



Dependency of litter decomposition on litter quality, climate change, and grassland type in the alpine grassland of Tianshan Mountains, Northwest China

SU Yuan^{1*}, GONG Yanming², HAN Wenxuan^{2,3}, LI Kaihui^{2,4*}, LIU Xuejun^{2,3}

¹ College of Grassland Science, Shanxi Agricultural University, Taigu 030801, China;

² State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China;

³ Beijing Key Laboratory of Farmland Soil Pollution Prevention and Remediation, College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China;

⁴ Research Center for Ecology and Environment of Central Asia, Chinese Academy of Sciences, Urumqi 830011, China

Abstract: Litter decomposition is an important component of the nutrient recycling process and is highly sensitive to climate change. However, the impacts of warming and increased precipitation on litter decomposition have not been well studied, especially in the alpine grassland of Tianshan Mountains. We conducted a manipulative warming and increased precipitation experiment combined with different grassland types to examine the impact of litter quality and climate change on the litter decomposition rate based on three dominant species (*Astragalus mongholicus*, *Potentilla anserina*, and *Festuca ovina*) in Tianshan Mountains from 2019 to 2021. The results of this study indicated there were significant differences in litter quality, specific leaf area, and leaf dry matter content. In addition, litter quality exerted significant effects on litter decomposition, and the litter decomposition rate varied in different grassland types. Increased precipitation significantly accelerated the litter decomposition of *P. anserina*; however, it had no significant effect on the litter decomposition of *A. mongholicus* and *F. ovina*. However, warming consistently decreased the litter decomposition rate, with the strongest impact on the litter decomposition of *F. ovina*. There was a significant interaction between increased precipitation and litter type, but there was no significant interaction between warming and litter type. These results indicated that warming and increased precipitation significantly influenced litter decomposition; however, the strength was dependent on litter quality. In addition, soil water content played a crucial role in regulating litter decomposition in different grassland types. Moreover, we found that the litter decomposition rate exhibited a hump-shaped or linear response to the increase of soil water content. Our study emphasizes that ongoing climate change significantly altered litter decomposition in the alpine grassland, which is of great significance for understanding the nutrient supply and turnover of litter.

Keywords: litter decomposition rate; litter quality; warming; increased precipitation; grassland type; Tianshan Mountains

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*Corresponding authors: SU Yuan (E-mail: suyuan@ms.xjb.ac.cn); LI Kaihui (E-mail: likh@ms.xjb.ac.cn)

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1 Introduction

Plant litter decomposition is closely linked to terrestrial carbon (C) budgets and provides strong feedback on climate change and nutrient recycling (Bradford et al., 2014). Litter decomposition is the major pathway to return CO₂ to the atmosphere, accounting for approximately half of the CO₂ (Couteaux et al., 1995), and releases nutrients that can be reused by plants (Parton et al., 2007). The majority of the studies on litter decomposition are primarily based on mesic temperate and tropical ecosystems; however, the important drivers of litter decomposition in dryland ecosystem remain completely unclear (Austin, 2011; Huang et al., 2017; Liu et al., 2018). Therefore, understanding litter decomposition is vital to predicting litter-mediated C fluxes and nutrient budgets, especially in arid and semi-arid regions.

The global average temperature has been estimated to increase by 0.74°C by the end of this century due to the increase in the concentrations of greenhouse gases and this unprecedented global warming has resulted in huge changes in the precipitation conditions in terrestrial ecosystems (IPCC 2014). A previous study indicated that warming, increased precipitation, and litter quality significantly regulated litter decomposition in terrestrial ecosystems (Wu et al., 2020). Although several previous studies have examined the responses of litter decomposition to increased temperature, and the results indicated that warming increased (Moise and Henry 2014; Liu et al. 2017), slowed (Prieto et al., 2019; Hong et al., 2021), and had no effects (Yu et al., 2019; Chuckran et al., 2020) on litter decomposition, depending on litter quality (Xu et al. 2012; Wu et al., 2020), ecosystem type (Aerts, 2006), warming method (open-top chamber or infrared heating), and experimental duration (Wu et al., 2020). Therefore, evidence is required to investigate the response of litter decomposition to warming.

In addition, the increase of precipitation increased (Wang et al., 2017; Liu et al., 2020), decreased (Wu et al., 2020), and did not influence (Zhao et al., 2013) litter decomposition in different grassland types. Moreover, the amount of precipitation could regulate the effect of warming on litter decomposition. For instance, warming generally tended to inhibit litter decomposition under lower precipitation conditions; however, it exerted no significant effect on litter decomposition under higher precipitation conditions (Liu et al., 2020). In addition, a meta-analysis by aggregating global data revealed that warming generally decreased litter decomposition when the average annual precipitation was lower than 400.0 mm; however, it significantly enhanced litter decomposition when the average annual precipitation was higher than 400.0 mm (Wu et al., 2020). Overall, these results suggested that the impact of increased precipitation on litter decomposition remains unclear, depending on the amount of precipitation.

