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# Effects of Terrain on Litter Decomposition and Nutrient Release in Typical Steppe of Eastern Gansu Loess Plateau

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ABSTRACT

Terrain can influence vegetation composition, diversity, and biogeochemical cycling in grassland ecosystems. Solar radiation, soil temperature, and moisture distribution are dependent on terrain, which, in turn, can affect plant community structure, rate of litter mass decomposition, and carbon, nitrogen, and phosphorus release. A litter decomposition experiment was conducted over 12 mo at a site representing typical steppe grasslands to better understand the effects of terrain on biogeochemical cycling. The study site had both northeast (shaded) and southwest (sunny) facing aspects with each aspect having three slopes: 15°, 30°, 45°. Litterbags were used for collection of plant community litter from each location. The results indicated that slope and aspect both have significant effects on decomposition rate of litter mass and release rate of C, N, and P. The most rapid decomposition rate of litter mass was on 45° sunny slopes (k value $1.82 \times 10^{-3}$ $d^{-1}$). The most rapid release of C was on 30° shaded slopes with release rate of 4.54 g C $yr^{-1}$. The release rate of N decreased with increasing slope steepness but was more rapid on shaded compared with sunny slopes. The most rapid release of P (10.51 mg P $yr^{-1}$) occurred on 45° shaded slopes. The total effects of solar radiation and soil temperature on litter mass decomposition were larger, with 0.91 and 0.93, respectively. Soil temperature, litter functional diversity, and initial C/N had positive effects on the litter C release. The release of litter N was mainly promoted by soil temperature. Soil moisture appeared to promote the release of litter P. Overall, terrain influenced litter mass decomposition and C, N, and P release by its effect on the distribution of solar radiation, soil temperature and moisture, and through modification of functional diversity, initial C/N ratios, and water content of litter in typical steppe.



## Introduction

Litter formation and decomposition is at the crux of energy flow and nutrient and organic matter cycling in grassland ecosystems (Henry et al. 2008; Chuan et al. 2018). Litter is a vital source of energy, organic matter, and nutrients for functioning and maintenance of the grassland ecosystem, providing the needs for soil and plant communities (Makkonen et al. 2012). Plant tissue nutrients are cycled through grassland ecosystems via litter and returned to the soil by a combination of animal trampling and microbial and enzyme action facilitating decomposition (Sun et al. 2018). At least 20–50% of the total net productivity of grassland communities enters the soil in the form of litter (Remy et al. 2018; Santonja et al. 2018). This litter serves as a "bridge" for connecting grassland plants with soil to facilitate energy and nutrient transfer. Thus, litter decomposition is critical for regulating availability of soil nutrients, and therefore grassland productivity.

Many experiments have shown that environmental factors, litter properties, and decomposer community composition and structure are the main factors that affect litter decomposition (Smith and Bradford 2003; Chuan et al. 2018; Penner and Frank 2018). Environmental factors such as moisture and temperature alone, and in combination, affect litter decomposition (Aerts 1997), with higher soil moisture and higher temperature generally promoting higher decomposition rates for litter (Wang et al. 2017). Smith and Bradford (2003) reported that the effect of litter quality on the

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rate of decomposition was influenced by the interactions of length of time since deposition and the soil fauna community composition. The quality of the litter directly determines its relative decomposability, and litter quality is dependent on the content and structure of the various constituents such as C and N, which make up the litter tissue (Gallardo and Merino 1993). Other nutrients such as phosphorus content are important, too. Aerts and Caluwe (1997) found that phosphorus and phosphorus-related quality parameters, such as phenol/P, lignin/P, C/P, and N/P, were significantly related to the rate of decomposition in the early decomposition period (< 3 mo) for sedge species. However, terrain is one of the important factors in litter decomposition, as it affects the quality and quantity of litter and further influences its decomposition by modifying temperature and moisture of the soil surface and type of vegetation (Martin and Timmer 2006). Photodegradation and thermal degradation both play a uniquely important role in different terrains in arid and semiarid areas (Austin and Vivanco 2006; Throop and Archer 2009; Barnes et al. 2015).

The Loess Plateau, located in the central and northern part of China, is the largest concentration and contiguous area of loess on the earth. It is also one of the regions with the most serious soil erosion problems and one of the most vulnerable ecological environments in the world (Hu et al. 2019). About 70% of the land area in the Loess Plateau is rolling hills with two aspects, and each side of the hill has steep to shallow slopes with narrow valleys in between. In response to the implementation of a national policy in 2000, grasslands in the Loess Plateau were banned from animal husbandry, which has resulted in the accumulation of plant litter due to the lack of grazing. Changes in vegetation community structure and soil physical and chemical properties after this exclusion from grazing have been widely reported (Eby et al. 2014; Ren et al. 2018). Although changes in litter mass and accumulation in the Loess Plateau have been documented, decomposition of litter after long-term exclusion from grazing has not been reported. Therefore, this study was initiated to examine the decomposition of litter in different terrains found within the Loess Plateau. We hypothesized that soil moisture and temperature differences, as influenced by the slope and aspect of the terrain, would result in differences in the rate of litter mass decomposition and the release of C, N, and P over time. We further hypothesized that these terrain differences would lead to differences in water content, initial C/N amounts, and functional diversity of litter among the slope/aspect combinations.

