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# Grazing effects on species diversity across different scales are related to grassland types

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## Abstract

**Background** Community species in different grassland types exhibit unique ecological traits and adaptation strategies, influencing the impact of grazing on species diversity at various scales. This study aimed to elucidate the response characteristics and rules of species diversity in different grassland types to grazing intensity by analyzing plant groups and species diversity.

**Results** Grazing intensity, grassland type, and their interaction significantly affected α, β, and γ diversity. In meadow steppes, α and γ diversity conformed to the intermediate disturbance hypothesis, exhibiting a unimodal trend with increasing grazing intensity—initially increasing and then decreasing. In typical steppes, α, β and γ diversity showed no clear pattern in response to changes in grazing intensity. In desert steppes, α, β and γ diversity consistently declined with increasing grazing intensity. In meadow steppes, dominant and common species were crucial for sustaining community (α diversity) and landscape (γ diversity) diversity, whereas rare species primarily contributed to increased gradient differences (β diversity). In typical steppes, rare species were pivotal for community (α diversity) and landscape (γ diversity) diversity, while dominant and common species were important in reducing gradient differences (β diversity). In desert steppes, rare species were vital for maintaining community diversity (α diversity), dominant species played a key role in reducing gradient differences (β diversity), and common species were important for maintaining landscape-level diversity (γ diversity).

**Conclusions** The characteristics and patterns of grazing intensity on species diversity at different scales, as well as the dominant plant group influencing plant species diversity at different scales, are controlled by grassland types. These findings highlight the need for tailored management strategies to conserve species diversity in various grassland ecosystems under different grazing pressures.

**Keywords** Desert steppe, Grazing intensity, Meadow steppe, Plant group, Plant species diversity, Typical steppe

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## Introduction

Grassland ecosystems are one of the most widely distributed ecosystems on Earth [1], which play a critical role in biodiversity conservation, soil and water preservation, climate regulation, and the sustainable development of human society [2]. In grassland ecosystems, species diversity is regarded as a key factor in maintaining ecological functions and long-term stability [3]. A rich diversity of species enhances ecosystem stability and resilience through functional complementarity among species [4, 5]. However, with increasing human activities and growing economic pressures, grassland ecosystems and their biodiversity are facing unprecedented threats.

Grazing is a principal utilization of grassland [6, 7], and its impact on grassland ecological diversity has always been a focal point in ecological research. Grazing disturbance can induce alterations in species composition, modify the structure of plant communities, and influence the diversity of species within grassland ecosystems. For instance, research conducted in alpine meadows of the Tibetan Plateau revealed that species richness and abundance exhibited an upward trend under light grazing conditions [8]. Subsequently, with the intensification of grazing, community height, cover, and biomass demonstrated a declining trend [9]. The intermediate disturbance hypothesis proposes that moderate disturbance can achieve a balance between inhibiting highly competitive species and promoting the coexistence of more species, thus maintaining a high plant species diversity [10], while overgrazing will lead to the increase of undesirable species [11], the decrease of plant cover and the plant species diversity [12, 13], and ultimately will lead to degradation of grassland ecosystems. These findings suggest that grazing can have a broad impact on plant species diversity, but the results may vary depending on grazing intensity and grassland type.

The study of diversity of plant communities is crucial for analysing and understanding changes in community structure. Whittaker divided plant species diversity into α, β and γ diversity according to different spatial scales [14], which are both related and different [15]. The α diversity refers to the number of plant species contained within a community; γ diversity takes into account the total number of all the different species found in an entire region or in multiple different communities; β diversity is a bridge between α and γ diversity, reflecting differences in species composition between different communities or treatments, and it can be used to measure species turnover among plant communities. These three dimensions of diversity offer a comprehensive local-to-global analytical perspective, enhancing the understanding of changes in plant community structure and their ecological implications.

The area of natural grassland in Inner Mongolia Autonomous Region is about $8.8\times10^7$ ha, accounting for 35% of the total grassland area in China. It is not only a crucial component of China's grassland ecosystem, but also serves as a foundational pillar for China's traditional pastoral industries [16]. Meadow steppe, typical steppe and desert steppe are the three main grassland types in Inner Mongolia grassland [17]. These three grasslands exhibit unique vegetation structures due to their geographical location, climate, soil and other environmental conditions, thus affecting plant species diversity. The response of grassland with rich plant species to grazing intensity is different from that of grassland with few plant species [18], and grassland with good initial ecological environment can often withstand greater grazing pressure [19]. Despite significant progress in research on the effects of grazing on species diversity, many studies have focused primarily on local-scale diversity (α diversity), neglecting the changes in species turnover (β diversity) and overall regional diversity (γ diversity). Additionally, existing research often concentrates on specific grassland types, lacking systematic comparisons of the relationships between different grassland types and grazing intensities. Ignoring the combined effects of these three factors may lead to generalized management strategies that fail to address the specific needs of different grassland types. Therefore, it is crucial to integrate research on different scales, grassland types, and grazing intensities, as this will provide a more comprehensive perspective and support the development of more precise grassland management strategies, ultimately achieving sustainable ecological protection.

In summary, this study takes three main grassland types (meadow steppe, typical steppe and desert steppe) in Inner Mongolia as research objects, aiming to explore the effects of different grassland types and different grazing intensity (control area, light grazing, moderate grazing and heavy grazing) on species diversity at different scales (α, β and γ), and to answer the following questions: 1) How does species diversity respond to grazing intensity and grassland type? 2) What are the variation characteristics and patterns of species diversity at different scales (α, β and γ) in different grassland types? 3) Whether the effects of plant group on α, β and γ diversity are consistent in different grassland types under grazing conditions? The answers to these questions cannot only clarify the effects of grazing on species diversity at different scales (α, β and γ) in different grassland types, but also provide scientific basis for grassland ecological protection and sustainable grassland utilization.