Warming or increased precipitation may interact with litter quality to influence litter decomposition. A previous study indicated that high-quality litter exhibited a stronger response to warming than low-quality litter (Liu et al., 2017). Another study demonstrated that warming had no significant effect on the decomposition of low-quality litter and accelerated the decomposition of high-quality litter (Xu et al., 2012). However, Hong et al. (2021) reported that litter type affected the response of litter decomposition to warming, with a stronger impact on lower-quality litter. The application of increased temperature in laboratory incubation experiments showed that warming had stronger impacts on the litter decomposition rate of *Eriophorum vaginatum* than that of *Sphagnum palustre* in the permafrost peatlands (Gao et al., 2022). In addition, the increased precipitation significantly enhanced the litter decomposition of *Agropyron cristatum* after a three-year field incubation experiment; however, it did not influence the litter decomposition of *Stipa krylovii* and *Artemisia frigida* (Wang et al., 2017). Liu et al. (2006) reported that the addition of water increased the litter decomposition of *Allium bidentatum*, but had no significant effect on the litter decomposition of *S. krylovii*. These studies indicated a high uncertainty about how the interaction between warming or increased precipitation and litter quality affects litter decomposition; these interactions are still not completely understood. In addition, a recent study showed that the litter decomposition rate was almost three times faster in wetlands than in upland ecosystems (Xie et al., 2019). These results indicated that many factors could interact with each other to influence litter decomposition. Therefore, the effect of litter quality, climate change, and

ecosystem type, as well as their interaction during the decomposition process, still need to be investigated in the alpine grassland.

The Bayanbulak grassland is a typical alpine grassland, where has experienced rapid warming ($0.71^{\circ}\text{C}/10\text{ a}$) and increased precipitation ($26.8\text{ mm}/10\text{ a}$) since 1984 (Li et al., 2020). However, the effect of these changes on litter decomposition in this alpine grassland has not been studied so far. In this study, we hypothesized that (1) increased precipitation would promote litter decomposition and warming would inhibit litter decomposition, and (2) warming and increased precipitation would have different effects on litter decomposition of different plant species. Therefore, we conducted a manipulative warming and increased precipitation experiment combined with different grassland types to examine the dependency of litter decomposition on litter quality and climatic change based on three dominant species (*Astragalus mongholicus*, *Potentilla anserina*, and *Festuca ovina*) from 2019 to 2021.

2 Materials and methods

2.1 Study area and experimental design

The study was conducted at the Bayanbulak Grassland Ecosystem Research Station, Chinese Academy of Sciences ($42^{\circ}53'\text{N}$, $83^{\circ}42'\text{E}$). Bayanbulak alpine grassland is located in the southern Tianshan Mountains, Xinjiang Uygur Autonomous Region of China, and covers a total area of approximately $2.3 \times 10^4\text{ km}^2$. The annual average temperature is -4.80°C and the average annual precipitation is 282.3 mm in the study area from 1980 to 2012 (Li et al., 2020).

In this study, four grassland types without significant human disturbance were selected including wetland, alpine meadow, alpine meadow steppe, and alpine steppe (Table S1). Detailed information has been provided in a previous study (Li et al., 2020). An area ($50.0\text{ m} \times 50.0\text{ m}$) was fenced against grazing by large animals in each grassland type. In the fenced area, there were five plots established to perform litter decomposition experiment, and the area of each plot was $2.0\text{ m} \times 2.0\text{ m}$, with a buffer zone of 1.0 m between each plot.

The field manipulative experiment of warming and increased precipitation was established in August 2019 in the alpine steppe (Site 2). The dominant species in the site is *F. ovina*, and the subdominant species is *P. anserina* and *A. mongholicus*. The treatment of field manipulative experiment included control, warming, and increased precipitation. Each treatment was arranged using a randomized block design with five replicates, resulting in 15 plots. Each plot ($1.5\text{ m} \times 2.0\text{ m}$) was 1.5 m away from other plots in each block. For the warming treatment, the air temperature was warmed using open-top chambers (Wang et al., 2014), which were hexagon chambers composed of six pieces of transparent plexiglass, each chamber with 1.2 m width at the top, 1.5 m width at the bottom, and 0.5 m high. The passive warming method with little effect on rainfall and snowfall interception is the favored option. For the treatment of increased precipitation, water was applied during the growing seasons from May to September in 2019–2021. For each water application, the intercepted precipitation was collected using PVC tubes and transferred into plastic containers. At the beginning and end of each month, 45-L water was added using a backpack sprayer to simulate an increase in the average precipitation by 50% of the corresponding long-term average precipitation (300 mm).

