Received: 11 September 2022 | Revised: 12 March 2023 | Accepted: 14 March 2023

DOI: 10.1002/glr2.12046

RESEARCH ARTICLE

Grassland Research Open Access

Self-stabilizing maintenance process in plant communities of alpine meadows under different grazing intensities

Li Lin[1,2] | **Xingliang Xu**[3] | **Guangmin Cao**[1] | **Fawei Zhang**[1] | **Yikang Li**[1] | **Junjie Huang**[4]

[1]Northwest Institute of Plateau Biology and Chinese Academy of Sciences, Xining, China

[2]College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, China

[3]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China

[4]School of Mechanical and Power Engineering, Henan Polytechnic University, Jiaozuo, China

Correspondence

Xingliang Xu, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China.
Email: xuxl@igsnrr.ac.cn

Handling Editor: Bernhard Schmid

Funding information

The Natural Science Foundation of Qinghai Province for providing funding for "Research on health assessment and sustainable development in alpine *Kobresia* meadows in Qinghai Province", Grant/Award Number: 2020-ZJ-720

Abstract

Backgrounds: Grazing prohibition and reduced grazing intensity, as two important "vegetation close-to-nature recovery" methods, have been suggested as economical and effective technologies for enhancing forage production. However, numerous studies have found that the yield of forage could be increased by removing or reducing grazing in a short time in some steady stage of alpine *Kobresia* meadows, but not in others. To reveal the mechanism behind this phenomenon, we proposed a series of experiments.

Methods: We monitored the plant and soil characteristics in the key steady stages of *Kobresia* meadows under reduced and prohibited grazing conditions in the same geographic and climatic environments in the northeastern Qinghai-Tibet Plateau for 6 years. We estimated the relationships between the plant community and soil nutrients and obtained the following results.

Results: All measured variables were positively correlated with each other. The plant community structure had higher path coefficients to aboveground biomass, soil organic matter, total nitrogen, and nitrate nitrogen than to other factors. The plant community structure played an important role in response to grazing intensity. Different plant functional groups (PFGs) had different responses to grazing intensity, which led to plant community re-establishment or re-organization under different grazing intensities. Poaceae and *Kobresia* were more sensitive to grazing intensity than other PFGs, and the ratio of *Kobresia* biomass (including *Kobresia humilis* and *Kobresia pygmaea*) to the total biomass of Poaceae and *Kobresia* could be used as an indicator of regime shifts within plant communities. With *Kobresia pygmaea* as the dominant species, the prohibition of grazing was not an efficient approach to increase the yield in the steady stages because this treatment needed more time to recover aboveground biomass. If Poaceae is the dominant PFG, grazing should only be prohibited for 3 years in the steady stages because the aboveground biomass will decrease if grazing is prohibited for more than 3 years.

Conclusions: Therefore, the different steady stages of alpine meadows require different recovery methods to increase recovery efficiency and speed.

KEYWORDS

coupling relationship, ecosystem stabilization, fragile ecosystem, plant functional groups, regime shift

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2023 The Authors. *Grassland Research* published by John Wiley & Sons Australia, Ltd on behalf of Chinese Grassland Society and Lanzhou University.

INTRODUCTION

Alpine meadows constitute more than 40% of the total area of the Qinghai-Tibet Plateau (QTP). They contribute considerably to the local and trans-local ecosystem, forage production, carbon sequestration, and water provision (Harris, 2010). The alpine meadows are located in a harsh environment and feature a simple structure, which poses difficulties in damaged ecosystem restoration or stabilization (Cao et al., 2010; Rong et al., 2018). In recent decades, approximately 80% of the alpine meadows on the QTP have experienced aboveground plant biomass decrease or steady stage regime shifts caused by anthropogenic disturbance (such as overgrazing, urban construction, road construction) and natural factors (such as climate change) (Y. Wang & Wesche, 2016; Zhou et al., 2005).

