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Investigating litter production of shrub and grass species in semi-arid rangeland using structural equation model

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Abstract

Litter is the main source of energy which provides nutrients as absorbable form for vegetation. The reaction of plant species to the amount of litter is different. This study aimed to measure litter production and soil carbon of four species (*Artemisa aucheri* Boiss, *Astragalus gossypinus* Fisch, *Stipa barbata* Desf. and *Hyparrhenia hirta* (L.) Stapf) under litter treatments (removing and adding). Four litter treatments (0%, 50 %, 100% and 200% litter) were applied in 20 plots for each species, and then plots were marked. Litter quantity and quality, soil carbon and moisture were measure in fall season. The four species were significantly different in terms of the litter quantity and quality. Response of litter production of the four species to adding and removing litter was different. For all the species, soil carbon were significantly reduced with the removal of litter and increased significantly with the increase of litter ($p<0.05$). Structural equation model indicated that litter removal was the most important driver of litter production directly ($p<0.01$). Litter removal had a significant effect on litter production indirectly through the effect on soil moisture ($P<0.05$). The addition of litter also had a significant effect on litter production indirectly through the effect on soil carbon ($p<0.05$). The findings of this study indicate the importance of maintaining litter (at least 50 %) for the next year's litter production of plants, which should be considered in the sustainable management of rangelands.

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Introduction

Litter includes the dead, above and below ground, organic material i.e. leaves, barks, needles, twigs and roots of plants (Veen et al., 2009). Plant litter is the main component of the ecosystem and plays an important role in regulating biogeochemical cycles in ecosystems (Porre et al., 2020). Litter maintains soil fertility and nutrient availability, thus influencing plant growth, diversity, composition, structure, and productivity (Ma et al., 2013). Plant litter plays a vital role in strengthening biodiversity–ecosystem functioning relationships by contributing decomposing detritus that releases carbon and nitrogen, enhancing soil fertility, altering soil community composition, and mitigating the effects of residue-borne pathogens and pests (Zhang et al., 2023). It also modifies the microclimate and provides essential food resources for arthropods (Cheng et al., 2023). Litter decomposition represents a critical pathway in carbon and nutrient cycling within ecosystems (Grau-Andrés et al., 2022). Furthermore, litter accumulation can influence plant community composition by altering nutrient availability, temperature, and light conditions in the soil, thus establishing an important link between ecosystem processes and productivity (Weltzin et al., 2005).

Decomposition rates are influenced by various factors, including litter quality parameters, microclimate (particularly temperature and soil moisture), soil chemistry, and the composition of the decomposer community (Porre et al., 2020). A layer of plant litter can also regulate soil temperature by intercepting incoming and outgoing radiation, thereby reducing temporal fluctuations. It may also protect plant species and soil from freezing (Facelli & Pickett, 1991). Litter helps stabilize above-ground net primary productivity, species composition, and biodiversity (Amatangelo et al., 2008), and can affect below-ground productivity in rangeland ecosystems. Increases in both above-ground biomass and below-ground net primary productivity have been linked to litter presence, potentially due to its effects on nitrogen availability and soil moisture (Shen et al., 2016).

Studies have reported both positive and negative impacts of litter on plant performance. Positive plant-plant interactions have garnered attention, especially in infertile or arid environments, where even small amounts of litter can alleviate environmental stress, such as low soil moisture (Porre et al., 2020; Zhang et al., 2023). The effects of rangeland plant litter on vegetation are closely linked to litter type, soil nutrient pool, climatic conditions, management practices, and rainfall.