2.2 Measurement of litter decomposition

In mid-August 2019, we collected the aboveground litter of *A. mongholicus*, *P. anserina*, and *F. ovina* from the alpine steppe Site 2. After being dried to constant mass, they were cut into fragments of 5 cm in length, and placed into $20\text{ cm} \times 25\text{ cm}$ polyethylene litterbags (0.5-mm mesh) (Wei et al., 2022), each litterbag containing 4 g of dried litter material. Each treatment plot contained 25 litterbags of the same species. We manually fixed these litterbags to the soil surface using small nails to ensure that the litterbags were in contact with the soil surface throughout the experimental period. A total of 600 litterbags were prepared and deployed to the treatment plots in September 2019.

The remaining litter was retrieved 8, 10, 12, 20, and 24 months after the initial deployment of

litterbags. For each sampling, five litterbags of each species from each treatment plot were collected. In the laboratory, fresh litter and rocks were handpicked from the litterbags. The retrieved litter was then oven-dried at 70°C for 48 h to determine the dry mass of litter remaining after carefully removing the soil particles with a brush and fresh plants by hand. We calculated the rate of litter remaining according to the following formula:

$$LR = \frac{m_t}{m_0} \times 100\%, \quad (1)$$

where LR is the rate of litter remaining, m_t is the remaining litter mass after a given time period t (g), and m_0 is the initial litter mass (g).

2.3 Physical and chemical analyses of litter quality and soil properties

Specific leaf area (SLA) and leaf dry matter content (LDMC) were measured by leaf area meter (LI-3000, LI-COR, Lincoln, USA) and electronic balance, respectively. The SLA was calculated as: $SLA \text{ (cm}^2\text{/g)} = \text{leaf area (cm}^2\text{)}/\text{leaf weight (g)}$. The LDMC was calculated using $LDMC \text{ (g/g)} = \text{dry leaf weight (g)}/\text{fresh leaf weight (g)}$.

Surface soil (0–10 cm) was randomly sampled in each plot in October 2018, May 2019, and August 2019, and sieved with a 2-mm mesh. Soil samples were dried at 65°C until they reached a constant weight, and then the soil water content (SWC; %) was measured by weight. Soil pH was measured by a pH meter.

The initial litter and soil were ground into fine powder by a ball mill. The concentrations of litter total C (litter C), litter total nitrogen (N) (litter N), soil total C (STC), and soil total N (STN) were analyzed using elemental analyzer (2400 II CHN Elemental Analyzer, Analytik Jena, Germany), and the concentrations of litter total phosphorus (P) (litter P) and soil total P (STP) were measured using continuous flow analyzer (AA3, Seal Analytical, Germany). The concentrations of lignin, hemicellulose, and cellulose in litter were determined using the Van Soest method (Van Soest and Wine, 1968).

2.4 Statistical analysis

We calculated the litter decomposition rate using the following exponential function (Olson, 1963):

$$\frac{m_t}{m_0} = e^{-kt}, \quad (2)$$

where k is the litter decomposition rate.

Levene's test was used to test the normality of all data before statistical analysis. Two-way analysis of variance (ANOVA) was used to assess the effects of litter quality and grassland type combined with warming or increased precipitation on the litter decomposition rate. Significant differences among treatments were analyzed using Tukey's multiple comparison post-hoc test and one-way ANOVA with a confidence level of $P < 0.05$. In addition, regression analysis was used to examine the relationship between SWC and the litter decomposition rate. All statistical analyses were conducted using SPSS 23.0 (IBM SPSS, Chicago, Illinois, USA).

3 Results

3.1 Soil properties and initial litter quality

Significant differences in STC, STN, STP, soil pH, and SWC were found in different grassland types (Table 1). STC was 167.99 mg/g in wetland, which was significantly higher than that in other grassland types. STN was higher in wetland and alpine meadow than that in alpine meadow steppe and alpine steppe. The highest STP was found in wetland and the lowest value in alpine meadow steppe; however, there was no significant difference in alpine meadow and alpine steppe. In addition, SWC varied greatly among different grassland types, with the highest value in wetland.

There were significant differences in initial litter quality among the three species (Fig. 1). *A.*

mongholicus had higher litter N, litter P, SLA, and lignin, but it had lower C:N ratio, C:P ratio, the ratio of lignin to litter N, and LDMC. *F. ovina* had lower litter N, litter P, and SLA, but it had higher LDMC, cellulose, hemicellulose, and the ratio of lignin to litter N. *P. anserina* had the lowest value of cellulose, hemicellulose, and N:P ratio.