Many factors could trigger plant aboveground biomass decrease in alpine meadows and steady stage regime shifts. Generally, the driving factors can be divided into internal and external factors (Cao et al., 2007). The internal factors refer to the characteristics of storage and supply in the soil nutrient and microorganism system, the numerical characteristics of plant communities, and the related characteristics among those components, including physiological and biochemical metabolism characteristics of those components, survival strategies for plant communities and microorganisms under over-disturbance, and the coupling relationships between biotics and the environment, while the external factors mainly include climate change, grazing management pattern, and other activities associated with livestock grazing (Cao, 2010; Cao et al., 2007). Overgrazing, considered as one of the oldest human-induced disturbance factors (Cao et al., 2007), could not only reduce the ability of husbandry service and disturb the balance between nutrient supply and demand of alpine meadows but also reduce the ability of ecosystem resistance to the environmental transition and thus lead to regime shifts among steady stages (Cao, 2010).

Soil and plant community characteristics of alpine meadows are fundamental internal factors to maintain the ability of ecological and economic stability in those ecosystems. Grazing intensity can slowly or dramatically alter the characteristics of cover, leaf area, photosynthetic uptake of carbon, biomass production (Dong et al., 2012; X. X. Wang et al., 2014; Wen et al., 2013), and diversity in plant communities (Rong et al., 2018; Shao & Cai, 2008; Wen et al., 2010; Zhao et al., 2013). Continuous overgrazing can change the ratio, quantity, and quality of soil nutrients and the soil texture (Dong et al., 2012; Wen et al., 2013), affect the strategies of plant communities in obtaining limited resources (Bloom et al., 1985; Mokany et al., 2006), alter the organization patterns of plant communities, decrease the ecological and economic functions of the meadows, and even lead to plant communities' regime shifts (Niu et al., 2008). Among these characteristics, the biomass of plant communities, which is influenced by temperature, annual rainfall, soil nutrients, disturbance type, and disturbance intensity (Kiaer et al., 2013; Miehe, Kerstin, et al., 2011; Miehe, Miehe, et al., 2011; Sun et al., 2016; Y. Yang et al., 2010), is considered a comprehensive indicator of internal factor change (Chen et al., 2011; Ma et al., 2008). However, the amount of plant aboveground biomass is not always correlated with soil nutrient contents, because grazing intensity can influence sexual and asexual reproduction (Sang, 2006) and the survival strategies and growth patterns of different plant functional groups (PFGs) in different ways (Peng et al., 2018). This can feed back to reconstruct the structure of the plant community, adjust the proportion of PFGs and content of soil nutrients, and even accelerate the speed of replacement between dominant PFGs (Cao et al., 2007). Therefore, the aboveground biomass of PFGs may have a closer relationship with grazing intensity than the total aboveground biomass when studying the relationship and the mechanism of ecosystem stabilization (Gamfeldt et al., 2008; Isbell et al., 2011; Zavaleta et al., 2010) between ecosystem components and their reaction strategies to disturbance (Bloom et al., 1985; Sun et al., 2018; Y. Yang et al., 2009).

Previous studies showed that many types of ecosystems undergo succession or steady stage regime shifts in response to drastic disturbances, and the regime shifts often follow similar trajectories or converge to the same state (Scheffer et al., 2001). With gradual changes in the disturbance intensity and environmental factors (such as precipitation, soil nutrient quality and quantity, and disturbance intensity), the characteristics of ecosystems (estimated by, e.g., vegetation cover, biomass, or nutrient contents) may be relatively stable in a steady stage, but after the disturbance intensity crosses a certain threshold, the characteristics of the stage may change to a new one, which may exist much longer and be more difficult to be returned to the former stage (Scheffer et al., 2001; Xu et al., 2020). Compared with the steady stage, a regime shift takes less time (Xu et al., 2020) and results in steady stages with different ability of forage production coexisting in the same geographical and climatic environments (Lin, 2017; Lin, Li, et al., 2022). A number of studies have shown that the forage production capacity of those steady stages can be degraded under overgrazing (Lin, 2017; Lin, Li, et al., 2022).