## Materials and methods

### Natural overview of the study area

The research area is located in Siziwang Banner, Ulanqab, Hulunbuir and Maodeng Ranch, Xilin Hot, Inner Mongolia Autonomous Region, respectively (Table 1). A total of 15 plant populations belonging to 6 families and 12 genera were found in the typical steppes of Maodeng Ranch in 2022, including 5 species of annual and biennial herbs and 10 species of perennial herbs. The families with the largest number of species were *Gramineae* (7 species) and *Compositae* (3 species), with single families accounting for 50% of the total family number. The community type was *Leymus chinensis* + *Stipa grandis* + *Cleistogenes squarrosa*. In the meadow steppes of Hulunbuir, a total of 69 plant populations belonging to 22 families and 53 genera were found during the 2022 monitoring, including 11 species of annual and biennial herbs and 58 species of perennial herbs. The most abundant species were *Compositae* (12 species), *Gramineae* (11 species), *Fabaceae* (8 species), *Liliaceae* (6 species) *and Rosaceae* (6 species). The single family accounted for 45% of the total family number, and the community type was *Leymus chinensis* + *Stipa baicalensis Roshev* + *Cleistogenes squarrosa*. A total of 29 plant populations belonging to 14 families and 24 genera were detected in the desert steppes of Siziwang Banner in 2022, including 5 species of annual and biennial herbs, 4 species of shrubs, and 20 species of perennial herbs. The most abundant species were *Gramineae* (6 species), *Amaranthaceae* (5 species), *Fabaceae* (3 species), and *Compositae* (3 species), with single species accounting for 57% of the total families. The community type was *Stipa brevifloris* + *Cleistogenes songorica* + *Artemisia frigida*. Based on the frequency data of various fields in the three types of grassland investigated and the results of years of observation, the plant species were divided into three parts: dominant species, common species and rare species (Dominant species were identified based on specific grassland types as defined by the Chinese grassland classification system, as these species are typically characteristic of their respective ecosystems and play crucial structural and functional roles; Common and rare species were classified based on species frequency. In the typical and desert steppes, we categorized species with a frequency of less than 0.03 as rare, while those with a frequency above this threshold were considered common. In the meadow steppe, we applied a stricter threshold of 0.4 to identify rare species, see Appendix Table 1-Table 3).

### Experimental design

The grazing experiment employed a randomized block design, comprising three block groups. Each group included four distinct grazing intensities: control (CK), light grazing (LG), moderate grazing (MG), and heavy grazing (HG), culminating in a total of 12 experimental plots. In meadow steppes, grazing intensities were established with 0, 2, 4, and 6 beef cows per treatment, corresponding to stocking rates of 0.00 Au/ha, 0.23 Au/ha, 0.46 Au/ha and 0.69 Au/ha, respectively, (Here, a 500 kg beef cattle was used as a standard cattle unit, and the number of grazing beef cattle of 250–300 kg was used to control the implementation of different grazing gradients, and the average weight of beef cattle was about 285 kg). One cattle unit was equivalent to 2.5 sheep units, and the stocking rates were 0.00, 0.58, 1.15 and 1.73 sheep units $\bullet(\text{ha}\bullet\text{y})^{-1}$, respectively. The annual grazing began on June 15 and ended on October 15, spanning 120 days, and the plot area was 5 ha. The typical steppes grazing 0, 4, 8 and 12 sheep (average weight of sheep in each plot 31.5 kg), equivalent to 50 kg sheep units, stocking rates were 0.00, 0.47, 0.93 and 1.40 sheep units $\bullet(\text{ha}\bullet\text{y})^{-1}$, respectively; the grazing time began in mid-June and ended in mid-September for about 90 days, and the area of the plot was 1.33 ha. The desert steppes grazed 0, 4, 8 and 12 wether (the average weight of wether was about 50 kg, with a range of 45–55 kg), and the stocking rates were 0, 0.45, 0.91 and 1.36 sheep units $\bullet(\text{ha}\bullet\text{y})^{-1}$, respectively. The annual grazing began in June (adjusting for later starts in drought years) and ended at the end of November. The grazing time was about 180 days, and the plot area was 4.4 ha. In August 2022, ten 1 m × 1 m sample plots were randomly selected from the 12 plots of desert steppes (grazing started in 2004 and has been grazed for 19 years), and five 1 m × 1 m sample plots were randomly selected from the 12 plots in each of typical steppes (grazing started in 2014 and has been

**Table 1** Basic overview of the study area

| Grassland types | Area | Geographic location | Altitude(m) | Annual precipitation(mm) | Average temperature(℃) |
|---|---|---|---|---|---|
| Meadow steppes | Hulunbuir | N49°19′–49°20′, E119°56′–119°57′ | 650–700 | 380–400 | 4.50 |
| Typical steppes | Xilin Hot | N43°26′–44°33′, E115°32′–117°12′ | 800–1200 | 350–380 | 3.63 |
| Desert steppes | Siziwang Banner | N41°10′–43°22′, E110°20′–113° | 1000–2100 | 240–386 | 6.24 |

grazed for 9 years) and meadow steppes (grazing started in 2009 and has been grazed for 14 years), for a total of 240 1 m×1 m sample plots were selected. The number of species in each sample plots were recorded. After recording, the plants in the sample plots were packed into numbered envelopes and brought back to the room by ground cutting method.

#### Calculation of plant species diversity

In this study, the plant species diversity index calculated based on frequency data was used to investigate the effects of different grazing intensity and grassland types on α, β and γ diversity. The calculation method was as follows:

α diversity index: $\alpha$=number of species in each survey sample plot;
β diversity index: $\beta = 1 - \overline{\alpha}/\gamma$ [20], where $\overline{\alpha}$ is the average of α diversity index under grazing intensity;
γ diversity Index: $\gamma$=total number of species recorded under each grazing intensity.

#### Statistical analysis

First, excel 2016 [21] was used to convert the data (logarithmic transformation for α diversity, power transformation for γ diversity), and then, leveneTest function in 'car' [22] and jarque.bera.test function in 'tseries' [23] in R [24] were used for normality test and variance homogeneity test, and aov function was used for repeated two-way ANOVA. The significance of grazing intensity and grassland type and their interactions on α, β and γ diversity were analyzed, and TukeyHSD multiple comparison was performed using TukeyHSD function in 'MASS' [25]. The resulting results are rendered in a bar plot using the geom_bar function in 'ggplot2' [26]. Then, the difference ratios of α (β, γ) diversity in other treatment areas relative to the CK treatment area were calculated using excel, and a bar chart was drawn using the geom_bar function in 'ggplot2'. Secondly, Origin 2024 [27] was used to plot the numerical contour maps of α, β and γ diversity under different grassland types and grazing intensity. Finally, with plant groups as fixed effects and grazing intensity as random effects, a mixed linear model was established using the lmer function in 'lme4' [28], and the total variation of α (β, γ) diversity was further divided into three parts: dominant species, common species and rare species. The glmm.hp function in 'glmm.hp' [29] was used to decompose the contribution rates of plant groups to α, β and γ diversity in different grassland types, and the ggplot function in 'ggplot2' was used to draw stacked bar charts to present the results.