Table 1 Soil properties in different grassland types

	Wetland	Alpine meadow	Alpine meadow steppe	Alpine steppe (Site 1)	Alpine steppe (Site 2)	Alpine steppe (Site 3)
STC (mg/g)	167.99±2.07 ^a	136.91±3.23 ^b	69.29±0.31 ^c	45.47±1.27 ^d	49.17±1.16 ^d	47.45±2.24 ^d
STN (mg/g)	8.42±1.27 ^a	8.46±0.41 ^a	4.99±0.24 ^b	4.30±0.11 ^b	3.98±0.36 ^b	4.15±0.47 ^b
STP (mg/g)	1.21±0.06 ^a	0.82±0.01 ^b	0.70±0.08 ^c	0.81±0.10 ^b	0.94±0.12 ^b	0.88±0.09 ^b
Soil pH	7.67±0.02 ^c	6.86±0.01 ^d	7.87±0.04 ^b	7.99±0.03 ^a	7.85±0.13 ^a	7.88±0.19 ^a
SWC (%)	79.67±3.80 ^a	56.17±2.41 ^b	35.17±0.60 ^c	15.67±0.88 ^d	3.41±0.57 ^f	5.52±0.39 ^e

Note: STC, soil total carbon; STN, soil total nitrogen; STP, soil total phosphorus; SWC, soil water content. Different lowercase letters indicate significant differences among the grassland types. Mean±SE.

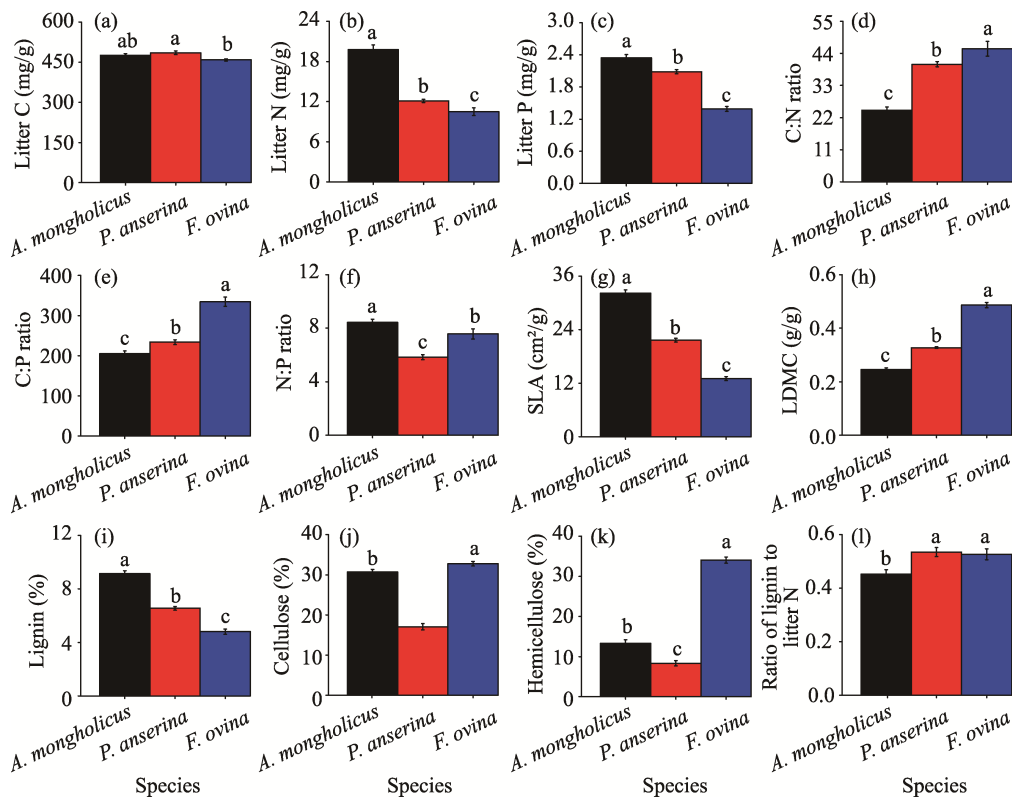


Fig. 1 Initial litter quality of *Astragalus mongholicus*, *Potentilla anserina*, and *Festuca ovina*. (a), litter total carbon (litter C); (b), litter total nitrogen (litter N); (c), litter total phosphorus (litter P); (d), C:N ratio; (e), C:P ratio; (f), N:P ratio; (g), specific leaf area (SLA); (h), leaf dry matter content (LDMC); (i), lignin; (j), cellulose; (k), hemicellulose; (l), the ratio of lignin to litter N. Different lowercase letters indicate significant differences among species. Bars mean standard errors.

3.2 Litter decomposition rate in different grassland types

Grassland type and litter type, as well as their interaction, significantly influenced the litter decomposition rate (Figs. 2 and 3). Overall, the litter decomposition rate of *A. mongholicus* was the fastest, and the litter decomposition rate of *F. ovina* showed the slowest. In addition, results indicated that the litter of *F. ovina* decomposed the fastest in wetland; however, the litter of *P. anserina* decomposed faster in alpine meadow steppe than in other grassland types.

