frontiers | Frontiers in Environmental Science

TYPE Brief Research Report
PUBLISHED 06 August 2025
DOI 10.3389/fenvs.2025.1560323

Check for updates

OPEN ACCESS

EDITED BY
Tianjiao Feng,
Beijing Forestry University, China

REVIEWED BY
Zhi-Cong Dai,
Jiangsu University, China
Pervaiz Dar,
University of Kashmir, India

*CORRESPONDENCE
Chun-Jing Wang,
wangchunjing00@163.com
De-Chao Chen,
chendechao519@163.com

RECEIVED 14 January 2025
ACCEPTED 25 June 2025
PUBLISHED 06 August 2025

CITATION
Ma Y-Q, Wang C-J, Chen D-C, Deng D-Z, Yan W-X, Yang J-Y and Wan J-Z (2025) Impacts of grazing on species diversity among different plant communities on the Qinghai–Tibet Plateau.
Front. Environ. Sci. 13:1560323.
doi: 10.3389/fenvs.2025.1560323

Impacts of grazing on species diversity among different plant communities on the Qinghai–Tibet Plateau

Yu-Qi Ma[1,2], Chun-Jing Wang[1,3]*, De-Chao Chen[1,3]*, Dong-Zhou Deng[1,3], Wu-Xian Yan[1,3], Jing-Yu Yang[1,3] and Ji-Zhong Wan[4]

[1]Sichuan Academy of Forestry, Chengdu, China, [2]College of Life Science, Qinghai Normal University, Xining, China, [3]Sichuan Provincial Forestry and Grassland Key Laboratory of Combating Desertilicatlon, Chengdu, China, [4]Key Laboratory of Mountain Surface Processes and Ecological Regulation, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, China

The Qinghai–Tibet Plateau is a region with rich biodiversity and fragile ecosystems, and its plant species diversity is greatly affected by grazing activities. In this study, we aimed to explore the impact of grazing on the diversity of different plant communities on the Qinghai–Tibet Plateau. To this end, we collected grazing and vegetation data for the period of 1982–2015; calculated the grazing, Shannon–Wiener diversity, inverse Simpson's, and Pielou's evenness indices along with species richness; and conducted correlation and regression analyses. The results show that the grazing index was positively correlated with the richness of grassland plant communities, and in particular, there were significant relationships between the variance and maximum value of the grazing data and plant species richness. However, no significant correlations were found between the grazing index and diversity indices in shrub land and desert plant communities. Moderate grazing promotes the renewal and growth of grassland vegetation and increases plant species diversity. Therefore, grazing management plans should be developed based on specific ecological environments to achieve sustainable ecosystem development and to protect species diversity.

KEYWORDS

China, grazing, plant communities, Qinghai-Tibet Plateau, species diversity, vegetation type

1 Introduction

The Qinghai–Tibet Plateau is the highest and largest plateau on Earth and is a key ecological functional area for water conservation, windbreaks, and sand fixation in Asia (Sun et al., 2012; Wang et al., 2022). It is also an important ecological security barrier in China, with rich ecosystems and unique biodiversity (Li et al., 2024). Biodiversity is crucial for maintaining ecosystem stability and plays an important role in water-source protection, climate regulation, and soil conservation (Li et al., 2022; Lee et al., 2015; Sun et al., 2023). The biodiversity of the Qinghai–Tibet Plateau also has a profound impact on the lives and cultures of local residents, especially pastoral communities that rely on natural resources as an indispensable foundation for their livelihood (Zhou et al., 2019). With the increase in human activities, especially overgrazing and infrastructure construction, the ecological environment of the Qinghai–Tibet Plateau is facing unprecedented pressure (Yang et al., 2024). Therefore, protecting the biodiversity of the Qinghai–Tibet Plateau is of great importance for maintaining regional ecological security and promoting sustainable development. Additional research is required to identify effective protective measures to preserve the biodiversity of the Qinghai–Tibet Plateau.

The high elevation and extreme climate of the Qinghai–Tibet Plateau region limit the growth and reproduction of many plant species, increasing their vulnerability and influencing plant species diversity (Mu et al., 2021; Chen et al., 2021; Bhattarai et al., 2021). Additionally, the intensification of climate change and human activity in this region has increased the survival pressure on plant species (Tilman and Lehman, 2001). With increases in temperature and changes in precipitation patterns caused by global warming, many plant species may experience habitat loss and display inadequate adaptability (Theodoridis et al., 2024). This lack of adaptability hinders the ability of plant species to cope effectively with rapidly changing environments, thereby increasing their risk of extinction (Losapio and Schöb, 2017). Temperature changes have led to an increase in forest and shrub land areas and a decrease in alpine meadows on the Qinghai–Tibet Plateau, whereas the intensification of drought has resulted in vegetation degradation in some areas of the southern Qinghai–Tibet Plateau (Gao et al., 2016; Wang et al., 2021). Protecting the plant species diversity of the Qinghai–Tibet Plateau is not only an urgent need for ecological protection but also an important measure to mitigate the impacts of climate change and maintain the ecological balance (Wang et al., 2022).