## Results

### Change of α, β and γ diversity of plant community

#### *Change of a diversity of plant community*

The results of two-way ANOVA (Table 2) showed that grazing intensity did not significant influence α diversity ($P>0.05$), whereas grassland type had a highly significant effect on α diversity ($P<0.01$), and the interaction between grazing intensity and grassland type significantly affected α diversity ($P<0.05$). There was no significant difference in the effects of grazing intensity on α diversity (Fig. 1A); meadow steppes exhibited significantly higher α diversity than both typical and desert steppes (Fig. 1B); the α diversity of meadow steppes was significantly higher than the other two grassland types, while there was no significant difference between typical and desert steppes (Fig. 1C). These results indicated that meadow steppes had higher α diversity, while typical steppes and desert steppes have relatively lower α diversity. There was no significant difference in α diversity of plant communities in the four grazing treatment areas of meadow steppes, typical steppes and desert steppes. The α diversity of meadow steppes showed a trend of first increasing and then decreasing with the increase of grazing intensity; the pattern of change of typical steppes α diversity was not obvious; the α diversity of desert steppes continued to decrease with the increase of grazing intensity (Fig. 1C), and this process of change resulted in insignificant differences in α diversity under grazing intensity (Fig. 1A). In meadow steppes, α diversity in LG, MG and HG treatment areas was increased compared with CK treatment area, and MG treatment area was more prominent. However, in typical steppes and desert steppes, α diversity in LG, MG and HG treatment areas decreased compared with CK treatment areas, and α diversity in desert steppes decreased with the increase of grazing intensity (Fig. 1D). The above results showed that α diversity was highest in meadow steppes, moderate grazing was beneficial to α diversity in meadow steppes, and the reduction of grazing intensity was more beneficial to α diversity in typical steppes and desert steppes.

**Table 2** Results of two-way ANOVA for the effects of grazing intensity and grassland type on α diversity of plant communities

| Indicator | Df | F value | *P* value |
|---|---|---|---|
| Grazing intensity | 3 | 0.91 | 0.45 |
| Grassland type | 2 | 380.91 | 0.00** |
| Grazing intensity×grassland type | 6 | 3.52 | 0.02* |

Note: ** means highly significant difference ($P<0.01$), * means significant difference ($P<0.05$)