The litter decomposition rates of *A. mongholicus* and *P. anserina* exhibited a hump-shaped

response to the increase of SWC and reached the peak at the medium level of SWC (Fig. 4). Furthermore, a significant positive relationship was observed between the litter decomposition rate of *F. ovina* and SWC (Fig. 4).

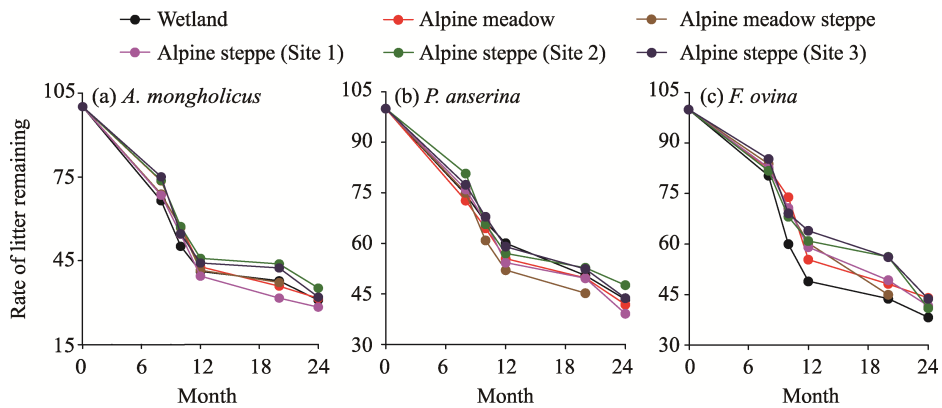


Fig. 2 Rate of litter remaining of *A. mongholicus* (a), *P. anserina* (b), and *F. ovina* (c) in different grassland types at 0, 8, 10, 12, 20, and 24 months after the litterbags deployment

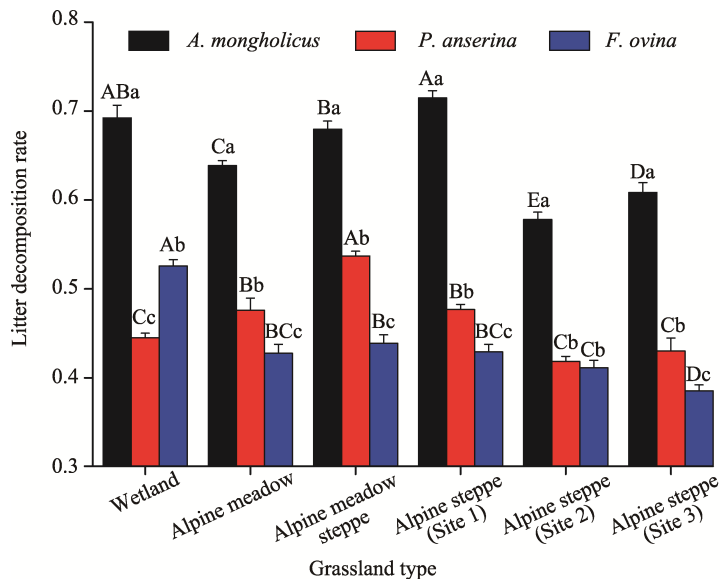


Fig. 3 Litter decomposition rate of *A. mongholicus*, *P. anserina*, and *F. ovina* in different grassland types. Different lowercase letters indicate significant differences among the three species in the same grassland ($P < 0.01$), and different capital letters indicate significant differences among grassland types for the same species ($P < 0.01$). Bars mean standard errors.

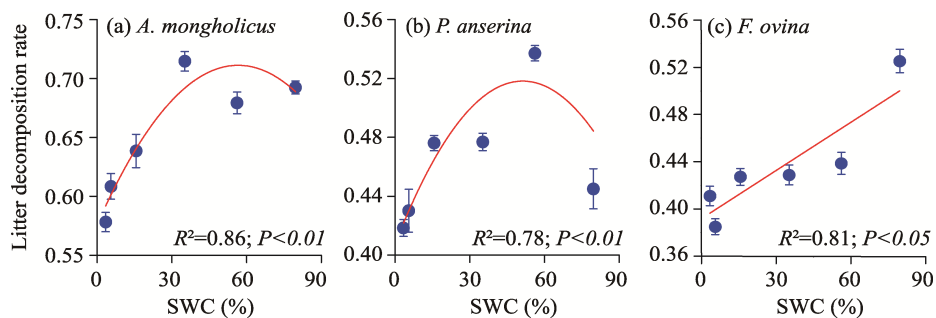


Fig. 4 Effect of soil water content (SWC) on the litter decomposition rate of *A. mongholicus* (a), *P. anserina* (b), and *F. ovina* (c). Bars mean standard errors.