Animal husbandry is a crucial part of the Qinghai–Tibet Plateau economy, and grasslands are the main locations where local herders engage in grazing activities. Grazing is a traditional agricultural activity that has potential impacts on biodiversity. Moderate grazing can promote the growth and renewal of grasslands (Luo et al., 2012; Zhang et al., 2018); however, a large number of livestock foraging and trampling on grasslands can damage vegetation and lead to soil erosion, which in turn affects biodiversity (Wang Q. X. et al., 2023; Barros and Pickering, 2014). In particular, concentrated grazing may lead to the excessive consumption of vegetation or overgrazing (Hao et al., 2018). With an increase in grazing intensity, the diversity and richness of herbaceous plants, shrubs, and other plant communities on the Qinghai–Tibet Plateau markedly increased and then decreased (Wang et al., 2022). Studies have also reported that high-intensity grazing reduced plant diversity on the Qinghai–Tibet Plateau, whereas both non-grazing and low-intensity grazing alleviated plant biomass loss (Wang Q. X. et al., 2023). Furthermore, community resistance was optimal under low-intensity grazing conditions (Wang Q. X. et al., 2023). However, livestock manure and urine add nutrients and organic matter to the soil, affecting nutrient cycling and organic matter decomposition, thereby influencing the accumulation and distribution of soil organic carbon (Du et al., 2022). Grazing also affects the soil biota and functions, which are important components of material cycling and energy flow in underground ecosystems (Zhou et al., 2023). Thus, rational grazing can help maintain plant diversity and enhance ecosystem productivity and stability, whereas overgrazing can lead to the degradation of grassland vegetation, thereby reducing the richness and diversity of plant species, which in turn affects the quality of animal habitats and ultimately causes ecosystem imbalances (Li et al., 2023; Hao et al., 2018). With human population growth and economic development, the scale and intensity of grazing activities have gradually increased, and grazing has become a major contributing factor to grassland degradation on the Qinghai–Tibet Plateau in recent years (Fayiah et al., 2020). Therefore, grazing management is crucial for protecting plants and animals, and the adoption of effective grazing management strategies can effectively maintain ecosystem health (Zhao et al., 2022).

With the intensification of global climate change and human activity, the stability of ecosystems and biodiversity is facing unprecedented challenges (Liu et al., 2024). The Qinghai–Tibet Plateau is a unique and fragile ecosystem, and changes in its biodiversity are influenced by various factors, with grazing activities playing a dominant role. Although previous studies have explored the impacts of different degrees of grazing on grassland ecosystems, the specific mechanisms of and differences in the effect of grazing on different vegetation types remain unclear. Therefore, in this study, we aimed to explore: (1) the effects of grazing on the species diversity of plant communities on the Qinghai–Tibet Plateau and (2) the differences in this effect among different plant communities. The results of this study provide a scientific basis for the ecological protection and sustainable management of the Qinghai–Tibet Plateau.

2 Materials and methods

2.1 Vegetation data

The plant-plot data used in this study were extracted from datasets published by Wang Q. et al. (2023) and Jin et al. (2022). The datasets include quadrat sampling data from 455 herb quadrats in the Huangshui River Basin, Qinghai Province, including Haiyan County in Haibei Tibetan Autonomous Prefecture; the main urban area of Xining City, Huangyuan County, Huangzhong District; and Datong Hui and Tu Autonomous County, as well as Ledu District, Ping'an District, Minhe Hui and Tu Autonomous County, Huzhu Tu Autonomous County, and Hehuang New District in Haidong City. The quadrats of grassland communities are dominated by plant species belonging to Leguminosae, Rosaceae, Ranunculaceaem Cyperaceae and Poaceae. Shrub species are included, but their abundances are low, and individual sizes are small in the herb quadrats (Wang Q. et al., 2023; Supplementary Figure S1). In shrub plots, the abundances of shrub species were relatively low due to grazing effects and human disturbance. The plots of shrubland communities are dominated by shrub species belonging to Dasiphora.

The sampling locations of the plot-based dataset of plant communities on the Qinghai–Tibet Plateau included the Three River source region, southern Tibetan mountains, Ali region, and Qaidam Basin, as well as high mountains, oases, and desert areas, such as the Qilian, Altun, and Kunlun mountains. These two datasets report detailed information on the species present in the survey plots, including species name, number of plants, and coverage of each species. Additionally, the datasets report information on each plot, such as the plot number, longitude, latitude, elevation, degree of human interference, and total coverage of the plot.

These two datasets contain 1,213 sample plots, and we merged the data into one table. After removing forest sample plots based on vegetation type data, 880 sample plots remained. Each plot retained the plot number, plant name, coverage, and vegetation type information. The study area encompasses three principal vegetation types: grassland, shrubland, and desert. Sampling protocols employed vegetation-specific plot dimensions: grassland quadrats were established at 0.5 m × 0.5 m or 1 m × 1 m scales, while shrubland communities were surveyed using nested plots of 2 m × 2 m, 5 m × 5 m, and 10 m × 10 m. The maps of shrub species richness, individual and relative abundance of plant communities were shown on Supplementary Figure S1, showing that shrub species were distributed in many plots of our study. It is certainly determined to identify grassland, shrubland, and desert based on vegetation classification ranges. Vegetation classification for Qinghai-Tibet Plateau plant communities was predominantly guided by the phytosociological framework delineated in the Revised Scheme of the Vegetation Classification System of China (Guo et al., 2020), with additional reference to biogeographic zonation descriptors in the Vegetation and Its Geographical Pattern in China: Specifications for the Vegetation Map of the People's Republic of China (1:1,000,000) (Editorial Committee of Vegetation Map of China, the Chinese Academy of Sciences, 2007).