## Materials and methods

### *Site description*

The research is part of a larger long-term research project initiated in 2001 and was previously described by Chen et al. (2015). Briefly, the study site is in Huanxian County, eastern Gansu Province, northwest China (37°07′N, 106°48′E), which has previously been identified as a pastoral farming basin area with hilly terrain. The average elevation of the study site is 1 700 m, and the mean daily air temperature across the yr is 7.5°C. Annual precipitation has averaged 265 mm over the past 17 yr, with 1993 mm of annual potential evapotranspiration. More than 70% of the precipitation occurs from July to September, which is typical for continental monsoon climates (Hu et al. 2019). The soil is classified as sandy, free-draining loess, and the rangeland is a typical temperate steppe (Cooperative Research Group on Chinese Soil Taxonomy 2001). Vegetation in the study area, mostly short herbaceous plants, is short. The community structure is simple with only about 10 plant species/m$^2$. The dominant plant species are *Artemisia capillaris* Thunb., *Stipa bungeana* Trin., and *Lespedeza davurica* (Laxm.) Schindl. (Hu et al. 2019).

### *Experimental design*

Plots were established at the study site on opposing aspects along a long hill typical of the terrain in the Loess Plateau. The site had been excluded from livestock grazing since 2001. The hill and its ridges were aligned in northwest-southeast direction, with steeper slopes in the southeast and slopes with less steepness in northwest direction. The study had two treatments, slope and aspect. The slope treatment had 3 levels representing degree of slope steepness: 15°, 30°, and 45°. The aspect treatment had two levels: 1) sunny, southwest facing aspect and 2) shaded, northeast facing aspect. Each treatment combination had three replicates. Each replicate was 15 m × 50 m and was randomly assigned to the areas representing the slope and aspect treatment combinations. All the treatments had the same soil type and elevation (±10 m).

In November 2010, litter biomass was collected from the soil surface in each of the treatment plots for subsequent use in litter bags. Only the current yr's litter was obtained. Plant roots, animal residues, and soil were removed from the biomass collected. Litter biomass was oven dried at 65°C and then 20 g of dried material was placed into nylon net bags (size 15 cm × 25 cm, aperture 0.5 mm). Litter biomass was placed in a total of 216 litter bags representing the treatment, replicate, and time period combinations (3 subreplicates × 3 replicates × 2 aspects × 3 slope positions × 4 sampling events). A subset of litter bags was kept to represent the time zero litter condition. The remaining bags were numbered and then randomly placed in the appropriate replicate plots. In April 2011, bags were placed directly on the soil surface and tethered to the soil surface with wire. Tethering was used to reduce removal of the bags by rodents and the chance that bags would shift position on steep slopes. Subsets of the remaining litterbags were removed at 5, 8, and 12 mo after placement. During retrieval, soil and plant material that had accumulated on the surfaces of the bags was carefully removed. After removal from the field, litter bags were dried at 65°C and weights were recorded.

After drying, biomass from the litter bags was crushed and sieved. Litter samples were analyzed for total carbon using external heating-potassium dichromate oxidation method (Nelson 1982), total nitrogen using the Kjeldahl method (Kirk 1950), and phosphorus using the molybdenum diatomite colorimetric method (Sumner 1944). Wet weights of samples were taken after retrieval from the field and before oven drying. The litter water content was measured by weighing the samples after drying the sample at 65°C.

To assess plant species composition, four quadrats (1 m$^2$) were randomly placed in each replicate plot and species composition was measured. The plant species traits information from the quadrats was used to calculate the functional diversity (FD), which measures the dispersion of species in the functional traits space. It was used as a proxy to represent functional diversity of the litter as in the following equation:

$$\mathrm{FD} = \sum_{h=1}^{N} \sum_{k=1}^{N} d_{hk}$$
$$d_{hk} = \sqrt{\sum_{t=1}^{T} (a_{th} - a_{tk})^2} \quad (1)$$

where $d_{hk}$ is the dissimilarity between functional units $h$ and $k$, $a_{th}$and $a_{tk}$ are $t$ trait value of $h$ and $k$ species, and $N$ is the number of species and T is the number of functional units (Schmera et al. 2009).

### *Soil temperature and moisture*

The surface soil temperature and soil moisture were measured in the top 10 cm within each replicate plot at midmonth during each month of the study. Temperatures were recorded at 8 a.m., 2 p.m., and 8 p.m. using a thermometer. Soil moisture in the top 10 cm was determined gravimetrically. Soil was removed and placed in a tin. The sample was then weighed to determine wet weight of the soil. Soil samples were then transported to the laboratory, where they were oven-dried at 105°C to determine dry weight.

### Solar radiation

Solar radiation was recorded once every hour by a weather station from the study site. The weather station is in the flat area. Compared with the weather station, the sampling sites only showed differences in slope and aspect. The solar radiation in each terrain was calculated by recorded solar radiation from weather station (Wang et al. 2002; Jin et al. 2014).