3.3 Effect of increased precipitation and warming on the litter decomposition rate

Litter type and increased precipitation, and their interaction significantly influenced the litter decomposition rate; however, no significant interaction was observed between litter type and warming (Figs. 5 and 6). Warming significantly slowed the litter decomposition rate; however, the magnitude of reduction varied among the three species (Fig. 5, Fig. 6). However, increased precipitation produced variable effects on the litter decomposition rate, with an increase in forbs litter and neutral effects for grass and legume litters.

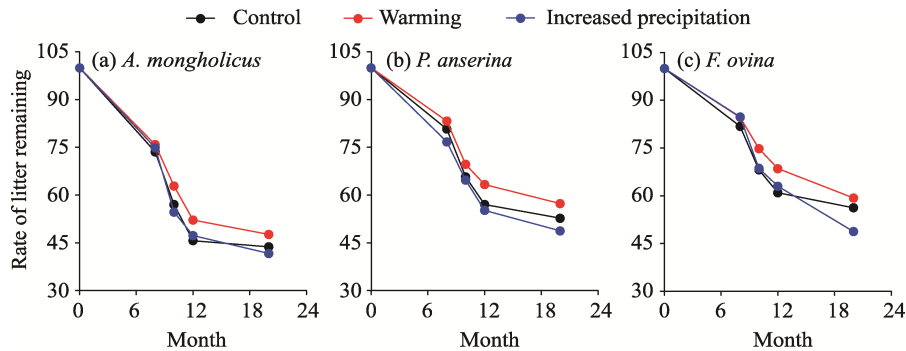


Fig. 5 Rate of litter remaining of *A. mongholicus* (a), *P. anserina* (b), and *F. ovina* (c) under different treatments at 0, 8, 10, 12, 20, and 24 months after the litterbags deployment

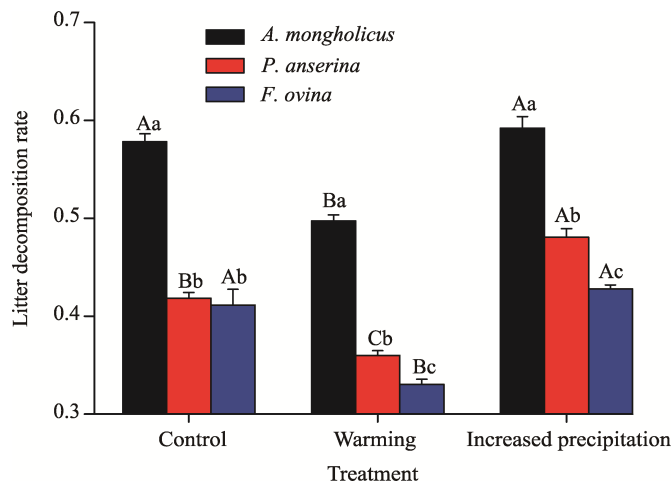


Fig. 6 Effects of different treatments on the litter decomposition rate of *A. mongholicus*, *P. anserina*, and *F. ovina*. Different lowercase letters indicate significant differences among the three species under the same treatment ($P < 0.01$), and different capital letters indicate significant differences among treatments for the same species ($P < 0.01$). Bars mean standard errors.

4 Discussion

Climate change have significantly influenced litter decomposition in the alpine grassland. Warming has been reported to exert inconsistent effects on litter decomposition; however, increased precipitation tended to increase litter decomposition (Table S2), which was consistent with previous studies stating that increased precipitation consistently promoted litter decomposition. However, Hong et al. (2021) reported that warming significantly reduced litter decomposition in a single alpine grassland. In contrast, Yin et al. (2022) stated that warming profoundly increased litter decomposition. These results suggested that the effect of warming on litter decomposition varied greatly in different grassland types. In addition, our results indicated that the impacts of increased precipitation on litter decomposition were highly related to SWC. Interestingly, the litter decomposition rates of *A. mongholicus* and *P. anserina* exhibited a

hump-shaped response to the increase of SWC; however, the litter decomposition rate of *F. ovina* significantly increased with the increase of SWC.

4.1 Impact of litter quality on the litter decomposition rate

Previous studies have indicated that there was significant relationship between the litter decomposition rate and initial litter quality, such as litter N, lignin, C:N ratio, and the ratio of lignin to litter N (Knorr et al., 2005; Veen et al., 2015; Zhang et al., 2016; Zhou et al., 2019). In addition, our results support most previous findings; high-quality litter, such as higher litter N and lower the ratio of lignin to litter N, usually had a rapid litter decomposition rate (Veen et al., 2015). A significantly positive correlation was observed between lignin and the litter decomposition rate in our study, suggesting that lignin content alone could not better predict the litter decomposition rate in the alpine grassland. In addition, a previous study reported that lignin or the ratio of lignin to litter N exerted different control on the litter decomposition rate among different sites and these differences were significantly correlated with the initial soil N concentration (Aber et al., 1980; Melillo et al., 1982). However, litter P and their stoichiometric ratio varied highly and significantly influenced the litter decomposition rate, which was consistent with previous studies that the litter decomposition rate was inversely related to C:P ratio (Manzoni et al., 2010; Chen et al., 2016). In addition, SLA and LDMC also played an important role in regulating the litter decomposition rate, which had been demonstrated by Bakker et al. (2011), Zhang et al. (2016) and de la Riva et al. (2019); they found that the litter decomposition rate was significantly positively and negatively correlated with SLA and LDMC, respectively, implying that litter decomposed faster with higher SLA and lower LDMC.