2.2 Grazing data

Grazing data were obtained from a dataset published by Meng et al. (2023). This dataset was constructed using a methodological framework that combined the cross-scale feature extraction method and a random forest model to produce a high-resolution gridded grazing dataset for the Qinghai–Tibet Plateau from 1982 to 2015. This framework included the following steps: identifying features that affect grazing, extracting theoretically suitable grazing areas, building a grazing spatialization model, and correcting the grazing spatialization dataset. When building the grazing spatialization model, combining a random forest model with partition and cross-scale features increased the model accuracy by 35.59% compared to that of traditional random forest models. Furthermore, Meng et al. (2023) compared this dataset with three other datasets (the actual livestock carrying capacity dataset, Gridded Livestock of the World 2.01, and Gridded Livestock of the World 3) and concluded that its time resolution was higher, making it more suitable for long-term research. Hence, we selected grazing data from Meng et al. (2023) for analysis. All grazing data is presented as sheep units/pixel/year, which was calculated based on the number of livestock (e.g., cattle, sheep, and horses), according to national standards. Livestock had strong accessibility to the study plots under grazing pressure. The sample plots were overlaid with the grazing data pixels.

2.3 Data analysis

We used ArcGIS 10.7 to extract grazing grid data from 1982 to 2015 and obtained the grazing status of each plot in each year through multi-value point extraction. We calculated the Shannon–Wiener diversity, inverse Simpson's diversity, and Pielou's evenness indices, along with species richness, for 880 plots; merged these indices with the grazing data; and removed invalid data. There were no correlations between diversity indices and plot size, which did not affect our results ($P > 0.1$). We used R 4.4.1 for data analysis and visualization and employed a generalized linear model to evaluate the differences in the impact of the grazing index on diversity among different vegetation types. We employed an analysis of variance (ANOVA) model to identify significant interactions and perform multiple comparisons of significant combinations, grouping them by vegetation type to establish a linear regression model.

3 Results

3.1 Relationships between grazing index and plant diversity indices

In grassland plant communities, the variance (SD) of the grazing data from 1981 to 2015 was directly proportional to plant species richness, and the fitting formula was: richness = 7.6860785 + 0.0012608 × SD ($P < 0.1$, $R^2 > 0.1$; Figure 1). The maximum value (Max) of the grazing index was directly proportional to plant species richness, and the fitting formula was: richness = 8.0253677 + 0.0001065 × Max ($P < 0.1$, $R^2 > 0.1$; Figure 1). There were no significant correlations between other grazing data and the grassland plant community diversity indices ($P < 0.1$; Figure 1). We calculated the following mean values for grassland plant diversity: Shannon–Wiener index, 1.54; inverse Simpson's index, 3.99; richness, 9.08; and Pielou's evenness index, 0.73. The Shannon–Wiener index ranged from 0.07 to 2.75, the inverse Simpson's index ranged from 1.03 to 11.28, the richness ranged from two to 26, and Pielou's evenness index ranged from 0.11 to 1 (Figure 2).

3.2 Comparison of relationships between grazing index and plant diversity indices among vegetation types

When comparing the models with and without interaction terms through ANOVA, $P < 0.05$ was considered significant, indicating a significant interaction effect. The impacts of the SD of the grazing data on the Shannon–Wiener index and species richness differed significantly between grassland and shrub land, with the slope of the grassland regression line being significantly steeper than that of the shrub land regression line. The diversity index of desert vegetation had no significant interaction with either the grazing index or other vegetation types (Figure 3).

4 Discussion

4.1 Impact of grazing on plant diversity

Grazing had different effects on the species diversity of different vegetation types. The results indicate that the Max from 1981 to 2015 was directly proportional to the grassland plant community richness, whereas grazing did not have a substantial impact on plant