Total solar radiation ($I_{total}$):

$$I_{total} = I_d + I_s + I_r \tag{2}$$

Direct solar radiation ($I_d$):

$$I_d = I_0 \tau_b \cos\theta \tag{3}$$

$$I_0 = S_0 \times \ (1 + 0.0344 \ \cos[360^\circ N/365]) \tag{4}$$

$I_0$ is solar radiation intensity incident to the upper boundary of the atmosphere, $N$ is the number of days in 1 yr, $S_0$ is the solar constant, the amount of solar radiation per unit area of the upper boundary of the atmosphere perpendicular to the direction of solar irradiation and here is taken as 1 367 W/m.

Coefficient of atmospheric transparency ($\tau_b$):

$$\tau_b = 0.56\left(e^{-0.56Mh} + e^{-0.095Mh}\right) \tag{5}$$

$$M_h = M_0 \times P_h/P_0 \tag{6}$$

$$M_0 = \left[1229 + (614 \sin\alpha)^2\right]^{1/2} - 614 \sin\alpha \tag{7}$$

$$P_h/P_0 = [(288 - 0.0065 \ \times \ h)/288]^{5.256} \tag{8}$$

$M_h$ is the mass of the atmosphere at altitude h; $M_0$ is the mass of the atmosphere at sea level; $P_h/P_0$ is the is the coefficient of pressure correction; $\alpha$ is the altitude angle of the sun; and $h$ is the altitude.

$$\begin{aligned}\cos\theta = {} & \sin\delta_s(\sin(lat)\cos(slope)) - \cos(lat)\sin(slope)\cos(aspect) \\ & + \cos\delta_s \cos h_s(\cos(lat)\cos(slope) + \sin(lat)\sin(slope)\sin(aspect)) \\ & + \cos\delta_s \sin(slope)\sin(aspect)\sin h_s\end{aligned} \tag{9}$$

where $\theta$ is the angle of optical incidence on an inclined surface under certain topographic conditions; $\delta_s$ is the declination of the sun; *lat* is geographical latitude; *slope* is the slope of the terrain; *aspect* is the aspect of the terrain; and $h_s$ is the declination of the sun at *s* time.

Scattered radiation ($I_s$):

$$I_s = I_0 \times \ (0.271 - 0.294\tau_b) \ \times \cos^2(slope)/2 \sin aspect \tag{10}$$

Reflection radiation ($I_r$):

$$I_r = \rho \times I_0 \times \ (0.271 + 0.706\tau_b) \ \times \sin^2(slope)/2 \sin aspect \tag{11}$$

where $\rho$ is the surface reflectance.

### Data analysis

The litter water content (lwc) was calculated using this equation:

$$\mathrm{Lwc} = (\mathrm{m_0} - \mathrm{m_1}) \cdot 100\%/\mathrm{m_0} \tag{12}$$

where $m_0$ was the fresh weight of the litter and $m_1$ was the dried weight of the litter. Lwc was used to evaluate the water content of litter from the different terrain treatments (slope, aspect).

The decay rate (k, $d^{-1}$) of litter mass during the incubation period was assessed using a negative exponential model (see Eq. 13] according to Swift et al. (1979):

$$\frac{x_t}{x_0} = e^{-(t \times k)} \tag{13}$$

where $x_t$ is the dry mass of litter remaining in the litter bags at time $t$ (days), $x_0$ is the initial litter mass (i.e., 20 g in this study). The difference in decay rate between treatments was compared according to Julious (2004), which stated that there is no significant difference in decay rate among treatments if there is a 95% confidence interval (CI) overlap. The decay rates across dates and the 95% CI were estimated by fitting the negative exponential model to a nonlinear least square regression model (NLIN Procedure).

To test for differences in measured litter attributes (biomass, decomposition rates, nutrient concentrations, nutrient release, C/N, and water content); soil attributes (moisture, temperature); and litter functional diversity, a general linear model was applied, with slope, aspect, and their interactions as independent factors. Differences in attribute means between the different levels of the slopes and aspect treatments and their associated interactions were verified by Tukey's post hoc test. All analyses were carried out using the SAS 9.3 software (SAS Institute Inc., Cary, NC). Only the data from the last litter bag collection (i.e., 12 months) were used in the general linear model and post-hoc test for the difference analyses. Multiple regression was used to calculate the total effect of the factors (e.g., solar radiation, soil temperature and moisture, litter functional diversity, initial C/N, and water content) on the litter mass loss and C, N, and P release. For these analyses, the regression model was deemed a good fit when $0 \leq \chi^2/\mathrm{df} \leq 2$ and $0.05 < P\ value \leq 1$ (Gherardi and Sala 2015).

## Results

### Initial litter biomass and chemistry

The initial litter biomass differed significantly for the slope and aspect treatments individually; however, the interaction between the treatments was not significant (Table 1). Litter biomass decreased with increasing slope, regardless of aspect. Initial litter biomass was greater on sunny aspects than on shaded ones.

Terrain characteristics also had a significant influence on litter C as indicated by the interaction between slope and aspect (see Table 1). On sunny aspects, litter C had a general trend decreasing with increasing slope; however, only the 15° and 45° slopes were significantly different (see Fig. 1B). On shaded slopes, the highest litter C (47.17% C) was at 30°. Litter C on the shaded, 45° slope was significantly lower (42.62% C) than all the slope aspect combinations (see Fig. 1B). No significant differences in litter C were measured between shaded and sunny slopes at 30°. At 15° and 45°, litter C content was significantly higher on sunny than shaded aspects (see Fig. 1B).