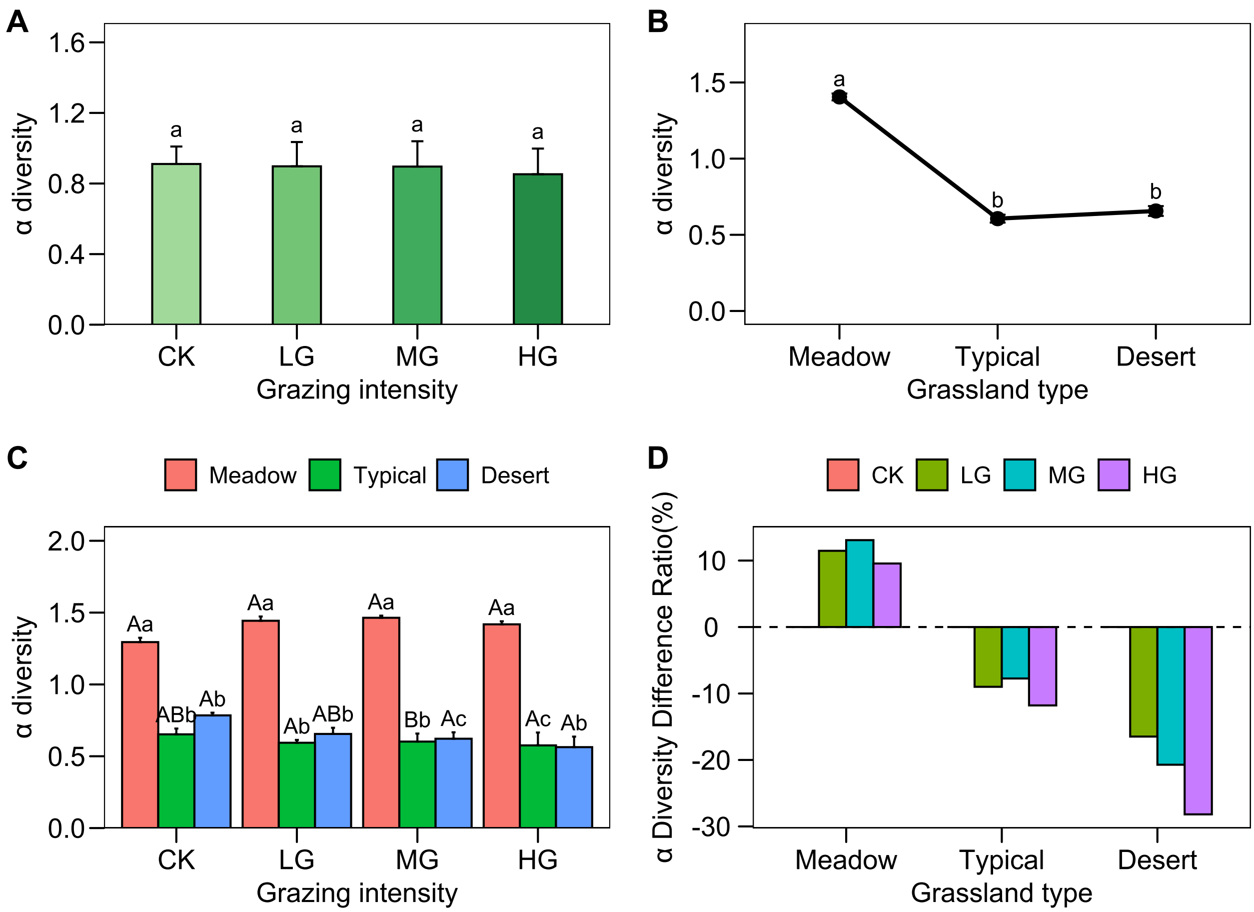


**Fig. 1** Effects of grassland type and grazing intensity on α diversity (mean values ± SE of A, B and C α diversity). Different letters in **A** and **B** indicated significant difference under different grazing intensity ($P < 0.05$); different lowercase letters in **C** indicated significant difference under different grassland types with the same grazing intensity ($P < 0.05$), and different capital letters indicate significant difference under different grazing intensity of the same grassland type ($P < 0.0$ 5). **D** is the difference ratio diagram in α diversity between the three grassland types and the CK treatment area. CK, control area; LG, light grazing; MG, moderate grazing; HG, heavy grazing

**Table 3** Results of two-way ANOVA for the effects of grazing intensity and grassland type on β diversity of plant communities

| Indicator | Df | F value | *P* value |
|---|---|---|---|
| Grazing intensity | 3 | 6.04 | 0.00** |
| Grassland type | 2 | 45.24 | 0.00** |
| Grazing intensity × grassland type | 6 | 3.08 | 0.02* |

Note: ** means highly significant difference ($P < 0.01$), * means significant difference ($P < 0.05$)

### *Change of β diversity of plant community*

The results of two-way ANOVA (Table 3) showed that grazing intensity and grassland type had significant effects on β diversity ($P < 0.01$), and their interaction terms had significant effects on β diversity ($P < 0.05$). Different grazing intensity had different effects on β diversity, and the β diversity in HG treatment area was significantly lower than that in CK treatment area (Fig. 2A); the order of β diversity of the three grassland types was desert steppes > meadow steppes > typical steppes (Fig. 2B). The β diversity of desert steppes was significantly higher than that of typical steppes in CK treatment area; the β diversity in desert steppes was significantly higher than that in meadow steppes and typical steppes in LG treatment area; there was no significant difference in β diversity among the three grassland types in MG treatment area; in the HG treatment areas, the β diversity of meadow steppes and desert steppes was significantly higher than that of typical steppes (Fig. 2C), which suggested that desert grassland had higher β diversity. There was no significant difference between the four grazing treatment areas in meadow steppes and typical steppes; while

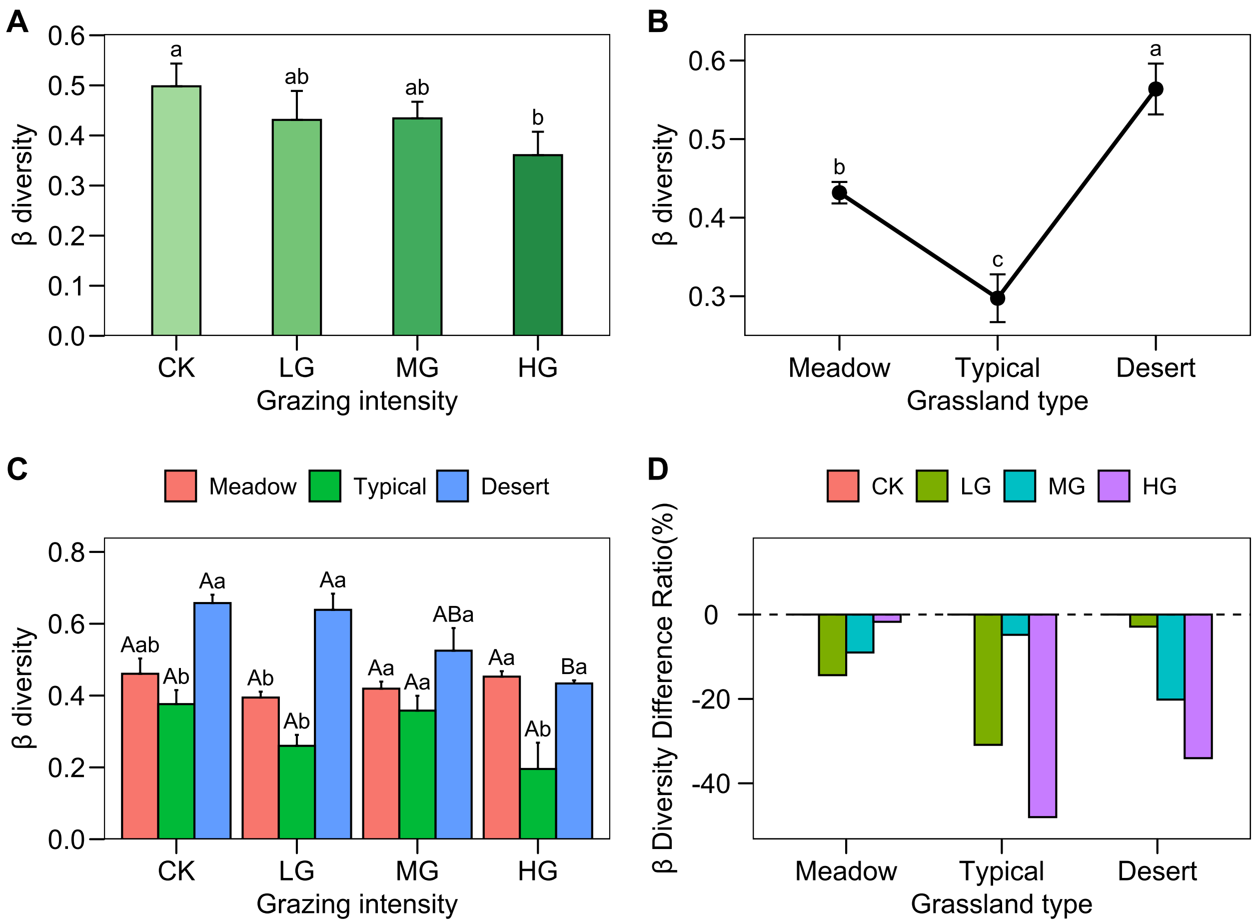


**Fig. 2** Effects of grassland type and grazing intensity on β diversity (mean values ± SE of A, B and C β diversity). Different letters in **A** and **B** indicated significant difference under different grazing intensity ($P < 0.05$); different lowercase letters in **C** indicated significant difference under different grassland types with the same grazing intensity ($P < 0.05$), and different capital letters indicate significant difference under different grazing intensity of the same grassland type ($P < 0.05$). **D** is the difference ratio diagram in β diversity between the three grassland types and the CK treatment area. CK, control area; LG, light grazing; MG, moderate grazing; HG, heavy grazing

