), while no significant difference was observed between spring and autumn litter for *S. grandis* (P>0.05). By the 12th month, the remaining mass of spring litter from *L. chinensis* was significantly lower than that of autumn litter, while no significant difference was observed between the spring and autumn litter of *S. grandis* (P>0.05).

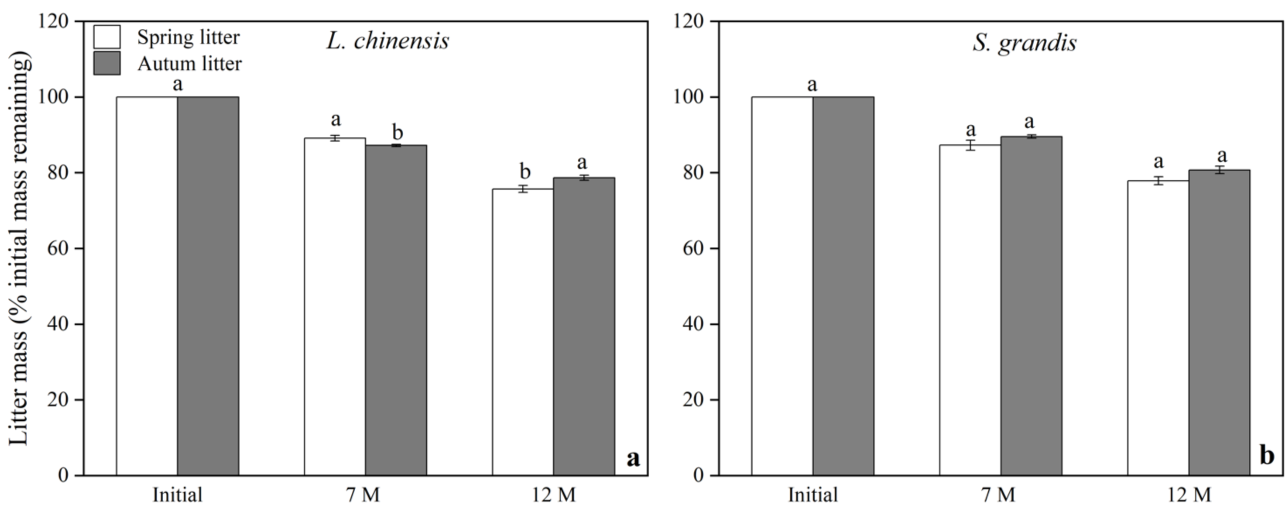

Fig. 1. Remaining litter mass (RM) of *L. chinensis* (a) and *S. grandis* (b) over the one-year experimental period. Bars represent means, and error bars indicate standard error. The spring litter was suspended as standing dead for the first 7 months (winter) under ambient conditions (7M) before being placed on the soil surface for the remainder of the one-year period, whereas the autumn litter was directly placed on the soil surface for the entire decomposition period. Different lowercase letters indicate significant differences between spring and autumn litter within the same period at $P < 0.05$.

Changes in litter quality

In the first 7 months, nitrogen content in spring litter of *L. chinensis* and *S. grandis* significantly decreased (P<0.05), while nitrogen content in autumn litter showed an increasing trend. After one year of decomposition, nitrogen content in all litter types significantly increased (P<0.05) (Table 1). Meanwhile, hemicellulose and cellulose contents in both spring and autumn litter continuously declined over the course of decomposition. Additionally, during the first 7 months of the standing-dead phase and the subsequent surface litter phase, lignin content in spring litter of both *L. chinensis* and *S. grandi*s significantly decreased (P<0.05). In contrast, lignin content in autumn litter of *L. chinensis* significantly increased throughout the decomposition period. After one year of decomposition, lignin content in spring litter was significantly lower than that in autumn litter (P<0.05) (Table 1).

Discussion [Conclusions/Implications]

The decomposition rate of litter varies significantly across different ecosystems, influenced by litter quality, decomposer communities, and environmental conditions (Bradford et al. 2016). Numerous studies have highlighted the impact of lignin content on the decomposition rate of litter (Liao et al. 2022). Our results show a significant positive correlation between litter decomposition rates and the contents of hemicellulose, cellulose, and lignin, which is consistent with previous studies (Duan et al. 2018; Wang et al. 2022).

Table 1 Nitrogen (N) content, hemicellulose, cellulose, and lignin content in initial litter (Initial) and subsequent treatments of *L. chinensis* and *S. grandis*. Values are means ± standard error. Different letters within a row indicate significant differences (P < 0.05).