Grazing prohibited and reduced grazing intensity, considered as two important "vegetation close-to-nature recovery" methods, have been suggested as economical and effective technologies for enhancing forage production (J. He et al., 2020). However, numerous studies have found that the yield of forage could be increased by removing or reducing grazing in a short time in some steady stage of alpine *Kobresia* meadows, but not in others (Cao et al., 2007; Y. F. Wang et al., 2022). This may be because overgrazing can trigger correlated changes in other factors, which leads the plant community to the steady stage with a lower forage production (Cao et al., 2007; Y. F. Wang et al., 2022).

In this study, we monitored the characteristics (including PFGs and soil nutrient content) in the key steady stages in a degradation succession process under

the same geographic and climatic environment (Lin, Cao, Guo, et al., 2022) in the northeastern QTP for 6 years. The purpose was to elucidate the variation of plant communities in different steady stages under the treatment of prohibited or reduced grazing, the coupling relationships between the characteristics of plant communities and soil nutrients in regime shifts, and the mechanism of self-stabilization in different steady stages under reduced and prohibited grazing. The findings may reveal the reaction of ecosystem components in different steady stages under varying disturbance intensities and improve the tactics of managing sustainable development in fragile ecosystems.

MATERIALS AND METHODS

Study area

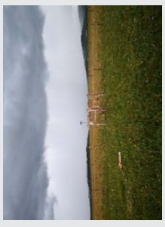
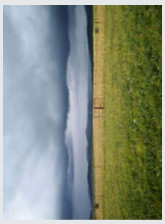
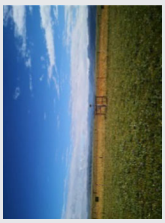
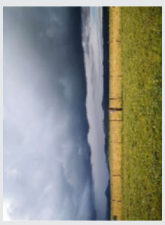
The vegetation at the study site was an alpine *Kobresia* meadow, located in Huangcheng Town, Menyuan County, Qinghai Province, China (Table 1). The average annual precipitation and temperature were 582.1 mm and −1.7°C, respectively. The warmest and coldest months were July and January, respectively. The dominant plants in the plant communities were *Stipa* spp., *Festuca* spp., and *Kobresia* spp. The growing season was from May to September, while plant community biomass peaked in August. Approximately 80%–90% of roots were concentrated in the upper 20 cm of soil (Lin, Cao, Guo, et al., 2022). The alpine meadow soil was clay loam with a thickness of 60–80 cm. It contained diluvial and highly permeable parent materials (Qinghai Agricultural Resources Zoning Office, 1997). The mattic epipedon, which is identified as a diagnostic soil layer in the Chinese Soil Taxonomy, was mainly distributed in the upper 20 cm (Qinghai Agricultural Resources Zoning Office, 1997). The characteristics of the study plots are detailed in Table 1.

Experimental design

Since 1995, a household contract system has been implemented in the study pastures. The pastures were divided into four grazing households with areas of 14.6, 13.5, 13.1, and 20.1 ha, respectively. The four grazing households were located in the same climatic and topographic area, but with different livestock densities. Over 20 years of different grazing intensities in these pastures remarkably changed the identity of the dominant plants, the yield of edible forage, surface landscape characteristics, and soil mattic epipedon thickness (Table 1).

We considered two grazing intensities as recovery treatments: (i) zero grazing (i.e., grazing was prohibited) and (ii) reduced grazing (i.e., half of the original grazing intensity); and the original grazing intensity applied by the herders as the control treatments, and the experiment began in 2013 (Table 1).

TABLE 1 General characteristics of the research site (Lin, Cao, Guo, et al., 2022).