The ecological role of plant litter has been examined across various ecosystems, including grasslands (Hassan et al., 2021), semiarid shrublands (Wang et al., 2017; Abubakar et al., 2025), and forests (Lin & Zeng, 2018; Giweta, 2020). Mohmedi Kartalaei et al. (2023) found that woody vegetation, particularly *Carpinus*, can enhance soil properties at high-altitude, semi-arid, and mountainous sites, which are often fragile and sensitive. In arid ecosystems, perennial grasses and shrubs—two dominant life forms—differ in their litter chemistry, quantity, and timing of litterfall (Campanella & Bertiller, 2008), which significantly affects decomposition rates, nutrient cycling, and related ecosystem functions (Chapin et al., 2000). Selective grazing often reduces plant cover, and various plant types create distinct microenvironments that influence the quality and quantity of litter and its contribution to ecosystem functioning (Vargas et al., 2006).

Climate change and rising atmospheric CO_2 generally increase litter production, while drought, acid rain, and human activities such as forage harvesting tend to reduce it (Zheng et al., 2020). Litter removal and addition treatments yield different impacts on microenvironmental variables and plant community composition, indicating the existence of critical thresholds in ecosystem responses to litter accumulation (Weltzin et al., 2005). Zhang et al. (2024) reported that global forest gaps reduce overall litter quantity but increase the release of carbon and phosphorus from litter. The effects of manipulated litter on species composition and community structure depend on litter type, soil-climate interactions, management practices, intensity, timing, precipitation, and nutrient reservoirs (Mohmedi Kartalaei et al., 2023). Moreover, changes in litter quantity and quality may influence soil microbial properties, including microbial biomass and activity.

Exploring different litter removal and addition treatments can help identify thresholds at which litter hinders or enhances nutrient cycling and plant growth (Wieder et al., 2013). In semi-arid ecosystems, litter accumulation may have negative, positive, or neutral effects, depending on the context (Xiong & Nilsson, 1999; Suding & Goldberg, 1999), suggesting the operation of distinct ecological mechanisms in different plant communities. However, there is limited information on the impacts of manipulated litter on species functioning in arid ecosystems. Understanding how litter production and soil nutrient cycling respond to litter manipulation can improve our knowledge of feedback mechanisms between rangeland ecosystems, climate variability, and land management. Therefore, the present study aims to investigate the effects of litter removal and addition—specifically from shrubs and grasses—on litter production in semiarid rangelands.

Materials and methods

Study area

This study was conducted in Jiroft rangelands located in the southeast of Iran (57°1' to 57°35'E and 28°40' to 29°21'N). The average annual rainfall is about 312 mm. The region has mild summers with an average daily temperature of around 28°C, and relatively cold winters when the average daily temperature of around 38°C. The study area covers about 1412 square kilometers and its average height above sea level is 2608 meters. The landform is alluvial plain with shallow bedrock within 0.7 to 1.5 m of the ground surface. The soils are loamy and sandy loam entisols. The main plant species are *Artemisa aucheri* Boiss, *Astragalus gossipynus* Fisch, *Stipa barbata* Desf. and *Hyparrhenia hirta* (L.) Stapf.

Data collection

To measure litter quantity, twenty 1 m × 1 m plots were established beneath the canopies of four species: *Artemisia*, *Astragalus*, *Hyparrhenia*, and *Stipa*, following the methodology of Triadiati et al. (2011). In each plot, all dead leaves on the soil surface were collected and weighed, and a 50-gram subsample was taken to determine litter carbon content. The carbon percentage of the litter samples was measured using the combustion method.

For litter treatment application, 20 adult individuals of each species were selected. The longest and perpendicular canopy diameters, leaf area, and height of three shrub species were measured. For each species, five plots were assigned to have all litter removed from the surface (0% litter) and this collected litter was then added to five other plots, effectively doubling the litter amount (200% litter). Another five plots had half of their litter removed (50% litter), and five plots served as controls with no litter manipulation (100% litter). All plots were clearly marked.

Soil samples weighing one kilogram were collected from a depth of 0–30 cm in each of the 80 plots during the fall season (MacDicken, 1979). Soil carbon content and soil moisture were measured, with soil carbon percentage determined using the Walkley-Black method (Nelson & Sommers, 1982). In addition, all dead leaves on the soil surface of each plot were collected and weighed, and a litter sample was taken to analyze litter carbon content.