Terrain had a significant influence on litter N with a significant interaction between slope and aspect (see Table 1). On the sunny aspect, litter N decreased with increasing slope, the highest litter N (8.92 mg N $g^{-1}$) being at 15° and the lowest (6.84 mg $g^{-1}$) at a 45° slope. On shaded slopes, the highest litter N (8.87 mg $g^{-1}$)

**Table 1**
Effects of slope (15°, 30°, 45°) and aspect (shaded and sunny) on initial litter production and concentration of litter C, N, and P.

| Parameter | df | Litter biomass (g $m^{-2}$ $yr^{-1}$) | | C (%) | | N (mg $g^{-1}$) | | P (mg $g^{-1}$) | |
|---|---|---|---|---|---|---|---|---|---|
| | | *F* | *P* value | *F* | *P* value | *F* | *P* value | *F* | *P* value |
| Slope | 3 | 4.95 | 0.027 | 35.66 | 0.000 | 68.91 | 0.000 | 249.82 | 0.000 |
| Aspect | 1 | 4.83 | 0.048 | 41.43 | 0.000 | 66.49 | 0.000 | 69.59 | 0.000 |
| Slope × aspect | 2 | 1.50 | 0.262 | 24.97 | 0.000 | 45.46 | 0.000 | 91.43 | 0.000 |

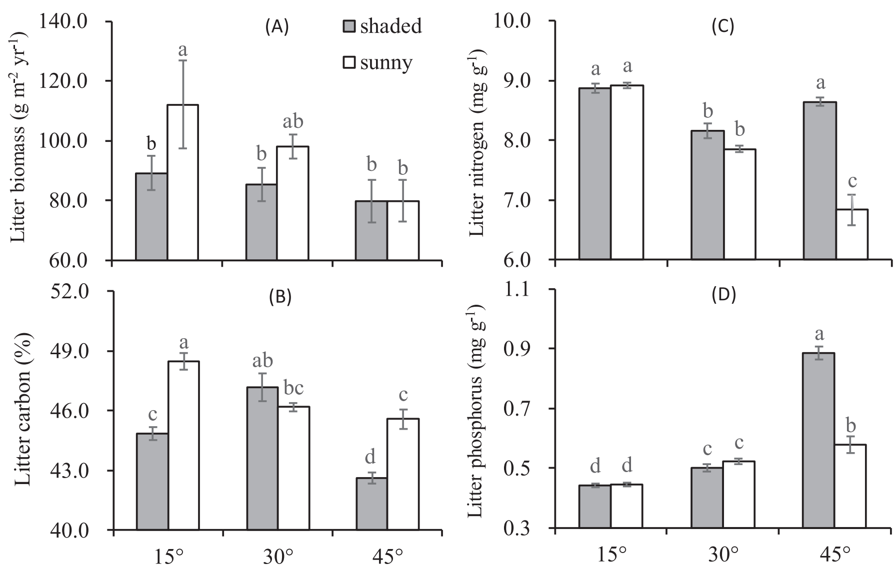


**Fig. 1.** Mean (±standard of error) annual litter biomass (**A**), carbon concentration (**B**), nitrogen concentration (**C**), and phosphorus concentration (**D**) of litter collected from two aspects (shaded and sunny) and three slopes (15°, 30°, and 45°). Different letters indicate significant differences among slopes and aspects ($P < 0.05$).

was at 15° and the lowest (8.16 mg $g^{-1}$) was at 30°, with no significant difference in litter N between the shaded and sunny aspects at both 15° and 30°. At 45°, litter N was significantly higher on shaded than sunny slopes (*P value* < 0.01; see Fig. 1C). And the shaded slope had comparable means to that of the shaded and sunny slopes at 15° (*P* value > 0.05; Fig. 1C).

The interaction of slope and aspect was significant for litter P (see Table 1). On both shaded and sunny slopes, litter P increased with increasing slope, the highest litter P being at 45° (0.89 and 0.58 mg P $g^{-1}$, respectively) and the lowest at 15° (0.44 and 0.45 mg $g^{-1}$, respectively). At 15° and 30° slopes, there was no significant difference in litter P between shaded and sunny faces. Litter P was significantly higher on shaded than sunny slopes at 45° and also represented significantly higher P than all other treatment combinations (*P* value < 0.05; see Fig. 1D).

### *Distribution of soil temperature and moisture and solar radiation*

Soil moisture on shaded slopes was significantly higher than on sunny slopes at 45°. However, soils on the steepest slope had significantly higher soil moisture than the 15° and 30° slopes, which were not significantly different ( Table 3 and Fig. 2A).

The interaction of slope and aspect was significant for temperature (see Table 3). The temperature of the sunny aspect increased with increasing slope, but it decreased with increasing slope on the shaded slope. The temperatures of slope treatments on the sunny aspect were significantly higher than that of the slopes on the shaded aspects (see Fig. 2B and Table 3).