Item	Plant succession process stage			
	Poaceae + *Kobresia humilis* community (PK)	*K. humilis* community (K)	Thickening mattic epipedon in the *Kobresia pygmaea* community (KPT)	Cracking mattic epipedon in the *K. pygmaea* community (KPC)
Location	37°39.023′ N, 101°10.638′ E	37°40.155′ N, 101°10.021′ E	37°40.054′ N, 101°10.620′ E	37°42.089′ N, 101°15.928′ E
Elevation (m)	3230	3241	3239	3278
Average grazing intensity (sheep units per ha)	3.65	7.50	8.25	11.25
Ground surface feature	No cracks	No cracks	Crack cover area of less than 8%	Crack cover area of 10%–15%
Mattic epipedon feature	< 5 cm thickness	5–6 cm thickness	7–8 cm thickness	8–9 cm thickness
Research site				

Soil and plant sampling

From 2013 to 2018, the aboveground biomass of each species was collected at the end of August or early September using a standard harvest method with frame quadrats (area: 25 cm × 25 cm, $n = 6$). The plant samples were placed in an oven at 105°C for 30 min for enzyme deactivation. Afterward, they were dried at 60–70°C for 48 h and then weighed.

In each plot and treatment, soil samples at five depths (0–5, 5–10, 10–20, 20–30, and 30–40 cm) were collected in an S-shaped pattern using a stainless-steel cylinder with an inner diameter of 5 cm. Six soil cores from the same depth were mixed to form one sample at each of the five depths in each treatment and plot. Debris was removed from the sample, and then, the sample was air-dried and divided into two parts, which were sieved to 2 and 0.25 mm, respectively (Lin, 2017). The sample sieved through a 2 mm screen was used to determine the concentrations of soil pH, ammonium nitrogen (NH_4^+), nitrate nitrogen (NO_3^-), available phosphorus (avP), and available potassium (avK), while the sample sieved through a 0.25 mm screen was used to determine the concentrations of total nitrogen (TN), total phosphorus (ThP), total carbon (TC), inorganic carbon (IC), and total potassium (TK).

Sample analysis

The TC and TN concentrations in soil were determined via dry combustion using an Elementar Vario EL Cube elemental analyzer (Elementar Inc.). The soil IC concentration was determined using the gas production volume method using an Eijkelkamp calcimeter (Eijkelkamp Instruments Inc.). The concentration of soil organic matter (OM) was calculated using the formula $OM_{concentration} = 1.724 \times (TC_{concentration} - IC_{concentration})$. Soil ThP was determined using an acid solution spectrophotometer. Soil TK was determined using an acid solution flame spectrophotometer (GB 7874-87). pH was measured using an acidimeter (FE28K; Mettler Toledo). Soil NH_4^+ and NO_3^- concentrations were analyzed by the potassium chloride extraction colorimetric method using Smartchem 140 (WESTCO Scientific Instruments Inc.). Soil avP was determined via bicarbonate-based extraction using a TMo-Sb colorimetric–spectrophotometric method, and avK was determined using a flame spectrophotometer (Lin, Cao, Xu, et al., 2022).

Statistical analyses

The aboveground biomass of the plant community was divided into five PFGs: Poaceae, *Kobresia pygmaea*, *Kobresia humilis*, Fabaceae, and forbs. The aboveground biomass of each PFG was calculated in each year, each plot, and each treatment.