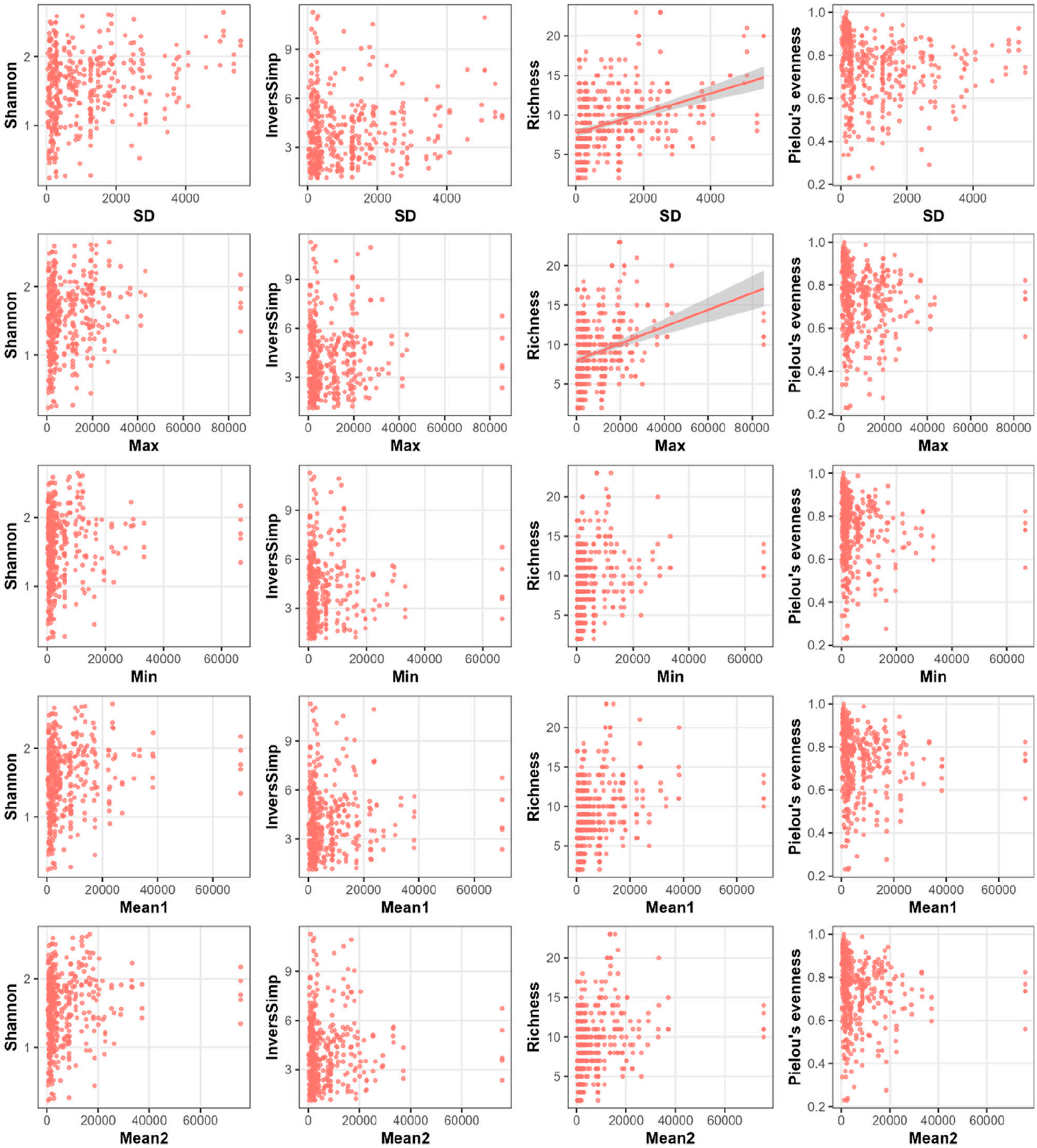

FIGURE 1
Scatter plots of grazing values and diversity indices of grassland communities. SD: variance of grazing data from 1981 to 2015; Max: maximum value of grazing data from 1981 to 2015; Min: minimum value of grazing data from 1981 to 2015; Mean1: mean of grazing data from 1981 to 2000; Mean2: mean of grazing data from 2001 to 2015. The red line represents the fitting line.

community diversity in shrub land and deserts. The Max reflects an extreme level of grazing, and its correlation with plant richness suggests that the grassland received high nutrient inputs from livestock manure and urine, which provided favorable growth conditions for the plants. Meanwhile, the SD reflects the differences in the grazing index at different temporal and spatial scales. Heterogeneity can create diverse habitat conditions and promote plant species coexistence. In addition, neither shrub land nor desert vegetation showed significant correlations in their responses to grazing. This difference from grassland may have arisen from the inherent life strategies of the vegetation. Shrubs typically possess deep root systems and lignified stems, enabling them to tolerate trampling and browsing by livestock. Jafarian et al. (2013) compared the soil physicochemical properties (organic carbon, total

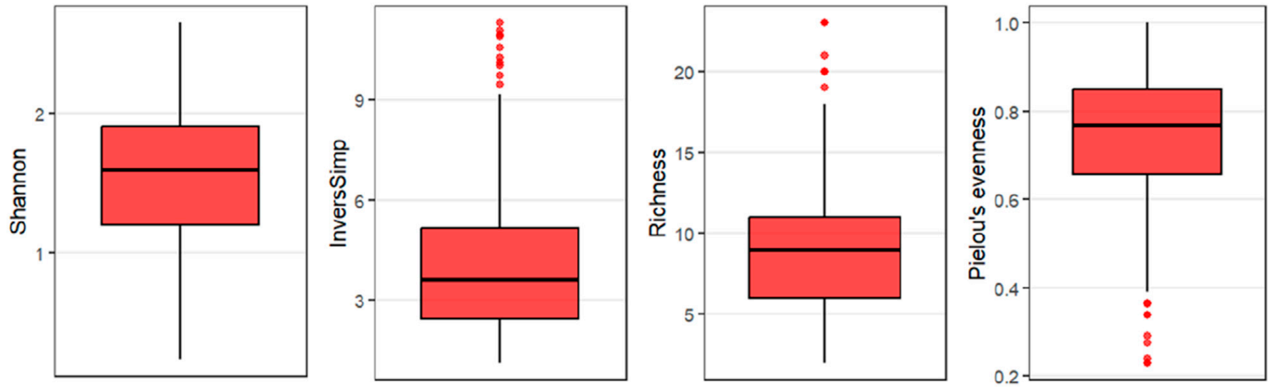

FIGURE 2
Boxplots of four species diversity indices of grassland communities. Boxplots show the medium values (black lines), 25% and 75% quartiles (boxes), and 5% minima and 95% maxima (bars) of four species diversity indices.

nitrogen, and electrical conductivity) of grasslands and shrub lands in Iran and found that the soil conditions in shrub lands were more suitable for plant growth than those in grasslands. Meanwhile, desert vegetation adapts to arid environments through physiological mechanisms such as succulent tissue and reduced transpiration. The conservative ecological niche of desert vegetation makes it less sensitive to grazing disturbance. In addition, by comparing the correlations between the grazing and species diversity indices among different vegetation types, we found that the correlations were stronger for grassland vegetation than for other vegetation types. Similar to the findings of this study, desert and dry grasslands in Mongolia have shown significant negative responses to severe grazing (Munkhzul et al., 2021). However, the increase in species richness in meadow steppes may be attributed to reduced competitive pressure from dominant species due to grazing, which aligns with the "intermediate disturbance hypothesis." These regional differences highlight the moderating effects of vegetation type and climatic context on grazing impacts. Due to the lack of recent data from 2016 to 2025, the current study was based on long-term observational data from 1982 to 2015, covering multiple climatic fluctuation cycles and grazing management phases. This study systematically revealed the response patterns of different vegetation types to grazing disturbance, providing a reference for future research.