Like temperature, there was a significant interaction between the slope and aspect treatments for solar radiation (see Table 3). The patterns of solar radiation difference among slope and aspect treatments were consistent with the distribution of soil temperature. On the shaded aspect, it decreased as the slope increased, and on the sunny aspect, it increased as the slope increased. Solar radiation of sunny aspects was significantly higher than the shaded aspects, with the exception of the 15° slope (see Fig. 2C).

### *Litter mass decomposition and elements release*

Decomposition of litter mass was calculated using the decay coefficient (k-value) (Fig. 3A). Slope and aspect, as well as their interaction, were significant for litter mass decomposition (Table 2). For sunny aspects, the k-value increased with increasing slope (i.e., $1.20 \times 10^{-3}$, $1.35 \times 10^{-3}$, and $1.82 \times 10^{-3}$ $d^{-1}$ at 15°, 30°, and 45° slopes, respectively). On shaded slopes, k-values were highest at 30° slope ($1.52 \times 10^{-3}$ $d^{-1}$), followed by $1.39 \times 10^{-3}$ $d^{-1}$and $1.36 \times 10^{-3}$ $d^{-1}$ at 15° and 45° slopes, respectively. At both 15° and 30° slope, k-values on the shaded slopes were significantly higher than they were on sunny slopes, but at 45°, the k-value was significantly higher on the sunny slope than it was on the shaded slopes (*P* value < 0.01; see Fig. 3A).

The interaction of slope and aspect was significant for litter C release rate (see Table 2). On sunny aspects, the C release rate was higher on 15° slopes than that on 30°, which had a rate of 3.69 g $yr^{-1}$ of carbon loss. On shaded aspects, the C release rate was greater on 30° slopes (4.54 g $yr^{-1}$) and lowest on 45° slopes (3.12 g $yr^{-1}$). The C release rate was significantly greater on sunny aspects at 15° and 45°, but at 30°, the rate was greater on the shaded aspect (see Fig. 2B).

Litter N release rate had general trends of decreasing N with increased slope angle on both the shaded and sunny aspects (see Fig. 3C). There was a significant difference in aspect, with shaded having higher N release than sunny. For the slopes, 15° and 30° slopes had significantly higher rates of N loss than 45° slope treatments. However, the N release rate on the shaded aspect was

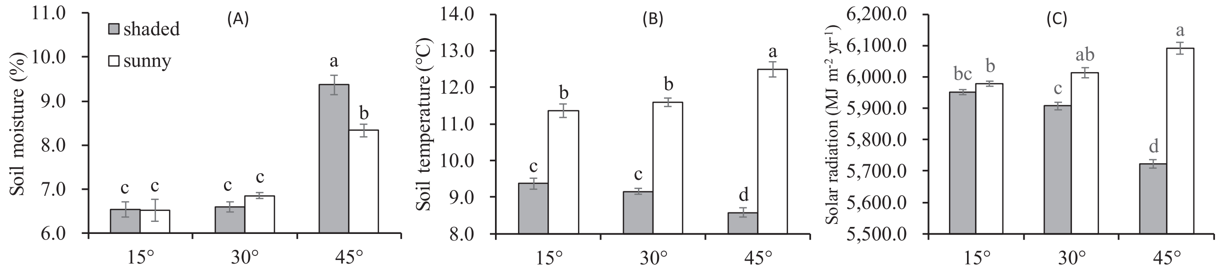


**Fig. 2.** Soil moisture (**A**) and temperature (**B**) and solar radiation of two aspects (shaded and sunny) with three slopes angles (15°, 30°, and 45°). Data presented are mean values, and the bars indicate standard errors. Different letters indicate significant differences among slopes and aspects (*P* value < 0.05).

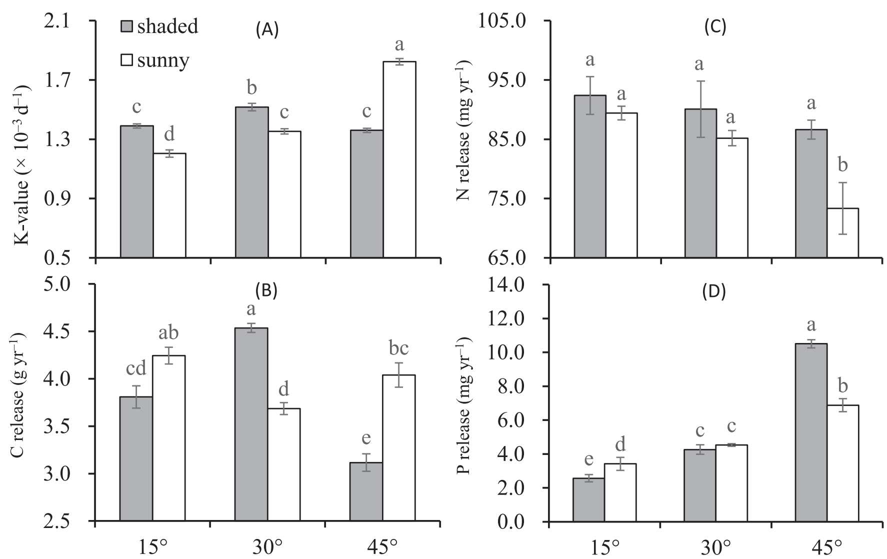


**Fig. 3.** Annual decomposition rate of litter mass (k-value, mean ± standard of error) and release rate of C, N, and P in two aspects (shaded and sunny) with three slopes (15°, 30°, and 45°). Different letters indicate significant differences among slopes and aspects (*P* value < 0.05).