Statistical analyses were conducted using SPSS (version 19.0; IBM) and R (version 4.0.2; R Core Team). The significance of the effects of community biomass and of the above ground biomass of different PFGs in different years and treatments corresponding to different steady stages was determined by analysis of variance and Duncan's multiple range test at a 5% significance level. The relationships between the characteristics of each site were analyzed using a structural equation model (lavaan package in R version 4.0.2; R Core Team). In the structural equation model, we structured two categories of latent variables, and all data had been standardized. The first category of latent variables included two latent variables associated with numerical characteristics of the plant community: one was "structure of plant community" and was structured based on the aboveground biomass of *K. humilis*, *K. pygmaea*, Poaceae, Fabaceae, and forb PFG and the other was "aboveground biomass of plant community" and was structured based on the biomass of living aboveground biomass and litter. The second category was associated with the characteristics of soil physical and chemical properties. We used each of the physical-chemical properties in five soil depths to construct their latent variable. In this way, we constructed 10 latent variables of soil physicochemical properties: soil pH (pH), the concentration of soil OM (OM), the concentration of soil TN, the concentration of soil ThP, the concentration of soil TK, the concentration of soil IC, the concentration of soil avK, the concentration of soil avP, the concentration of soil NH_4^+, and the concentration of soil NO_3^-.

We took prohibited grazing treatments in K and KPC steady stages as the example to expound the variation of production of different steady stages under no grazing. The turning points of those two steady stages in the prohibited grazing treatment were determined as the inflection point of the first derivative of the temporal trend line.

RESULTS

Characteristics of the plant community

Biomass of the plant community under different recovery treatments and steady stages

The aboveground biomass of plant communities increased in the order of KPC, KPT, K, and PK steady stage in original grazing intensity treatments (Figure 1). The influences on aboveground biomass variation were similar in reduced and prohibited grazing in the same steady stage, but their influences differed among steady stages.

Plant community biomass could be recovered within about 3 years through prohibited or reduced grazing in the PK and K steady stages, but the aboveground biomass in the KPT and KPC steady stages did not reach the turning point in the temporal trend lines of prohibited or reduced grazing treatments within 6 years (Figure 1).