in desert steppes, β diversity in CK and LG treatment areas was significantly higher than that in HG treatment areas (Fig. 2C). In meadow steppes, typical steppes and desert steppes, β diversity in LG, MG and HG treatment areas all showed different degrees of decline compared with CK treatment areas (Fig. 2D). Among them, the decrease rates of LG, MG and HG in meadow steppes were relatively small, and the decrease rates decreased with the increase of grazing intensity, the decrease rates of MG in typical steppes were the smallest, and the decrease rates of β diversity in desert steppes increased with the increase of grazing intensity. The above results showed that the increase of grazing intensity would lead to the decrease of β diversity, and the β diversity of desert steppes was higher, while the relative β diversity of grassland with more species (meadow steppes and desert steppes) was less affected by grazing.

### *Change of γ diversity of plant community*

The results of two-way ANOVA (Table 4) showed that grazing intensity had no significant effect on γ diversity

**Table 4** Results of two-factor ANOVA for the effects of grazing intensity and grassland type on γ diversity of plant communities

| Indicator | Df | F value | *P* value |
|---|---|---|---|
| Grazing intensity | 3 | 2.75 | 0.06 |
| Grassland type | 2 | 278.15 | 0.00** |
| Grazing intensity × grassland type | 6 | 4.70 | 0.00** |

Note: ** means highly significant difference ($P < 0.01$), * means significant difference ($P < 0.05$)

($P > 0.05$), while grassland type and their interaction had significant effect on γ diversity ($P < 0.01$). There was no significant difference in the effects of different grazing intensities on γ diversity (Fig. 3A); The order of γ diversity of the three grassland types was meadow steppes > desert steppes > typical steppes (Fig. 3B). There were significant differences in γ diversity among the three grassland types in CK and LG treatment areas, and the order of γ diversity was meadow steppes > desert steppes > typical steppes; in MG and HG treatment areas, γ diversity in meadow steppes was significantly higher than that in typical steppes and desert steppes (Fig. 3C), indicating that meadow steppes γ diversity always maintained a high level, while desert steppes and typical steppes γ diversity levels were relatively low. There was no significant difference in γ diversity of plant communities in the four grazing treatment areas between meadow steppes and typical steppes; the γ diversity of meadow steppes showed a trend of increasing and then decreasing with the enhancement of grazing intensity; the pattern of change in the γ diversity of typical steppes was not obvious; the γ diversity of desert steppes was continuously decreasing with the enhancement of grazing intensity and γ diversity in CK treatment area was significantly higher than that in HG treatment area (Fig. 3C), and this process resulted in no significant difference in the γ diversity under grazing intensity (Fig. 3A). In meadow steppes, γ diversity in LG, MG and HG treatment areas increased compared with CK treatment area, and MG treatment area increased the most; whereas in typical steppes and desert steppes, γ diversity in LG, MG and HG treatment areas all showed a downward trend compared with CK treatment areas, and the decline rate was the smallest in MG treatment areas of typical steppes; while the decline rate of γ diversity in desert steppes increased with the increase of grazing intensity (Fig. 3D). The above results showed that the γ