4.2 Mechanisms of the impact of grazing on plant diversity

Grazing is an essential component of animal husbandry on the Qinghai–Tibet Plateau and can directly or indirectly affect vegetation. Direct impacts are typically manifested when herbivores directly feed on plants, which can lead to a reduction in species biodiversity and vegetation biomass (Zhu et al., 2012). Selective grazing by livestock may reduce high-nutrient species and increase low-nutrient ones (Török et al., 2018), thus altering plant community structure and function. Indirect impacts arise in several ways. Livestock excreta release nutrients into the soil, changing its properties (e.g., nutrient levels and water content) and affecting plant growth (Du et al., 2022). Moreover, grazing can indirectly influence plant productivity and ecosystem services by altering the soil microbial community composition and functions. A global meta-analysis by Zhou et al. (2023) demonstrated that moderate grazing boosts soil nematode diversity and organic matter decomposition efficiency.

The grazing index, which is based on the number of grazing animals, grazing time, and grazing frequency, is used to evaluate the pressure and impact of grazing on grassland ecosystems (Zhang et al., 2018). Many studies have been conducted on the effects of the grazing index. Different grazing intensities and durations were found to have different effects on the species diversity of grassland plant communities (Deng et al., 2014). Moderate grazing increased grassland species diversity, whereas heavy and long-term grazing reduced it. Along with the grazing intensity, different grazing practices have been found to impact grassland ecosystems. Liu et al. (2015) found that for grasslands with high plant diversity, mixed grazing by cattle and sheep significantly improved plant diversity; however, grazing by either cattle or sheep alone had no effect. Meanwhile, for grasslands with low plant diversity, both individual and mixed grazing significantly increased plant diversity but significantly reduced plant biomass (Liu et al., 2015). Additionally, the impacts of grazing on vegetation can become more complex through interactions with other ecological factors. For instance, climate change may alter vegetation growth conditions and herbivore behavior, thereby amplifying or mitigating grazing effects (Qiqige et al., 2023).

4.3 Recommendations

Based on our findings regarding the impact of grazing on plant diversity and its mechanisms on the Qinghai–Tibet Plateau, we propose the following grazing management practices. First, grazing strategies that are tailored to different vegetation types should be developed. Our results indicate that grassland vegetation is highly responsive to grazing, and moderate grazing can enhance species coexistence and community stability. Thus, a dynamic moderate grazing strategy should be implemented in grasslands to prevent biodiversity loss and ecological degradation from long-term high-intensity grazing. For