Data Analysis

Before data analysis, the Kolmogorov–Smirnov test was applied to assess the normality of the data distribution. Two-way ANOVA followed by LSD tests were used to compare plant species regarding litter production, litter carbon, and soil carbon under different litter treatments. Litter treatments influence litter production through multivariate interactions involving soil and plant characteristics.

Structural equation modeling (SEM) is a robust multivariate technique increasingly used in environmental studies to analyze complex causal relationships. SEM combines regression analysis with confirmatory factor analysis and has recently been employed to explore the direct and indirect interactions among ecosystem components (Wang et al., 2018; Li et al., 2020; Langlois et al., 2021).

Results

The results of the ANOVA analysis indicated significant differences among the four species in both litter production and litter carbon content (Table 1). The LSD test revealed that *Hyparrhenia* had the highest average litter production at 245 ± 43 g·m⁻². Following *Hyparrhenia*, *Astragalus*, *Artemisia*, and *Stipa* ranked next with average litter production values of 138 ± 25, 112 ± 25, and 94 ± 31 g·m⁻², respectively (Figure 1). Regarding litter carbon content, significant differences were observed among the species ($p < 0.01$, Table 1). *Astragalus* had the highest average litter carbon at 5.75 ± 2.8%, followed by *Artemisia* (2.66 ± 0.8%), *Hyparrhenia* (1.46 ± 0.5%), and *Stipa* (0.92 ± 0.2%).

The ANOVA test also showed significant differences in litter production across different litter treatments for all species (Table 2). For *Hyparrhenia*, the highest litter production occurred under the 0% litter treatment, averaging 360 ± 23 g·m⁻², while the lowest was observed in the 200% litter treatment with 130 ± 36 g·m⁻². In contrast, *Stipa* produced the most litter in the 200% litter treatment, averaging 152 ± 43 g·m⁻². Similarly, *Artemisia* and *Astragalus* showed their highest litter production under the 200% litter treatment, with averages of 187 ± 39 and 223 ± 68 g·m⁻², respectively. However, no significant differences were detected in litter carbon content among treatments for any of the species (Table 2).

ANOVA results also indicated significant differences in soil carbon content across litter treatments for all species. For *Hyparrhenia*, the highest soil carbon percentage was found in the 200% litter treatment (5.9 ± 0.23%), whereas the lowest was under the 0% litter treatment (0.13 ± 1.4%). In *Stipa*, soil carbon was lowest at 0% litter (0.07 ± 0.15%) and highest at 200% litter (0.26 ± 1.18%). For *Artemisia*, the greatest soil carbon percentage was recorded in the 200% litter treatment (0.33 ± 1.73%), with the lowest observed under 0% litter (0.63 ± 0.26%). In *Astragalus*, soil carbon did not differ significantly between the 0% and 50% litter treatments, averaging 0.14 ± 1.11% and 0.59 ± 1.41%, respectively. The highest soil carbon content for *Astragalus* was observed in the 200% litter treatment at 3.17 ± 0.54% (Table 2).

Table 1. One-way variance analysis results for litter production of studied species

Litter carbon	Litter production	
80	80	df
0.432	3.43	MS
5.24	12.34	F
0.00	0.00	p-value

AVE and CR values for the SEM model components were calculated to assess the impact of litter quantity and quality, as well as soil and plant characteristics, on litter production (Table 3). All model components exhibited AVE values above 0.5 and CR values above 0.7, indicating the validity and reliability of the presented model. Figure 2 illustrates the relationships between litter quantity and quality, soil and plant characteristics, and litter production. Among the direct effects, litter removal emerged as the most significant driver of litter production ($p < 0.01$, Table 4), followed by litter addition ($p < 0.01$). Leaf area and photosynthetic pathway were two important plant traits influencing litter production ($p < 0.01$). Additionally, soil carbon and soil moisture were the most influential soil-related factors affecting litter production ($p < 0.01$). Considering both direct and indirect effects, litter removal had a stronger overall impact on litter production than litter addition. Specifically, litter removal significantly influenced litter production indirectly through its effect on soil moisture ($p < 0.05$), while litter addition affected litter production indirectly via soil carbon ($p < 0.05$).