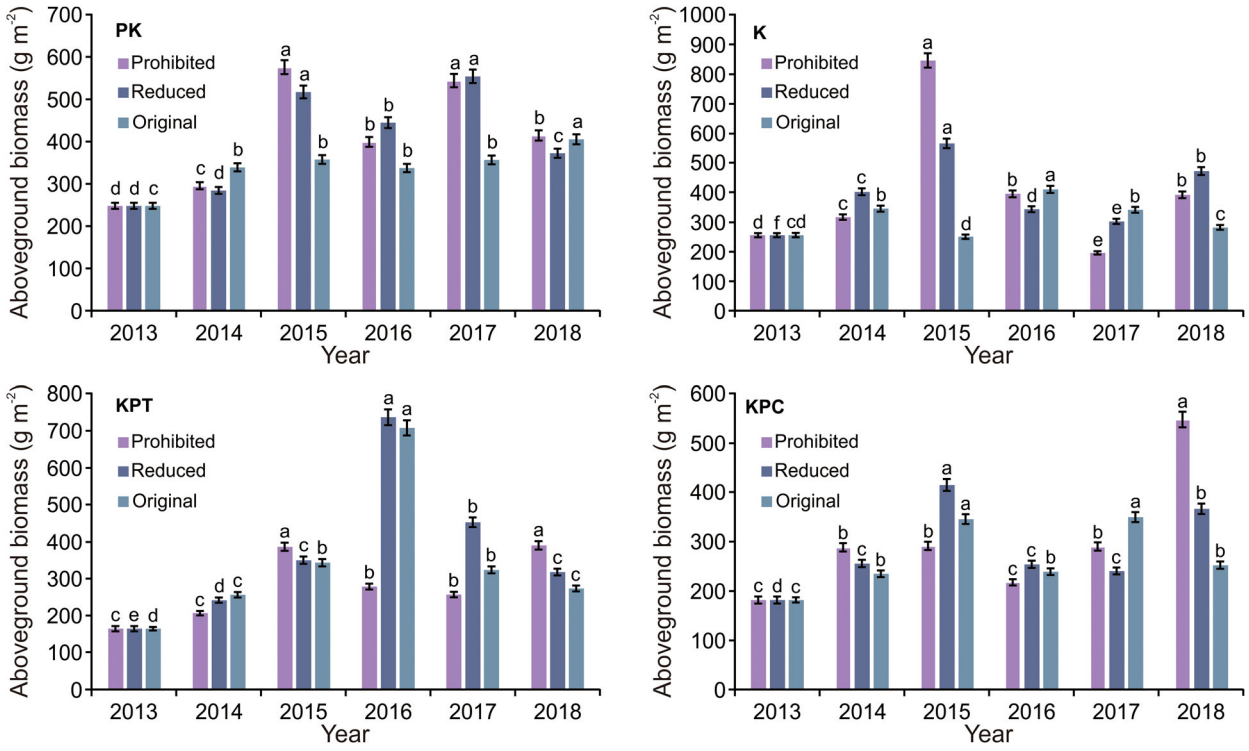


FIGURE 1 Total aboveground biomass in different steady stages under different grazing intensities. "PK" denotes the "Poaceae + *Kobresia humilis*" stage, "K" denotes the "*K. humilis*" stage, "KPT" denotes the "thickening mattic epipedon in *Kobresia pygmaea*" stage, and "KPC" denotes the "cracking mattic epipedon in *K. pygmaea*" stage. "Prohibited" denotes the grazing prohibition treatment, "Reduced" denotes the treatment in which the grazing intensity is half of that under Original, and "Original" denotes the original grazing intensity in the pasture. All significant differences were tested at $p < 0.05$ level.

Structures of plant communities under different recovery treatment and steady stages

Response of the Poaceae PFG under different recovery treatments and steady stages

The aboveground biomass of Poaceae declined in the order of PK, K, KPT, and KPC steady stages in original grazing intensity treatments, while the treatments of original grazing intensity controlled by the herders increased along this order (Table 1); therefore, we selected Poaceae as the sensitive PFG representative of plant communities to elucidate the sensitivity of PFGs to grazing intensity.

The response of the Poaceae was different under different recovery treatments in different steady stages. In the first 3 years of the study period, this PFG significantly increased in the PK and K steady stages. Throughout the research period, the biomass of Poaceae showed an unsteady increasing trend in the recovery treatments of KPT and KPC steady stages. Therefore, prohibiting or reducing grazing can allow for the recovery of Poaceae within a short time in PK and K steady stages, but not in KPT and KPC steady stages (Figure 2).

Response of K. humilis under different recovery treatments and steady stages

The biomass of *K. humilis* also showed sensitivity to steady stages with different grazing intensities and the recovery treatments. In the PK steady stage, *K. humilis* biomass steadily increased within about 4 years and then decreased after prohibited or reduced grazing; however, in other steady stages, the biomass of *K. humilis* continuously decreased after prohibited or reduced grazing. Therefore, this kind of PFG was not suitable for growth in communities with tall plants, particularly communities subjected to prohibited or reduced grazing treatments (Figure 3).

Response of K. pygmaea under different recovery treatments and steady stages

The *K. pygmaea* PFG was also sensitive to grazing intensity, but the responses of the *K. pygmaea* PFG biomass to prohibited or reduced grazing differed among steady stages. In all steady stages, the biomass of the *K. pygmaea* increased over time in the first 1–2 years but decreased with time over the next 3 years under both prohibited and reduced grazing treatments. In the KPT and KPC steady stages, the reduced grazing treatment increased the biomass of *K. pygmaea* for 3–4 years, longer than the periods in the PK and K steady stages in the same treatments. The ratios of the biomass of the *K. pygmaea* to the total aboveground biomass were 6% and 4% in PK and K, respectively, but 12% and 16% in the KPT and KPC steady stages, respectively.