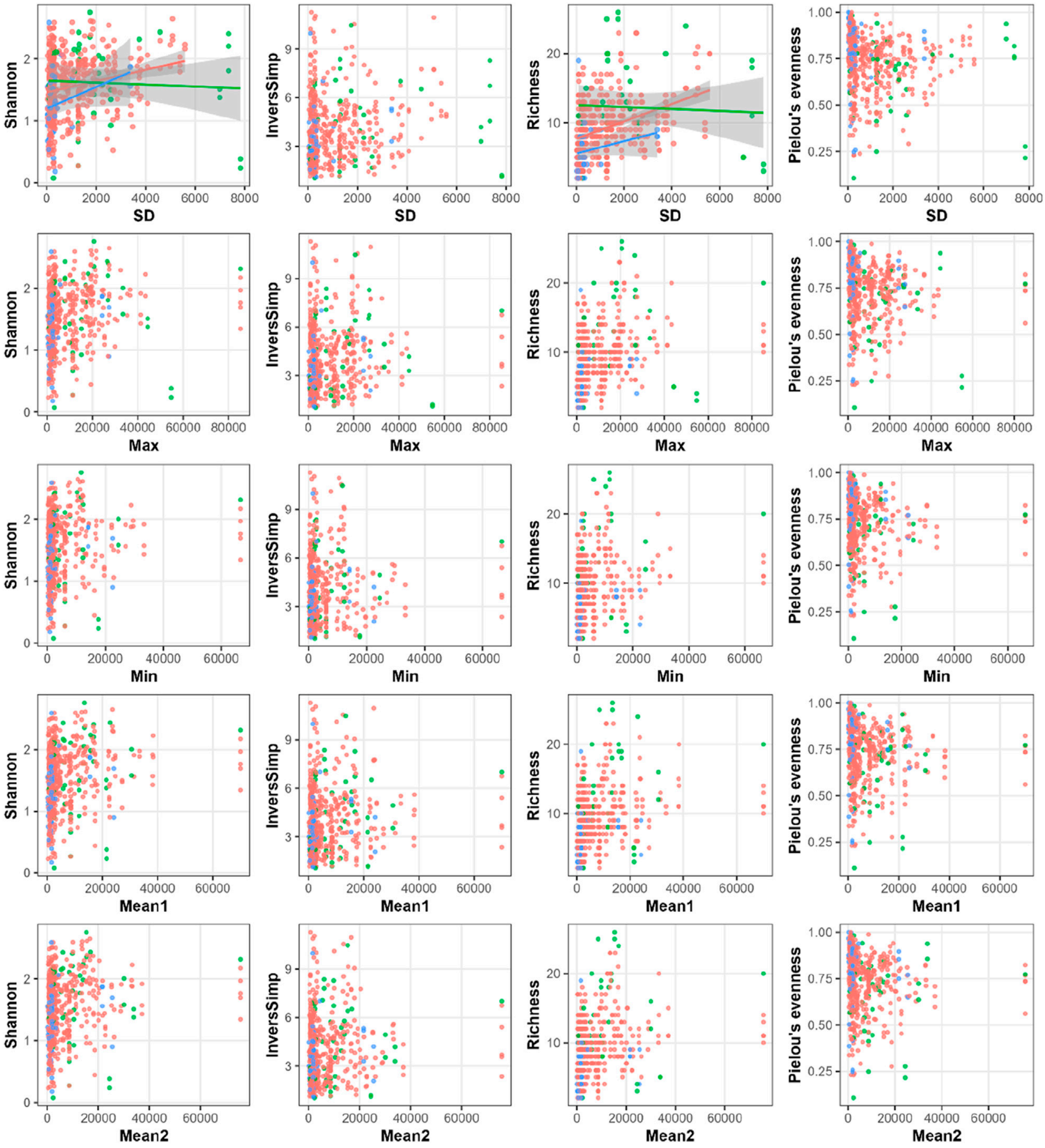

FIGURE 3
Correlations between grazing index and plant species diversity across different vegetation types. Red, green, and blue lines represent fitted lines for relationships between grazing index and plant species diversity in three vegetation types, namely, grassland, shrub land, and desert, respectively. SD: variance of grazing data from 1981 to 2015; Max: maximum value of grazing data from 1981 to 2015; Min: minimum value of grazing data from 1981 to 2015; Mean1: mean of grazing data from 1981 to 2000; Mean2: mean of grazing data from 2001 to 2015.

shrub lands and deserts, which show weak or complex responses to grazing, more conservative and observation-driven grazing measures are recommended. Second, the monitoring and management of grazing intensity and timing should be strengthened. For example, remote sensing and ground observations could be integrated to establish a grazing index monitoring and early warning system. Continuous monitoring and assessment of the risks of extreme grazing events will help to avert irreversible grassland degradation beyond the ecological carrying capacity. Additionally, the ecological role of a fluctuating grazing index should be recognized by adjusting grazing rhythms to create diverse microhabitat conditions, which can boost species coexistence and plant diversity (Du et al., 2022). Moreover, mixed cattle and sheep grazing should be promoted as an effective approach to enhance grassland plant diversity. Liu et al. (2015) reported that mixed grazing regulates interspecific competition among different plant functional groups, optimizes the vegetation structure, and improves resource-use efficiency, particularly in high-diversity grasslands. Therefore, multi-species livestock combination grazing should be prioritized, and the types and ratios of cattle, sheep, and other livestock should be scientifically allocated based on local ecological conditions and forage composition to achieve the dual goals of biodiversity conservation and improved forage-use efficiency.

5 Conclusion

Grazing activities have varying effects on the species diversity of different vegetation types on the Qinghai–Tibet Plateau. For grassland vegetation, the grazing index was positively correlated with plant community richness. Among the shrub land and desert vegetation types, grazing activity had no significant effect on plant community diversity. In addition, there were differences in the correlations between the grazing and diversity indices among the different vegetation types, with stronger correlations for grassland vegetation. These results indicate that the impact of vegetation type and grazing activity on plant community diversity on the Qinghai–Tibet Plateau is complex and diverse. Moderate grazing can promote vegetation renewal and growth and improve plant species diversity. Rational grazing plans should be developed based on specific ecological environments and biological community characteristics to achieve sustainable ecosystem development and to preserve species diversity.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

Y-QM: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Writing – original draft. C-JW: Conceptualization, Project administration, Supervision, Writing – original draft, Writing – review and editing. D-CC: Funding acquisition, Validation, Visualization, Writing – review and editing. D-ZD: Funding acquisition, Project administration, Supervision, Writing – review and editing. W-XY: Funding acquisition, Project administration, Supervision, Validation, Visualization, Writing – review and editing. J-ZW: Conceptualization, Supervision, Visualization, Writing – review and editing.

Funding

The Project of Sichuan Forestry and Grassland Technology Innovation Team from C-JW. Sichuan Provincial Science and Technology Planning Project (No. 2024YFNH0005) from D-CC, Central Financial Forest and Grass Science and Technology Promotion Demonstration Project - Promotion and Demonstration of Technology for Consolidating and Enhancing Ecological Effects of Severe Desertification Land Management in the High-Altitude Cold Region of the Upper Reaches of the Yellow River and Forestry Ecological Construction and Industrial Development Scientific Research Project - 2021 Annual Monitoring Project on the Effectiveness of Governance in Vulnerable Regions form Wu-Xian Yan.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1560323/full#supplementary-material

SUPPLEMENTARY FIGURE S1
Maps of shrub species richness **(a)**, individual **(b)** and relative abundance **(c)** of plant communities. The circle size represents the increasing values of shrub species richness, individual and relative abundance. The color from light blue to red indicates the higher attitude of the Qinghai–Tibet Plateau.