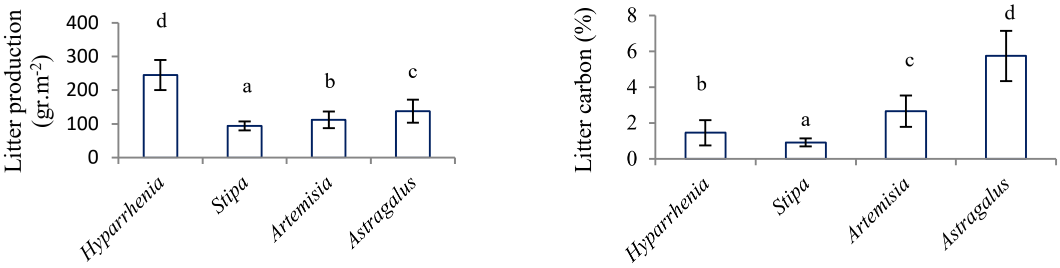

Figure 1. Average litter production and litter carbon of studied species

Table 2. Average litter production, litter carbon and soil carbon of studied species under litter treatment

	Species	F	0% Litter	50% Litter	100% litter	200% Litter
Litter production (gr.m^2)	*Hyparrhenia*	5.56 **	360± 23 d	280± 45 c	200± 15 b	130 ±36a
	Stipa	5.23**	45± 13 a	68± 17 b	110± 27 c	152± 43 d
	Artemisia	7.27 **	35± 19 a	53± 22 b	126± 46 c	187± 39 d
	Astragalus	8.31 **	61± 23 a	90± 37 b	179± 32 c	223± 68 d
Litter carbon (%)	*Hyparrhenia*	1.25 ns	1.49±0.32a	1.34±0.45a	*1.33±0.12a*	*1.23 ±0.43a*
	Stipa	1.47 ns	0.95±0.34a	0.85±0.28a	0.82±0.31a	0.83±0.32a
	Artemisia	1.63 ns	2.77±0.51a	2.65±0.78a	2.45±0.24a	2.54±0.68a
	Astragalus	1.61 ns	5.79±0.39a	5.63±0.91a	5.78±1.21a	5.67±0.47a
Soil carbon (%)	*Hyparrhenia*	8.32 **	1.4± 0.13 a	1.9± 0.21 a	2.7±0.35 b	5.9±0.23c
	Stipa	6.73**	0.15± 0.07 a	0.40± 0.16 b	0.98± 0.36 c	1.18±0.26d
	Artemisia	5.18 **	0.26±0.63 a	0.98± 0.32 b	1.58± 0.72 c	1.73±0.33c
	Astragalus	8.56 **	1.11± 0.14 a	1.41± 0.59 a	2.25± 0.89 b	3.17±0.54c

Table 3. Composite reliability (CR) and convergent validity (AVE) for drivers of litter production

Factors	AVE	CV
Remove litter	0.78	0.82
Add litter	0.81	0.80
Soil carbon	0.89	0.89
Soil moisture	0.76	0.92
Plant height	0.83	0.93
Life form	0.82	0.84
N fixing	0.92	0.87
Cover area	0.85	0.83
Leaf area	0.86	0.92
Photosynthesis pathway	0.73	0.93
Litter production	0.86	0.91