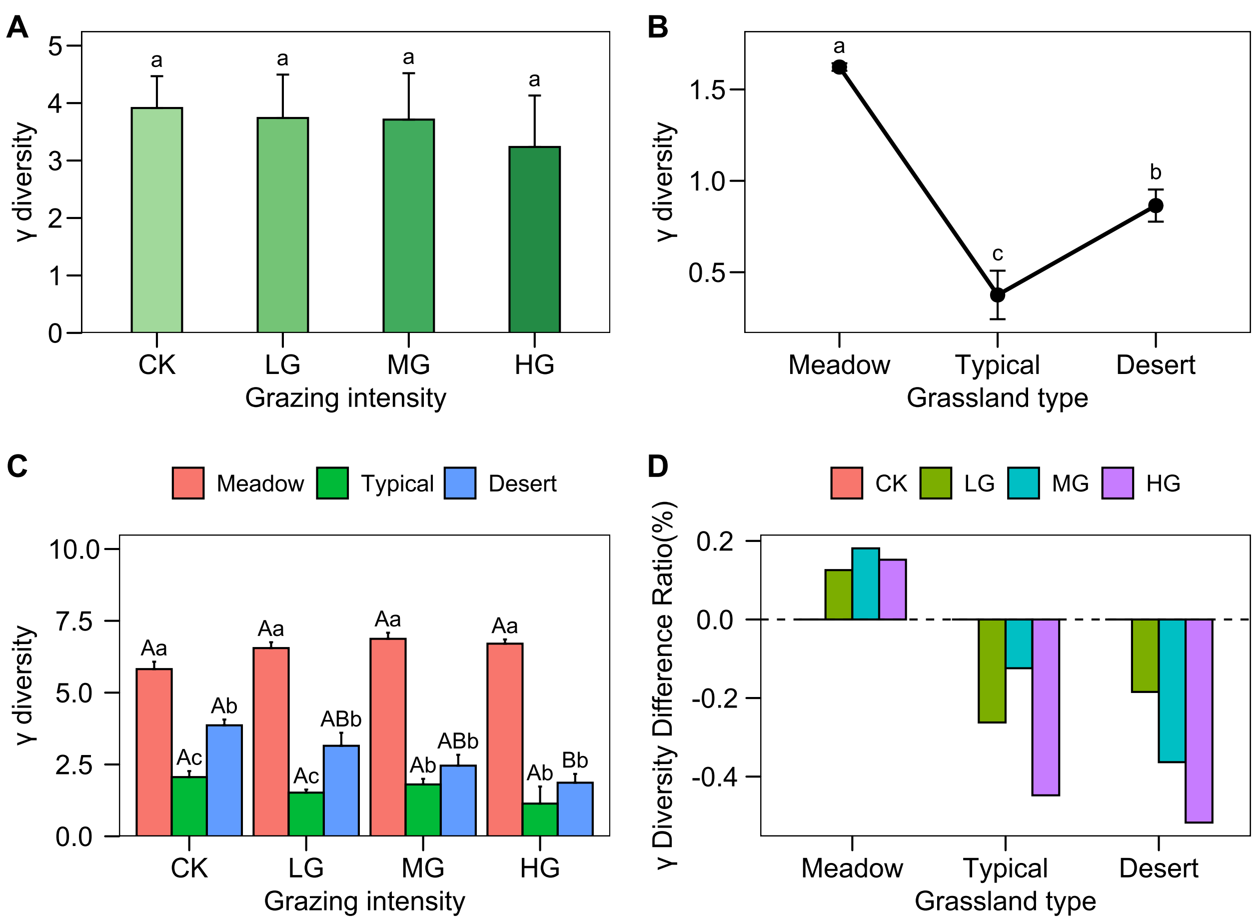


**Fig. 3** Effects of grassland type and grazing intensity on γ diversity (mean values ± SE of A, B and C γ diversity). Different letters in **A** and **B** indicated significant difference under different grazing intensity ($P < 0.05$); different lowercase letters in **C** indicated significant difference under different grassland types with the same grazing intensity ($P < 0.05$), and different capital letters indicate significant difference under different grazing intensity of the same grassland type ($P < 0.05$). **D** is the difference ratio diagram in γ diversity between the three grassland types and the CK treatment area. CK, control area; LG, light grazing; MG, moderate grazing; HG, heavy grazing

diversity was higher in meadow steppes and the relative γ diversity of desert steppes decreased significantly with the increase of grazing intensity.

## Changes in plant diversity under the combined influence of grazing intensity and grassland type

In the transition from typical steppes to meadow steppes, the influence of grazing intensity on meadow plant community α diversity was weak. Close to the meadow steppes, the impact of grazing was primarily evident in the presence or absence of grazing, and the differences among grazing intensities were minimal (Fig. 4A). The response of β diversity in typical steppes and meadow steppes to grazing intensity was more complex. During the transition from typical steppes to desert steppes, β diversity in desert steppes showed a decreasing trend with an increase in grazing intensity (Fig. 4B). With typical steppes serving as a watershed, γ diversity decreased sharply with the increase of grazing intensity when moving towards desert steppes; whereas, when moving towards meadow steppes, grazing intensity had a lesser effect on γ diversity (Fig. 4C). This reflected that the plant community in meadow steppes can maintain relatively stable plant diversity under the influence of grazing, while the plant community in desert steppes is more sensitive to grazing disturbance.

## Effects of plant groups on α, β and γ diversity

The results of the mixed linear model showed that, except for the β diversity of typical steppes, plant groups had extremely significant effects on the three grassland types α, β and γ diversity ($P<0.01$, Table 5), and had significant effects on the β diversity of typical steppes ($P<0.05$). Therefore, the total variation of α (β, γ) diversity was further decomposed into three parts: dominant species, common species and rare species, to analyze the contribution rate of different plant groups. The results showed that,in meadow steppes, common species contributed the most to α diversity, followed by the dominant species, and rare species contributed the least; in terms of