**Table 2**
Effects of slope (15°, 30°, 45°) and aspect (shaded and sunny) on annual decomposition rate of litter mass (k-value) and release rate of C, N, and P.

| Parameter | df | k-value | | C (g yr$^{-1}$) | | N (mg yr$^{-1}$) | | P (mg yr$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|---|
| | | *F* | *P* value | *F* | *P* value | *F* | *P* value | *F* | *P* value |
| Slope | 3 | 162.26 | 0.000 | 28.00 | 0.000 | 9.90 | 0.000 | 330.35 | 0.000 |
| Aspect | 1 | 7.97 | 0.015 | 7.35 | 0.019 | 11.73 | 0.005 | 19.61 | 0.001 |
| Slope × aspect | 2 | 253.17 | 0.000 | 71.75 | 0.000 | 2.38 | 0.135 | 55.46 | 0.000 |

higher than that on the sunny aspect at each slope, and as the slope increases, the rate of N release decreases slower on shaded than sunny aspects.

The interaction of slope and aspect was significant for P loss in litter biomass (see Table 2). The loss of phosphorus from litter increased with increasing slope on both sunny and shaded aspects (see Fig. 3D). The loss was significantly higher on the shaded (10.51 mg yr$^{-1}$) at 45° slope than on the sunny (6.88 mg yr$^{-1}$) at 45° slope. This trend was opposite on the 15° slopes with significantly higher loss on the sunny slope (3.42 mg yr$^{-1}$) than on the shaded slope (2.57 mg yr$^{-1}$). There was no significant difference between shaded (4.26 mg yr$^{-1}$) and sunny aspects (4.53 mg yr$^{-1}$) at 30°.

*Functional diversity, initial C/N, and water content of litter on different terrains*

A significant interaction was found between the slope and aspect treatments for litter functional diversity. No obvious trends in slope and aspect treatment means were apparent. Functional diversity was highest on 30° slopes with shaded aspects and significantly different from all other slope/aspect combinations. Functional diversity was similar on 15° slopes regardless of aspects, and these were not significantly different from 45° shaded slopes (Fig. 4A). Sunny aspects at 30° and 45° had the lowest functional diversity (see Fig. 4A).

Initial litter C/N content at the time of litter collection had significant differences among slope/aspect combinations (see Table 3). Initial C/N values were highest for the 45° slope with the sunny aspect. However, the shaded aspect at this same slope angle had the lowest C/N value (see Fig. 4B). The 30° slope exhibited no significant differences in the aspect treatments with both having moderate C/N levels compared with the 45° sunny aspect and both aspects for the 15° slope angle, which had the lowest values (see Fig. 4B).

The interaction between slope and aspect was significant for the litter water content at the time of litter collection. Sunny

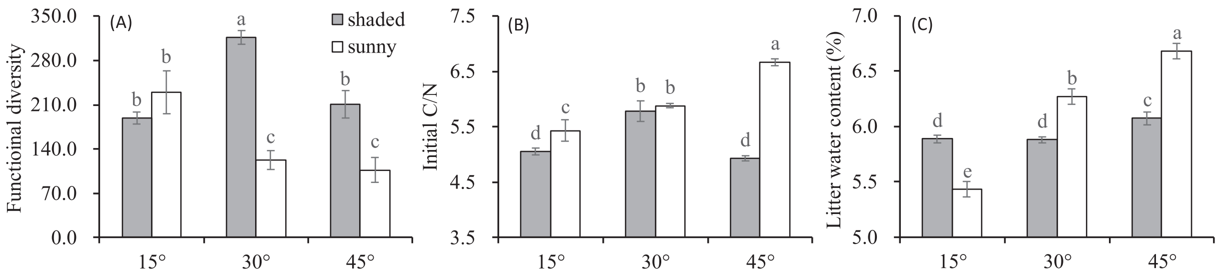


**Fig. 4.** Functional diversity (**A**), initial C/N (**B**), and water content of litter (**C**) in different terrains. Different letters indicate significant differences among slopes and aspects ($P$ value $< 0.05$).

**Table 3**
Effects of slope (15°, 30°, 45°) and aspect (shaded and sunny) on soil temperature and moisture, solar radiation, and functional diversity, initial C/N, and water content of litter.

| Parameter | Soil temperature | | Soil moisture | | Solar radiation | | Functional diversity | | Initial C/N | | Litter water content | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $F$ | $P$ value | $F$ | $P$ value | $F$ | $P$ value | $F$ | $P$ value | $F$ | $P$ value | $F$ | $P$ value |
| Slope | 1.97 | 0.182 | 45.05 | 0.000 | 6.93 | 0.020 | 2.61 | 0.129 | 8.30 | 0.012 | 191.6 | 0.000 |
| Aspect | 762.14 | 0.000 | 0.88 | 0.364 | 87.14 | 0.000 | 11.28 | 0.005 | 21.94 | 0.000 | 19.16 | 0.001 |
| Slope × aspect | 60.44 | 0.000 | 2.16 | 0.163 | 61.75 | 0.000 | 5.32 | 0.037 | 12.51 | 0.003 | 110.83 | 0.000 |

slopes on steeper terrain had the highest water content (see Fig. 4C) with significantly higher water content on the 45° slope compared with the 30° slope. Litter on shaded terrain with 15° and 30° slope angles had similar initial water content and was significantly lower than the 30° and 45° sunny aspects and the 45° shady aspect. The 15° sunny aspect treatment had the lowest initial water content of all treatment combinations (see Fig. 4C).