References

Barros, A., and Pickering, C. M. (2014). Impacts of experimental trampling by hikers and pack animals on a high-altitude alpine sedge meadow in the andes. *Plant Ecol. and Divers.* 8 (2), 265–276. doi:10.1080/17550874.2014.893592

Bhattarai, P., Zheng, Z., Bhatta, K. P., Adhikari, Y. P., and Zhang, Y. (2021). Climate-driven plant response and resilience on the Tibetan Plateau in space and time: a review. *Plants* 10, 480. doi:10.3390/plants10030480

Chen, C., Li, T., Sivakumar, B., Sharma, A., Albertson, J., Zhang, L., et al. (2021). Combined effects of warming and grazing on rangeland vegetation on the Qinghai-Tibet Plateau. *Front. Environ. Sci.* 9, 797971. doi:10.3389/fenvs.2021.797971

Deng, L., Sweeney, S., and Shangguan, Z. P. (2014). Grassland responses to grazing disturbance: plant diversity changes with grazing intensity in a desert steppe. *Grass Forage Sci.* 69, 524–533. doi:10.1111/gfs.12065

Du, Z. Y., Wang, X. D., and Cai, Y. J. (2022). Short-term effects of yak and Tibetan sheep urine deposition on soil carbon and nitrogen concentrations in an alpine steppe of the northern Tibetan Plateau, China. *J. Mt. Sci.* 19, 1156–1167. doi:10.1007/s11629-021-7026-6

Editorial Committee of Vegetation Map of China, the Chinese Academy of Sciences (2007). *Vegetation map of the people's Republic of China (1:1 000 000)*. Beijing: Geology Press.

Fayiah, M., Dong, S., Khomera, S. W., Rehman, S. A., Yang, M., and Xiao, J. (2020). Status and challenges of Qinghai-Tibet plateau's grasslands: an analysis of causes, mitigation measures, and way forward. *Sustainability* 12, 1099. doi:10.3390/su12031099

Gao, Q. Z., Guo, Y. Q., Xu, H. M., Ganjurjav, H., Li, Y., Wan, Y. F., et al. (2016). Climate change and its impacts on vegetation distribution and net primary productivity of the alpine ecosystem in the Qinghai-Tibetan Plateau. *Sci. Total Environ.* 554-555, 34–41. doi:10.1016/j.scitotenv.2016.02.131

Guo, K., Fang, J. Y., Wang, G. H., Tang, Z. Y., Xie, Z. Q., Shen, Z. H., et al. (2020). A revised scheme of vegetation classification system of China. *Chin. J. Plant Ecol.* 44, 111–127. doi:10.17521/cjpe.2019.0271

Hao, L., Pan, C., Fang, D., Zhang, X., Zhou, D., Liu, P., et al. (2018). Quantifying the effects of overgrazing on mountainous watershed vegetation dynamics under a changing climate. *Sci. Total Environ.* 639, 1408–1420. doi:10.1016/j.scitotenv.2018.05.224

Jafarian, Z., Kargar, M., and Ghorbani, J. (2013). Comparison of soil physical and chemical properties in grassland and shrub land communities, Iran. *Commun. Soil Sci. Plant Analysis* 44, 331–338. doi:10.1080/00103624.2013.741944

Jin, Y. L., Wang, H. Y., Wei, L. F., Hou, Y., Hu, J., Wu, K., et al. (2022). A plot-based dataset of plant community on the Qingzang Plateau. *Chin. J. Plant Ecol.* 46, 846–854. doi:10.17521/cjpe.2022.0174

Lee, J. H., Lee, M. J., and Lee, G. G. (2015). National level assessment of biodiversity importance-focusing on South Korea. *KSCE J. Civ. Eng.* 19, 46–62. doi:10.1007/s12205-013-0678-1

Li, H., Tan, L., Li, X., and Cai, Q. (2024). Aquatic protected area system in the Qinghai-Tibet Plateau: establishment, challenges and prospects. *Front. Ecol. Evol.* 12, 1204494. doi:10.3389/fevo.2024.1204494

Li, S., Zhu, Y. P., Cao, M., and Li, J. S. (2022). Current status, issues, and suggestions for the standard system of biodiversity conservation in China. *Biodivers. Sci.* 30, 192–200.

Li, W., Su, T., Shen, Y., Ma, H., Zhou, Y., Lu, Q., et al. (2023). Effects of warming seasonal rotational grazing on plant communities' structure and diversity in desert steppe. *Ecol. Evol.* 13, e9748. doi:10.1002/ece3.9748

Liu, J., Feng, C., Wang, D. L., Wang, L., Wilsey, B. J., and Zhong, Z. W. (2015). Impacts of grazing by different large herbivores in grassland depend on plant species diversity. *J. Appl. Ecol.* 52, 1053–1062. doi:10.1111/1365-2664.12456

Liu, L., Zhang, S., Liu, W., Qu, H., and Guo, L. (2024). Spatiotemporal changes and simulation prediction of ecological security pattern on the Qinghai-Tibet Plateau based on deep learning. *Land* 13, 1073. doi:10.3390/land13071073

Losapio, G., and Schöb, C. (2017). Resistance of plant-plant networks to biodiversity loss and secondary extinctions following simulated environmental changes. *Funct. Ecol.* 31, 1145–1152. doi:10.1111/1365-2435.12839

Luo, G. P., Han, Q. F., Zhou, D. C., Li, L., Chen, X., Li, Y., et al. (2012). Moderate grazing can promote aboveground primary production of grassland under water stress. *Ecol. Complex.* 11, 126–136. doi:10.1016/j.ecocom.2012.04.004