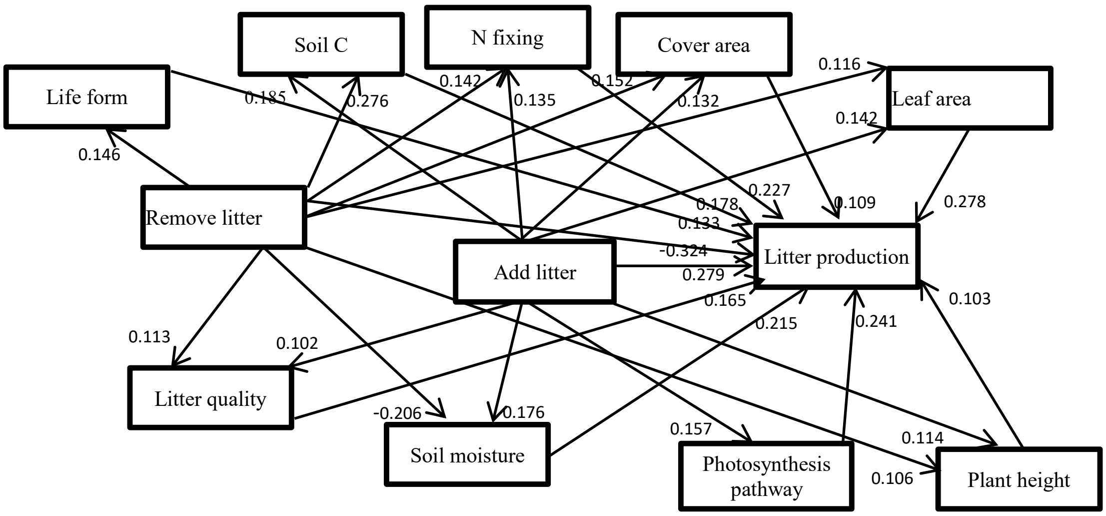

Figure 2. Structural equation modeling (SEM) examining the impacts of litter treatments, litter quality, soil and plant characters on litter production

Table 4. Direct, indirect and total standardized impacts of litter treatments, litter quality, soil and plant characteristics on litter production. Significant impacts are at $P<0.05$(*), $P<0.01$(**), and $P<0.001$(***).

Standard B	pathway	Factors
-0.324**	Direct	Removing litter
0.053	Indirect through soil carbon	
-0.123*	Indirect through soil moisture	
0.032	Indirect through plant height	
0.041	Indirect through life form	
0.021	Indirect through N fixing	
0.037	Indirect through cover area	
0.026	Indirect through leaf area	
0.034	Indirect through photosynthesis pathway	
0.659***	Total	
0.279**	Direct	Adding litter
0.135*	Indirect through soil carbon	
0.065	Indirect through soil moisture	
0.031	Indirect through plant height	
0.024	Indirect through life form	
0.018	Indirect through N fixing	
0.019	Indirect through cover area	
0.021	Indirect through leaf area	
0.016	Indirect through photosynthesis pathway	
0.608***	Total	
0.227**	Direct	Soil carbon
0.215**	Direct	Soil moisture
0.103*	Direct	Plant height
0.178*	Direct	Life form
0.138*	Direct	N fixation
0.109	Direct	Cover area
0.278**	Direct	Leaf area
0.241**	Direct	Photosynthesis pathway

Discussion

The results of this study showed that Hyparrhenia, a C4 grass species, produced the highest amount of litter. Previous research has indicated that C3 species exhibit lower photosynthetic activity compared to C4 grasses (Li et al., 2023). In arid and semi-arid regions, temperature positively influences the growth of C4 plants (Jiang et al., 2018; Hadi et al., 2020). Higher temperatures and stronger radiation during the growing season promote C4 plant growth (Areejit & Martin, 2013; Jiang et al., 2018). Due to their efficient water use and optimal nitrogen utilization during photosynthesis, C4 grasses often outperform C3 species in dry environments and exhibit greater competitive ability (Taylor et al., 2014). The above-ground biomass of C4 plants also helps stabilize ecosystem carbon exchange (Liu et al., 2018; Wu et al., 2021).