4.2 Impact of increased precipitation on the litter decomposition rate

After a two-year field manipulative experiment, we concluded that increased precipitation during the growing season accelerated the litter decomposition rate. Litter decomposition of *F. ovina* was significantly stimulated under the treatment of increased precipitation; however, no effects were observed in litter decomposition of *A. mongholicus* and *P. anserina* (Fig. 6). Previous numerous studies have reported that increased precipitation promoted litter decomposition (Prieto et al., 2019; Liu et al., 2020) or had no significant impact on litter decomposition (Liu et al., 2006; Zhao et al., 2013). Even in a single system, increased precipitation produced variable effects; it increased and did not significantly affect the litter decomposition rate (Liu et al., 2006; Schuster et al., 2016). These results supported our study results and reflected the crucial role of precipitation in the litter decomposition process in arid and semi-arid regions. In addition, the litter decomposition rate decreased from higher SWC (wetland) to lower SWC (alpine steppe), indicating that litter decomposition was limited by soil water availability. Furthermore, we observed that the litter decomposition rates of *A. mongholicus* and *P. anserina* exhibited a hump-shaped response to the increase of SWC (Fig. 4). This could be related to a larger SLA of the two species, which was better for water retention, and inhibited microbial decomposition under higher SWC in wetland (Song et al., 2011). In addition, a previous study indicated that waterlogging conditions significantly decreased microbial activity and inhibited litter decomposition (Song et al., 2011), and changes in water chemistry affected litter decomposition (Warrinnier et al., 2020). Furthermore, oxygen availability significantly affected litter decomposition, the litter decomposition rate decreased when SWC increased due to a reduction in oxygen-based processes in wetlands (Bragazza et al., 2016). Therefore, changes in litter quality and SWC may have interactive or complex effects on litter decomposition, and more experimental evidence is required to verify this point. A previous study has demonstrated that drought treatment significantly inhibited litter decomposition, with a stronger effect on low-quality litter (Sanaullah et al., 2011). In addition, the results of a meta-analysis showed that the effect of increased precipitation on litter decomposition varied highly with experimental duration, litter quality, and amounts of precipitation, and produced an insignificant increase in litter decomposition in grassland (Wu et al., 2020).

4.3 Impact of warming on the litter decomposition rate

Warming significantly influenced the litter decomposition rate in this study. These differential

responses were likely attributed to the intensity of warming. In a recent study, warming reduced the moisture content of surface soil (0–10 cm) by 5% (Gong et al., 2021), which probably decreased the activity of soil enzymes and inhibited microbial involvement in litter decomposition (Li et al., 2022). A recent study reported that the litter decomposition rate was significantly reduced by warming treatment in alpine steppe (Hong et al., 2021). This suggested that warming did not necessarily accelerate litter decomposition even in alpine grassland. Warming produced an increase in litter decomposition when the average annual precipitation is greater than 400.0 mm. Inversely, warming reduced litter decomposition when the average annual precipitation is less than 400.0 mm (Wu et al., 2020). In addition, previous studies showed that warming promoted litter decomposition only when soil moisture was not the limiting factor (Aerts, 2006). These results indicated that soil water availability regulated the impact of warming on litter decomposition in drylands.

In addition, the impact of warming on the litter decomposition rate was dependent on litter quality (Xu et al., 2012; Liu et al., 2020; Wu et al., 2020). We reported that the litter decomposition rate of *F. ovina* decreased by 20% and the litter decomposition rates of *A. mongholicus* and *P. anserina* decreased by 14%, indicating that litter quality controlled the response of litter decomposition to warming. The results of Hong et al. (2021) revealed that litter type significantly affected the response of litter decomposition to warming, with a stronger impact on low-quality litter. However, another study reported that warming exerted a stronger effect on the decomposition rate of high-quality litter than on low-quality litter (Liu et al., 2017). A recent study observed that the litter decomposition rate increased with increase of temperature; however, the intensity of the impact depended on litter quality and the increase of temperature (Huang et al., 2021), indicating that litter quality and warming interactively affected litter decomposition. After two-year field manipulative experiment, litter decomposition was significantly reduced by short-term warming, which was not consistent with the result that warming exerted limited effects on litter decomposition during the first two years and significantly inhibited litter decomposition in the last three years (Hong et al., 2021). In addition, the intensity of warming influenced litter decomposition; the litter decomposition rate was not influenced by the temperature of less than 5°C but was inhibited by the temperature of greater than 5°C (Wu et al., 2020). Overall, the response of litter decomposition to warming was complex and regulated by experimental duration, litter quality, SWC, and intensity or way of warming, as well as their interactions.