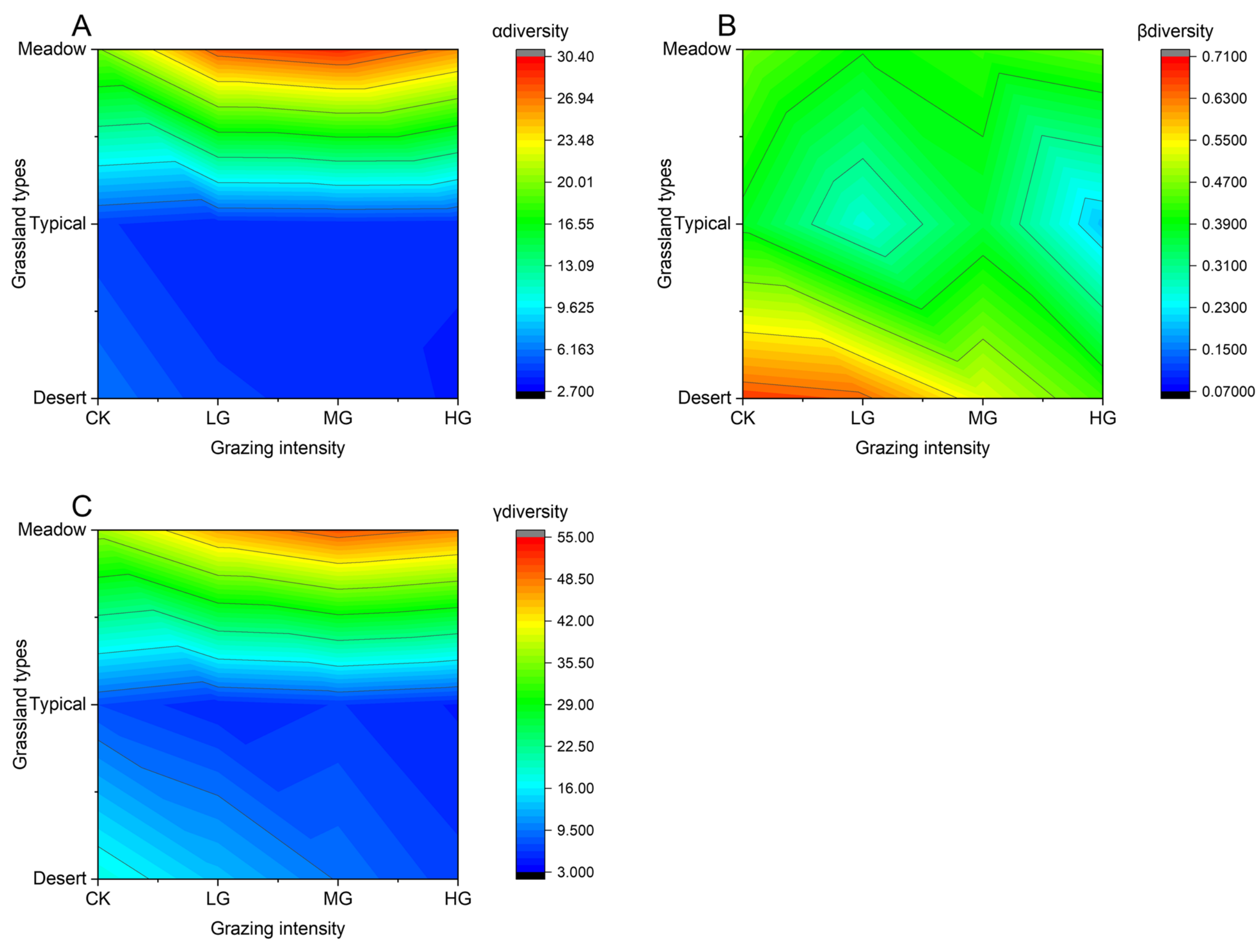


**Fig. 4** Changes of α, β and γ diversity under different grazing intensity and grassland type. **A**, α diversity, **B**, β diversity, **C**, γ diversity. CK, control area; LG, light grazing; MG, moderate grazing; HG, heavy grazing

**Table 5** Effects of plant groups on different grassland types α, β and γ diversity

| Grassland Type | Response variable | Main effect | F value | *P* value |
|---|---|---|---|---|
| Meadow steppes | α diversity | plant groups | 336.68 | 0.00** |
| | β diversity | plant groups | 175.31 | 0.00** |
| | γ diversity | plant groups | 182.7 | 0.00** |
| Typical steppes | α diversity | plant groups | 103.95 | 0.00** |
| | β diversity | plant groups | 3.79 | 0.03* |
| | γ diversity | plant groups | 31.86 | 0.00** |
| Desert steppes | α diversity | plant groups | 137.68 | 0.00** |
| | β diversity | plant groups | 9.36 | 0.00** |
| | γ diversity | plant groups | 36.72 | 0.00** |

Note: ** means highly significant difference ($P < 0.01$), * means significant difference ($P < 0.05$)

β diversity, rare species contributed the most, dominant species the second, and common species the last; regarding γ diversity, dominant species contributed the most, followed by common species, and rare species contributed the least (Fig. 5A). In typical steppes, the contribution of rare species to α diversity was the largest, followed by dominant species, and the contribution of common species was the least; in terms of β diversity, dominant species contributed the most, followed by common species, and rare species contributed the least; for γ diversity, rare species contribute the most, dominant species the second, and common species the least (Fig. 5B). In desert steppes, the contribution of rare species to α diversity was the largest, followed by common species and dominant; for β diversity, dominant species were the main contributors, followed by common species, and with rare species contributing the least; in terms of γ diversity, common species contribute the most to γ diversity, followed by dominant and rare species (Fig. 5C).

## Discussion

### Response of plant species diversity to grazing intensity

The diversity of plant species' response to grazing intensity depends on the type of grassland, as each possesses unique ecological characteristics, productivity levels, and compositions of plant species [30]. Such disparities lead to different responses of grasslands to external environmental shifts. From meadow steppe to typical steppe and then to desert steppe, an ecological gradient from humid to arid forms in Inner Mongolia, accompanied by a gradual decline in productivity. Our results indicate that at the wetter end of this gradient (meadow steppes), α and γ diversity conform to the intermediate disturbance hypothesis, showing a unimodal trend with increasing grazing intensity, reaching their peak under moderate grazing. This is because abundant rainfall and moderate climate conditions favour the predominant growth of tall, perennial herbaceous vegetation, thereby establishing a complex vegetative hierarchy. When grazing intensity increases to a moderate level, according to the competitive release hypothesis [31], moderate grazing curtails the dominance of highly competitive species, reduces competitive pressures among species, enhances light utilisation [32], and creates more space

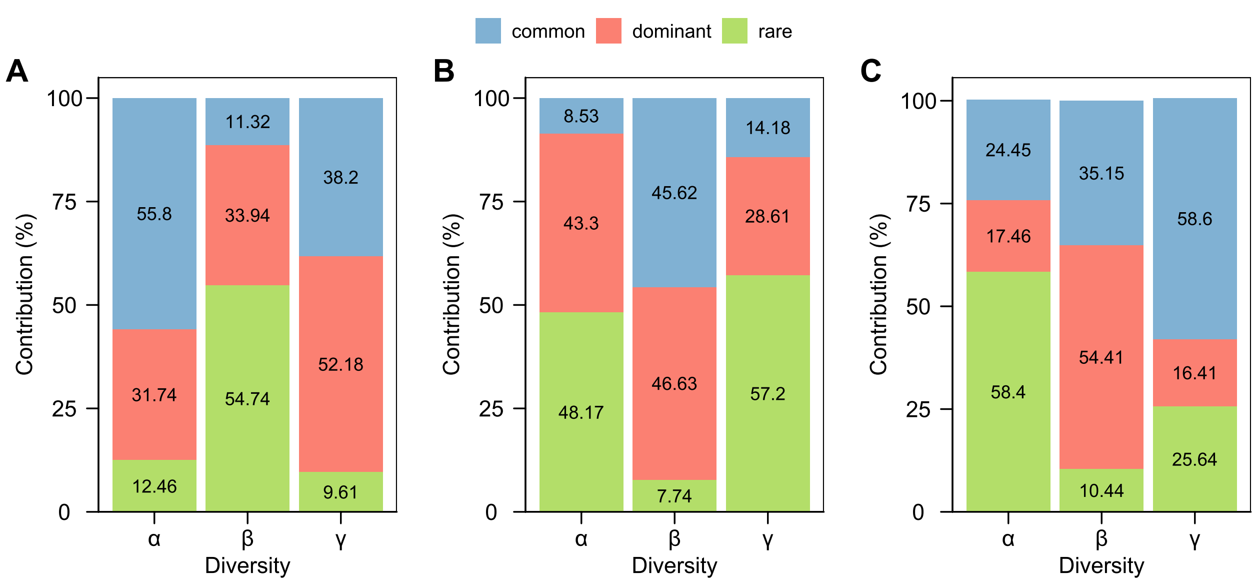


**Fig. 5** Contribution of dominant, common and rare species to α, β and γ diversity in three grassland types. **A**, meadow steppes; **B**, typical steppes; **C**, desert steppes. dominant, dominant species; common, common species; rare, rare species