## Discussion

### *Mechanisms and processes of terrain influencing litter decomposition*

Our results support the hypothesis that characteristics of terrain can influence litter mass decomposition and C, N, and P release by modifying the local environment (solar radiation, soil temperature, and moisture), which, in turn, leads to differences in litter functional diversity and initial C/N and water content of plant litter as aspect and slope vary across the landscape in typical steppe (Fig. 5A). In general, both slope and aspect interacted to influence decomposition. Sunny aspects with steep slopes had the highest rates of decomposition and lowest release of N (see Fig. 3A and 3C).

Soil temperature and solar radiation were also highest for the sunny, steep areas. But they were lowest for the shaded aspect on steep slopes (see Fig. 2B, 2C). Given the differences in solar radiation across the slope and aspect treatment combinations (see Fig. 2C), photodegradation likely played a role in litter decomposition, with the importance of this role mostly driven by aspect on the steepest slopes. Recent studies have shown that photodegradation can be an important driver of litter decomposition in arid and semiarid ecosystems (Austin and Vivanco 2006; Almagro et al. 2016). Austin and Vivanco (2006) reported that photodegradation is a process that breaks down organic matter through solar radiation and directly releases $CO_2$, thereby promoting the decomposed carbon to be directly discharged into the atmosphere without entering the soil organic matter pool. We found that solar radiation was very dependent on the terrain (see Fig. 2C and Table 3), and solar radiation has a significant positive total effect on the mass decomposition of litter but has shown a negative effect on elemental release (C, N, and P) (see Fig. 5B). Effects of soil temperature on litter decomposition has been widely reported (Fiere et al. 2005; Xiao et al. 2014). Aerts (2010) stated that soil warming resulted in increased decomposition rate. Changes in soil temperature with slope were affected by aspect in this study (see Fig. 2B and Table 3). An analysis of the total effects indicated that soil temperature was the main positive factor influencing litter mass decomposition, in addition to C and N release (see Fig. 5B); however, higher temperature appeared to inhibit the release of P (see Fig. 5B). This may be an indication of the differential effect of temperature on C, N, and P microorganisms. Butenschoen et al. (2011) suggested that litter decomposition increased with increasing temperature in the high moisture treatments and decreased with increasing temperature in the low moisture treatments.

In this study, soil moisture exhibited a general trend of increasing soil moisture with increasing slopes on both shaded and sunny aspects; however, differences were significantly only on the steepest slope (see Fig. 2A). Only the release rate of P was consistent with the soil moisture distribution (see Fig. 3D), and we found that the P release was moderately influenced by increasing soil moisture (see Fig. 5B). Peng et al. (2019) found similar results where the P may be subject to the effects of local-scale environmental factors (e.g., moisture or temperature). Soil moisture has been found to be most important during the early decomposition stage (Santo et al. 1993; Cortez 1998) and litter decomposition rates have been found to be positively correlated to increasing soil moisture (Lee et al. 2014).

Litter traits for the plant community appear to influence litter decomposition and nutrient release rates. Some types of litter are rich in nutrients or carbon that can be easily used (labile carbon), whereas others are nutrient-poor or contain high concentrations of organic compounds, such as lignin, that are resistant to degradation (recalcitrant carbon) (Gessner et al. 2010). Initial litter quality (C/N) showed a general trend of increasing quality with increasing slope, except for the steepest, shaded slopes (see Fig. 4C). Wang et al (2018) found that plant litter quality (higher C/N ratio) increased the decay rate of the litter. Our results generally followed this trend with the highest decomposition rates on the sunny, steep slopes where quality was highest and lower decay rates on the flatter slopes where initial quality was lower (see Fig. 3A, Fig. 4B). The total effects analysis indicated that initial litter quality had slightly positive effects on decomposition rate but strong negative effects on N release and moderate positive effects on C release (see Fig. 5B). The litter water content trends across slope and aspect combinations had similar trends to that of decomposition