5 Conclusions

A two-year field manipulative experiment was conducted to examine the impact of climate change (warming and increased precipitation) and litter quality on the litter decomposition rate of three dominant plant species in the alpine grassland of Tianshan Mountains, Northwest China. Results indicated that warming significantly slowed litter decomposition and increased precipitation accelerated litter decomposition, however, the intensity of the impact depended on litter type. In addition, changes in grassland type notably influenced litter decomposition, with the litter decomposition rate exhibiting a hump-shaped or linear response to the increase of SWC. SWC played a crucial role in regulating litter decomposition in different grassland types. Our results suggested that ongoing climate change significantly altered litter decomposition in the alpine grassland of Tianshan Mountains.

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Appendix

Table S1 Characteristics of different grassland types in this study

Grassland type	Dominant species	Altitude (m)	Longitude	Latitude	Species richness	Aboveground biomass (g/m ²)
Wetland	<i>Carex stenocarpa</i>	3260	83°42'11"E	42°52'48"N	11.8±1.0	65.7±12.8
Alpine meadow	<i>Carex stenocarpa</i> and <i>Kobresia capillifolia</i>	3160	83°35'34"E	42°53'24"N	12.1±2.4	103.3±18.2
Alpine meadow steppe	<i>Carex stenocarpa</i> and <i>Kobresia capillifolia</i>	2960	83°22'18"E	42°54'21"N	9.5±1.5	59.5±10.1
Alpine steppe (Site 1)	<i>Festuca ovina</i>	2460	83°02'36"E	42°54'57"N	8.5±1.5	65.2±20.2
Alpine steppe (Site 2)	<i>Festuca ovina</i>	2560	83°03'12"E	42°54'27"N	7.8±1.3	52.5±17.6
Alpine steppe (Site 3)	<i>Festuca ovina</i>	2660	83°06'43"E	42°54'28"N	8.7±1.2	48.4±10.1

Table S2 Summary of the effects of warming and increased precipitation on litter decomposition from field experiments in different grassland types

Treatment	Treatment intensity	Effect	Grassland type	Precipitation (mm)	Reference
Open-top chamber	2.00°C	–	Alpine grassland	300	Hong et al. (2021)
Open-top chamber	2.50°C	–	Semiarid shrubland	358	Prieto et al. (2019)
Open-top chamber	No data	–	Semiarid grassland	425	Li et al. (2021)
Infrared heater	0.00°C–4.00°C	+	Alpine grassland	406	Lv et al. (2020)
Infrared heating	1.20°C–1.70°C	+	Alpine grassland	500	Luo et al. (2010)
Wave heater	1.50°C–1.80°C	–/no	Alpine grassland	489	Liu et al. (2020)
Open-top chamber	1.00°C–2.00°C	–	Dry tundra	No data	Christiansen et al. (2017)
Open-top chamber	2.00°C	no	Wet grassland	561	Yu et al. (2019)
Open-top chamber	1.00°C–2.00°C	no	Alpine grassland	593	Shu et al. (2019)
Open-top chamber	1.20°C–1.30°C	+	Subalpine forest	801	Xu et al. (2015)
Open-top chamber	1.10°C	–	Arid alpine system	327–456	Brigham et al. (2018)
Open-top chamber	3.20°C	+/no	Subalpine forest	801	Xu et al. (2012)
Infrared heat	2.50°C	no	Dry grassland	241	Chuckran et al. (2020)
Reduced precipitation	30% total annual precipitation	–	Semiarid shrubland	358	Prieto et al. (2019)
Reduced precipitation	No data	–/no	Temperate grassland	654–787	Schuster et al. (2016)
Enhanced precipitation	30% total annual precipitation	no	Desert grassland	70–150	Zhao et al. (2013)
Enhanced precipitation	50% total annual precipitation	+	Alpine grassland	489	Liu et al. (2020)
Enhanced precipitation	30% total annual precipitation	+/no	Typical grassland	385	Liu et al. (2006)
Enhanced precipitation	50% total annual precipitation	+/no	Typical grassland	379	Wang et al. (2017)
Enhanced precipitation	50%–100% total annual precipitation	+	Alpine grassland	406	Lv et al. (2020)

Note: "+", "–", and "no" in the row of effect indicate that there are increase, decrease, and no significant relationships between the treatment and litter decomposition, respectively.

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