for growth of species like *Carex tristachya Thunb* and *Potentilla acaulis* [33, 34]. This dynamic, in turn, contributes to an enhancement in both α and γ diversity. Furthermore, vegetation in high-productivity grasslands typically features high specific leaf areas, specific root lengths, and nitrogen and phosphorus content. This facilitates the rapid recovery of plants after being grazed by livestock [35–37]. Even if some species recover slowly, others can fill the ecological gap quickly, thereby stabilizing species diversity. However, a further increase in grazing intensity to heavy grazing leads to sparse vegetation and a bare surface [38], causing serious damage to the ecosystem, and subsequently, α and γ diversity decreases. Particularly, in this study, the β diversity of meadow steppes decreases slightly during light grazing, and then increases with the increase of grazing intensity. This may be due to the fact that some species are more sensitive to external disturbances and cannot withstand even light grazing, and the subsequent change in grazing intensity increases environmental heterogeneity, promotes the coexistence of grazing-tolerant species, and thus increases the species composition difference between different grazing areas. The gradual transition along the ecological gradient to the typical steppes region, which slightly differs from the meadow steppes, indicates that its α, β and γ diversity decrease slightly with light grazing, suggesting that light grazing is not sufficient to change the pattern of competition between species, leaving some species suppressed. As precipitation decreases and evaporation increased, the ecosystem further transforms into arid desert steppes. The results of this study indicate that the increase in grazing intensity leads to a continuous decline in α, β and γ diversity in desert steppes, accelerating the degradation of their ecosystems, which is consistent with the findings of Zhang, R. et al. [39]. Desert steppes are the driest ecosystem in Eurasian steppes [40], characterized by scant precipitation and high evaporation, and such extreme environmental conditions constrain its species richness and primary productivity to relatively low levels [41]. In these low productivity grasslands, the vegetation mainly consists of resource-conservative species, whose growth strategies and morphological characteristics make it difficult for them to recover rapidly after grazing disturbance [42], thereby leading to a decline in plant species diversity. Moreover, we found that although the three grassland types responded differently to grazing intensity, overall, plant diversity under heavy grazing was lower than at other grazing intensities, indicating that heavy grazing suppresses plant diversity. This is consistent with the findings of Zhao et al. [43].

**Response of the relationship between plant groups and species diversity to grazing intensity**

In different grassland ecosystems, the contribution of plant groups to species diversity and their response to grazing intensity are inconsistent. For meadow steppes, dominant species and common species are primarily responsible for enhancing α and γ diversity. This phenomenon can be attributed to the rich variety of vegetation species in meadow steppes, coupled with a high abundance of dominant and common species, which can occupy and utilize various resources and ecological niche in the grassland, and recover quickly and even show a trend of growth in the face of grazing disturbance. Moreover, with the increase of grazing intensity, certain rare species, such as *Plantago depressa* and *Taraxacum mongolicum*, emerge in some specific locales, thereby enriching the species composition difference across different gradients and increasing the β diversity. For typical steppes, marked decline in the frequency of rare species predominantly accounts for the reduction in α and γ diversity. The scarcity of rare species, coupled with their limited habitat and vulnerability to environmental disturbances [44], exacerbates this effect. And some rare species like *Potentilla tanacetifolia* and *Potentilla freyniana,* which have soft leaves and high water content, are high palatability and are easy to be foraged by livestock, and light grazing can lead to their significant reduction or even disappearance [45]. Dominant species and common species play a significant role in the reduction of β diversity in typical steppes. Under different grazing gradients, the presence of dominant species remained relatively stable, and these species, being widespread within the community, established a stable vegetative cover, thereby fostering uniformity in species composition. And certain common species, such as *Carex tristachya Thunb*, *Agropyron michnoi* and *Artemisia frigida*, gradually vanished as grazing intensity increased, which increased the proportion of common species within the community and weakened the species composition differences among different gradients. In desert steppes, the plant groups are sensitive to grazing intensity, and rare species made important contributions to the change of diversity within the community. With the increase of grazing intensity, some rare species begin to decrease, resulting in the decline of α diversity. Dominant species, as the dominant force in the ecosystem [46], have strong competitive advantages and wide ecological niches [47], which restrict the available living space for other species and drive species towards convergent development across grazing gradients, thus reducing β diversity. Common species have an important effect on the change of γ diversity, which may be due to the reproduction of common species leads to the enhancement of certain environmental conditions. Only species that are adapted to these intensified environmental conditions can thrive, subject to the environmental condition's filtering effect, thereby leading to a reduction in γ diversity. Common species have an important effect on γ diversity, which may be due to their reproduction and expansion enhancing their competitive advantage in specific environmental conditions. Therefore, these species become more dominant, limiting the survival of less adapted species, and only those species that are well-adapted to the intensified conditions can thrive, leading to a reduction in γ diversity.

## Conclusion

Grazing intensity, grassland type and their interaction had significant effects on α, β and γ diversity. The α and γ diversity of wet meadow steppes were consistent with the intermediate disturbance hypothesis and showed a unimodal trend; the α, β and γ diversity of typical grasslands with intermediate moisture conditions showed a neutral response to grazing; and the α, β and γ diversity of arid desert steppes decreased progressively with an increase in grazing intensity. The dominant plant group of species diversity at different scales also varied by grassland. Moreover, regardless of grassland type, overgrazing will suppress plant species diversity and thus lead to ecosystem degradation. Therefore, differentiated grazing management strategies should be developed for different grassland ecosystems to achieve the conservation of species diversity and the sustainable management of ecosystems.

## Supplementary Information

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Supplementary Material 1.

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Not applicable.

**Authors' contributions**
S.L. and J.H. conceptualized the study. S.L. also conducted the investigation, provided data, and secured funding. J.H. wrote the manuscript, performed data analysis, and handled visualization. H.L. participated in the investigation and secured funding. S.M. analyzed and curated the data.

**Data availability**
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Ethics approval and consent to participate**
Not applicable.

**Consent for publication**
Not applicable.

**Competing interests**
The authors declare no competing interests.

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