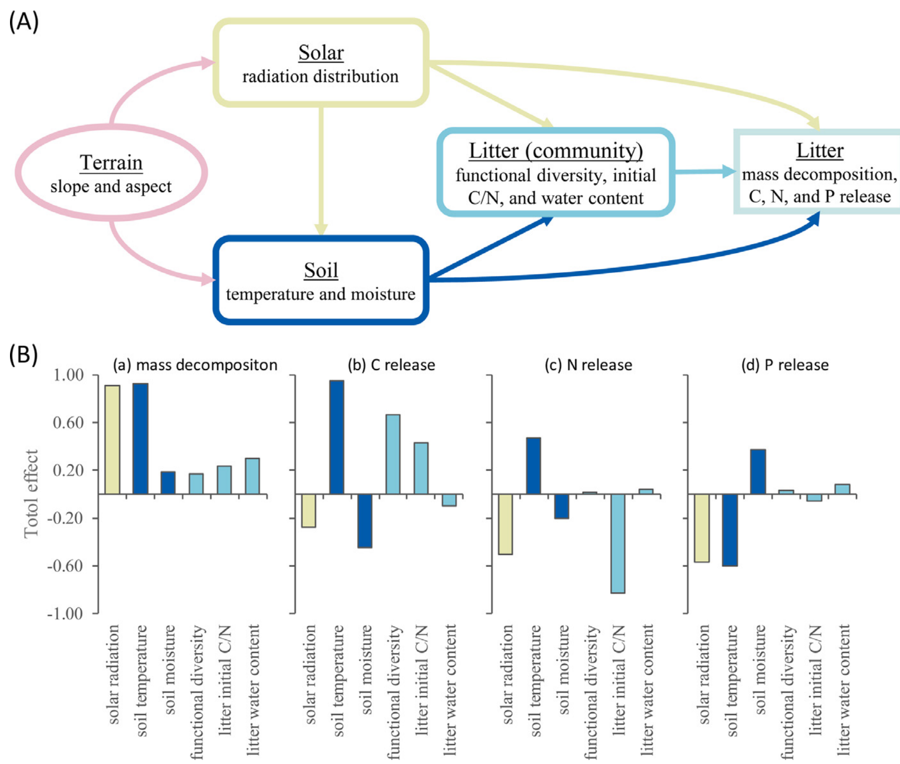


**Fig. 5.** (**A**) A conceptual framework that terrain (slope and aspect) affects litter mass decomposition (k-value) and C, N, and P release through altering soil temperature and moisture and solar radiation and through modifying litter functional diversity, initial C/N, and water content. (**B**) The total effect is the sum of direct (unmediated) and indirect (mediated) effects and is calculated by the covariance matrix of variables. The model is well supported by data ($\chi^2 = 0.275$, df = 2, $P$ value = 0.872).

rates (see Fig. 3A, Fig. 4B). Gogo et al. (2017) found that litter decomposition is sensitive to litter water content with decomposition rates being higher with litter having relatively higher water content, which is similar that observed in this study. When using the community variables to evaluate the total effects, litter water content had the highest effect for decomposition rate, but low effects for C, N, and P release (see Fig. 5B). Interactions between slope and aspect were significant for functional diversity, but no obvious trends across slope and aspect were apparent. The total effects analysis indicate that it had moderate, positive influence on C release and slight positive effects on litter decomposition rate and P release (see Fig. 5B). Litter functional diversity having positive effects on decomposition have also been found in grasslands (Patoine et al. 2017). Litter functional diversity, initial C/N, and water content all appear to play important roles in promoting litter mass decomposition. Functional diversity and initial C/N appear to have the strongest influence on C release. But the higher initial C/N inhibits the release of N. That was consistent with Seneviratne (2010).

*Litter mass decomposition*

The mass decomposition of litter is expressed by the extinction coefficient or k-value. Solar radiation, soil moisture and temperature, litter functional diversity, initial C/N, and water content all exhibited positive effects on the k-value (see Fig. 5B). Solar radiation and surface temperature appear to contribute the most to litter mass decomposition (see Fig. 5B). Petraglia et al. (2018) found similar results in that the k-value was influenced by warmer soil temperatures only in dry and wet sites, whereas in moist soils the decomposition rate did not exhibit any significant response to temperature variation. Austin and Vivanco (2006) have stated that photodegradation can be an important driver of litter decomposition in arid ecosystems.

Using the k values derived for each slope/aspect combination (see Fig. 3A), we calculated the months required for decomposition to remove half (50%) and 90% of litter mass (**Table S1;** available online at …). Values ranged from 42.1 months for the sunny, steep slopes to 63.8 months for the sunny, flatter slopes. The litter in this system mainly comes from aboveground vegetation, and the lack of grazing from long-term exclusion results in litter buildup that some consider as a waste of grassland resources. So, we can use the grass (e.g., mowing or grazing), depending on the time of litter decomposition. Rotational grazing can be implemented in this area, first grazing in the terrain with slow decomposition rate, and then to another terrain with slow decomposition rate, for it can ensure that the grassland is not overgrazed while reducing the litter, and effectively use the forage resources (Bailey and Brown 2011).

## Implications

Our study highlights the importance of solar radiation, soil temperature and moisture, litter functional diversity, initial C/N and water content on litter mass decomposition, and C, N, and P release in different terrains in typical steppe. The distribution of solar radiation, soil temperature, and moisture were influenced by the terrain components of slope and aspect. Overall, terrain influences litter mass decomposition and C, N, and P release by affecting the solar distribution, soil temperature, and moisture, which in turn influence the functional diversity, initial C/N, and water content of litter in this semiarid area. Therefore, the time required for the decomposition of litter varies with the terrain. Grazing may be used in plots where the decomposition rate of litter is slower. On one hand, livestock can reduce the accumulation of litter by feeding, and on the other hand, livestock can promote the decomposition of litter by trampling.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rama.2020.06.004.

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