The ratios of *Kobresia* (K) biomass (including *K. humilis* and *K. pygmaea*) to the total biomass of *Kobresia* + Poaceae [K/(K + P)], which was considered as the main body of edible forage in alpine meadows, were 15%, 27%, 37%, and 49% under original grazing treatments in the order of PK, K, KPT, and KPC steady stages, respectively, which was also the order of increasing grazing intensity. In the four original grazing treatments, the highest aboveground biomass occurred in the PK steady stages. The first regime shift occurred at K/(K + P) ratios of 27%, and after this regime

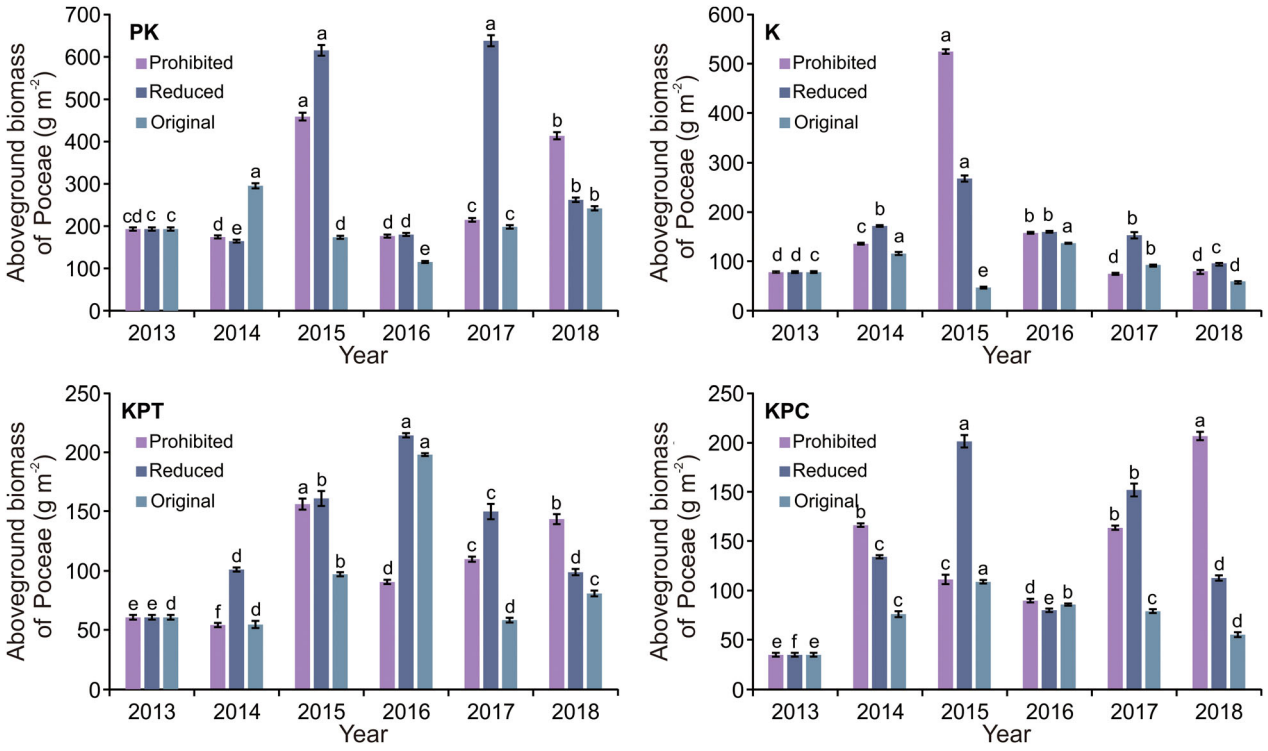


FIGURE 2 Aboveground biomass of Poaceae plant functional groups (PFGs) in different steady stages under different grazing intensities. "PK" denotes the "Poaceae + *Kobresia humilis*" stage, "K" denotes the "*K. humilis*" stage, "KPT" denotes the "thickening mattic epipedon in the *Kobresia pygmaea*" stage, and "KPC" denotes the "cracking mattic epipedon in the *K. pygmaea*" stage. "Prohibited" denotes the grazing prohibition treatment, "Reduced" denotes the treatment in which the grazing intensity is half of that under Original, and "Original" denotes the original grazing intensity in the pasture. All significant differences were tested at $p < 0.05$ level.