	L. chinensis		*S. grandis*	
	Spring	Autumn	Spring	Autumn
N				
Initial	1.16	1.16	1.05	1.05
7 M	1.00±0.40b	1.17±0.42a	0.72±0.03b	1.19±0.01a
12 M	1.32±0.04a	1.16±0.04b	1.00±0.05b	1.23±0.04a
Hemicellulose				
Initial	31.48	31.48	33.7	33.7
7 M	34.68±0.29a	29.05±0.33b	32.63±0.56a	29.67±0.49b
12 M	28.22±1.54a	27.46±0.88a	31.83±0.67a	28.68±0.53b
Cellulose				
Initial	30.15	30.15	28.62	28.62
7 M	29.42±0.21a	27.00±0.89b	24.61±0.80b	30.61±0.48a
12 M	25.59±0.83a	22.63±0.45b	26.9±0.79b	29.08±1.76a
Lignin				
Initial	7.64	7.64	8.00	8.00
7 M	5.26±0.17b	8.44±0.37a	7.61±0.31a	7.18±0.21a
12 M	4.77±0.18b	8.46±0.22a	5.13±0.29b	7.41±0.55a

Relationships of litter decomposition rate with litter quality

The remaining mass of litter showed significantly positively correlated with the contents of hemicellulose, cellulose and lignin (P<0.05), but it was no significant correlation with nitrogen content (P>0.05) (Fig. 2).

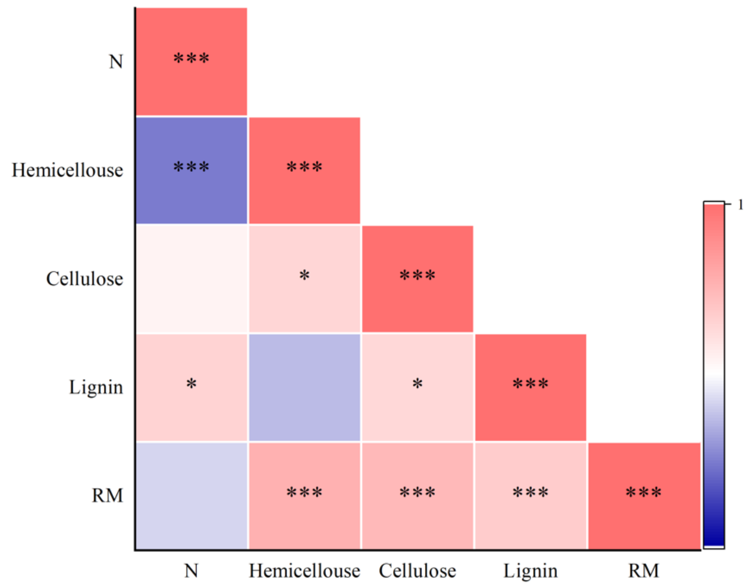

Fig. 2. Heatmap of the correlation between litter mass remaining and litter quality

In addition to soil microbial communities, solar radiation also plays a significant role in litter decomposition (Wang et al. 2021; Jiang et al. 2022). We found that after 7 months of exposure, spring litter experienced greater mass loss than autumn litter, both at the 12th and 17th months. This indicates that spring litter, having undergone the standing-dead phase, decomposed faster than autumn litter, which had not. This result is in line with previous studies, which suggest that the retention of standing-dead biomass promotes subsequent decomposition in the soil surface (Day et al. 2015; Angst et al. 2017). Moreover, after 7 months of winter exposure to sunlight, spring litter decomposed more rapidly than autumn litter, likely due to photodegradation. Lignin, a key component of plant cell walls, is difficult to biodegrade (Huang et al. 2022), but it is highly susceptible to photodegradation when exposed to UV and blue-green light, promoting subsequent microbial decomposition (King et al. 2012; Austin et al. 2016). Our data show that after 7 months of exposure, the lignin concentration in spring litter decreased, whereas in autumn litter, lignin concentration increased. A similar trend was observed in the decomposition of *S. grandis* litter. This suggests that the significant breakdown of lignin enhances microbial decomposition, leading to a faster decomposition rate in spring litter than in autumn litter.

Our study suggests that the enhanced photodegradation of refractory structures in standing litter, compared to that in litter lying on the ground, likely explains why the standing-dead phase contributes to overall faster decomposition. Our findings highlight the importance of considering litter status (standing dead or lying on the soil surface) and factors like grazing that alter this status when modelling or calculating litter decomposition in semi-arid grassland ecosystems.

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