Meng, N., Wang, L. J., Qi, W. C., Dai, X. H., Li, Z. Z., Yang, Y. Z., et al. (2023). A high-resolution gridded grazing dataset of grassland ecosystem on the Qinghai-Tibet Plateau in 1982-2015. *Sci. Data* 10, 68. doi:10.1038/s41597-023-01970-1

Mu, X., Jia, K., Zhao, W., Liu, S., Wei, X., and Wang, B. (2021). Spatio-temporal changes of ecological vulnerability across the Qinghai-Tibetan Plateau. *Ecol. Indic.* 123, 107274. doi:10.1016/j.ecolind.2020.107274

Munkhzul, O., Oyundelger, K., Narantuya, N., Tuvshintogtokh, I., Oyuntsetseg, B., Wesche, K., et al. (2021). Grazing effects on Mongolian steppe Vegetation-A systematic review of local literature. *Front. Ecol. Evol.* 9, 703220. doi:10.3389/fevo.2021.703220

Qiqige, B., Wei, B., Wei, Y., Liu, M., Bi, Y., Xu, R., et al. (2023). Climate, not grazing, influences soil microbial diversity through changes in vegetation and abiotic factors on geographical patterns in the Eurasian steppe. *Front. Plant Sci.* 14, 1238077. doi:10.3389/fpls.2023.1238077

Sun, H. L., Zheng, D., Yao, T. D., and Zhang, Y. L. (2012). Conservation and construction of the national ecological security barrier on the Qinghai-Tibet Plateau. *Acta Geogr. Sin.* 67, 3–12.

Sun, Y., Liu, S., Liu, C., Sun, J., Liu, Y., and Wang, F. (2023). Interactive response and spatial heterogeneity of alpine grassland biodiversity to soil, topography, climate, and human factors on the Qinghai-Tibet Plateau. *Land Degrad. and Dev.* 34, 4488–4502. doi:10.1002/ldr.4735

Theodoridis, S., Hickler, T., and Thines, M. (2024). Mountain greening and rising temperatures erode habitats of ironwort (sideritis), an important natural medicinal resource. *Plants, People, Planet* 6, 862–874. doi:10.1002/ppp3.10497

Tilman, D., and Lehman, C. (2001). Human-caused environmental change: impacts on plant diversity and evolution. *Proc. Natl. Acad. Sci.* 98, 5433–5440. doi:10.1073/pnas.091093198

Török, P., Penksza, K., Tóth, E., Kelemen, A., Sonkoly, J., and Tóthmérész, B. (2018). Vegetation type and grazing intensity jointly shape grazing effects on grassland biodiversity. *Ecol. Evol.* 8, 10326–10335. doi:10.1002/ece3.4508

Wang, Q., Shang, C., Wang, C. J., and Wan, J. Z. (2023). A dataset of quadrat sampling of 455 herb quadrats in Huangshui River Basin, Qinghai Province. *China Sci. Data* 8 (1), 328–336. doi:10.57760/sciencedb.03329

Wang, Q. X., Cao, W., and Huang, L. (2023). Evolutionary characteristics and zoning of ecosystem functional stability on the Qinghai-Tibet Plateau. *Acta Geogr. Sin.* 78, 1104–1118.

Wang, X., Zhu, J. L., Peng, S. T., Zheng, T. L., Qi, Z. Y., Hu, J. B., et al. (2022). Patterns of grassland community composition and structure along an elevational gradient on the Qinghai-Tibet Plateau. *J. Plant Ecol.* 15, 808–817. doi:10.1093/jpe/rtab119

Yang, Y., Yu, C., Liu, M., and Wei, H. (2024). Uncovering the coupling relationships and key factors linking ecosystem services to human well-being through system dynamics: a case study in the Qinghai-Tibet Plateau. *Ecol. Indic.* 166, 112408. doi:10.1016/j.ecolind.2024.112408

Zhang, C., Dong, Q., Chu, H., Shi, J., Li, S., Wang, Y., et al. (2018). Grassland community composition response to grazing intensity under different grazing regimes. *Rangel. Ecol. and Manag.* 71, 196–204. doi:10.1016/j.rama.2017.09.007

Zhao, L., Liu, Z., Hu, Y., Zhou, W., Peng, Y., Ma, T., et al. (2022). Evaluation of reasonable stocking rate based on the relative contribution of climate change and grazing activities to the productivity of alpine grasslands in Qinghai Province. *Remote Sens.* 14, 1455. doi:10.3390/rs14061455

Zhou, J., Xiang, Y., Sheng, X., and Wu, J. (2023). Effects of grazing on soil nematodes in grasslands: a global meta-analysis. *J. Appl. Ecol.* 60, 814–824. doi:10.1111/1365-2664.14374

Zhou, Q. R., Shuai, L. L., Hu, J., Tian, L. H., Chen, Y. J., Wang, H., et al. (2019). The connotation of agricultural ethics in the Qinghai-Tibet Plateau grassland civilization and its reference to grassland ecological protection. *Pratacultural Sci.* 36 (11), 2997–3006.

Zhu, H., Wang, D., Wang, L., Bai, Y., Fang, J., and Liu, J. (2012). The effects of large herbivore grazing on meadow steppe plant and insect diversity. *J. Appl. Ecol.* 49, 1075–1083. doi:10.1111/j.1365-2664.2012.02195.x