Astragalus species produced the highest litter carbon content. Since organic carbon in litter serves as the primary energy source for decomposers (Liu, 2012), the growth rate and efficiency of decomposers are mainly determined by nutrient availability and litter quality (Giebelmann et al., 2013). Oli et al. (2018) reported that leguminous species contribute more nutrients to the soil than non-leguminous species, which also enhances soil microbial biomass. Although C4 grasses produced more litter overall than shrubs, their litter quality was lower. Zhou et al. (2012) found that grass litter quality is lower than that of shrubs in dry regions, with decomposition rates in perennial grasses being 61.8% slower than in shrubs.

Soil carbon content was higher under *Hyparrhenia* grass compared to shrub species. Zhou et al. (2012) similarly reported greater soil organic carbon under perennial grasses due to the high volume input of low-quality litter that resists decay and the limited microbial decomposition capacity. This litter accumulates over years, enhancing soil carbon. Astragalus ranked second in soil carbon content. Beyond litter quantity, leguminous species improve soil nitrogen, positively influencing soil carbon storage (Chen et al., 2015). Legumes also accelerate nutrient return from litter to soil. In rangeland ecosystems, legumes are crucial for improving forage quality, stabilizing atmospheric nitrogen, and enhancing soil fertility by maintaining soil organic matter and improving soil physical properties (Porqueddu et al., 2016). Non-legume litter decomposes slowly, releasing nutrients gradually, whereas leguminous residues decompose more readily, providing faster nutrient availability (da Silva et al., 2020; Hou et al., 2021).

The study further showed that both litter removal and addition significantly affected overall litter production. Litter removal positively and significantly stimulated *Hyparrhenia* growth, while increased litter reduced litter production. Previous studies have also demonstrated that in some grasslands, a thin litter layer enhances performance more than a thick one, as thick litter can hinder species growth and development (Violle et al., 2006). Under the 50% litter treatment, litter production decreased by 49% and 57% for Astragalus and Artemisia, respectively, and dropped further by 65% and 72% with complete litter removal. Thus, litter production was more sensitive to litter removal, a factor that should be considered in semi-arid rangeland grazing management. Sustainable rangeland management should adjust exploitation intensity to maintain at least 50% of the litter cover in desert communities. The presence of Astragalus alongside Artemisia may positively influence species performance, as Song et al. (2020) found that proximity to legumes mitigates the negative effects of leaf and debris harvesting.

The most substantial impact of litter removal on litter production was indirect, mediated by soil moisture. Prior research has shown that soil moisture regulates ecosystem carbon exchange in grasslands (Ganjurjav et al., 2018; Liu et al., 2019). Li et al. (2020) argued that increased soil moisture promotes plant productivity, and generally, soil moisture plays a vital role in carbon fixation (You et al., 2020). Kamruzzaman et al. (2019) demonstrated that in dry areas, litter production and decomposition are closely linked to rainfall events. Litter increases soil moisture by absorbing rainwater and by intercepting sunlight, thereby reducing evaporation from the soil surface and enhancing moisture retention (Ogée et al., 2001). Therefore, litter removal can reduce the soil's capacity to absorb water and nutrients (Cadish & Giller, 1997). Conversely, the main effect of litter addition on litter production was indirect, through increased soil carbon. Pang et al. (2021) highlighted a strong linkage within the plant-litter-soil continuum.

Conclusion

Considering the greater sensitivity of litter production to litter removal than to litter addition, this study's findings emphasize the importance of maintaining litter for sustaining future litter production. This consideration is critical for the sustainable management of rangeland ecosystems. Specifically, grazing management in semi-arid rangelands should ensure that at least 50% of the litter cover remains to support plant productivity and ecosystem stability. The positive effects of leguminous species, such as Astragalus, in improving soil fertility and mitigating stress on neighboring species like Artemisia, further highlight the importance of plant community composition in rangeland management.

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