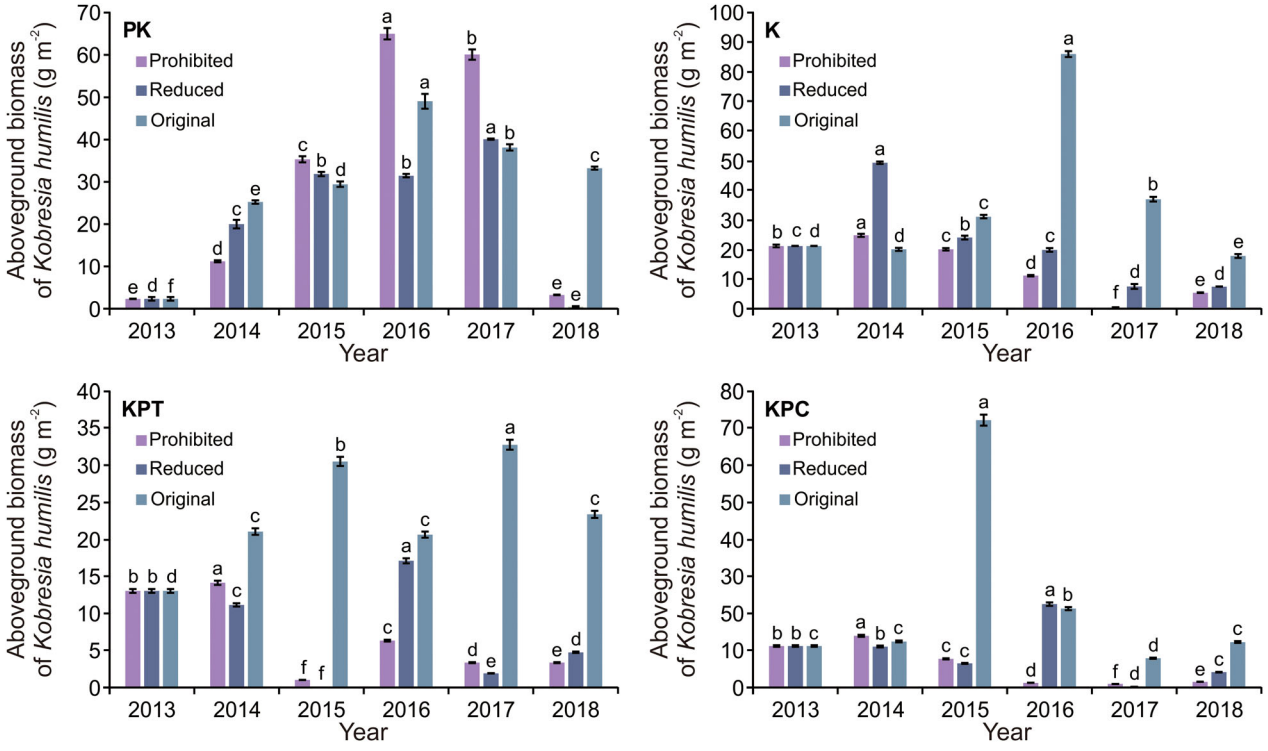


FIGURE 3 Aboveground biomass of the *Kobresia humilis* plant functional group (PFG) in different steady stages under different grazing intensities. "PK" denotes the "Poaceae + *K. humilis*" stage, "K" denotes the "*K. humilis*" stage, "KPT" denotes the "thickening mattic epipedon in *Kobresia pygmaea*" stage, and "KPC" denotes the "cracking mattic epipedon in *K. pygmaea*" stage. "Prohibited" denotes the grazing prohibition treatment, "Reduced" denotes the treatment in which the grazing intensity is half of that under Original, and "Original" denotes the original grazing intensity in the pasture. All significant differences were tested at $p < 0.05$ level.

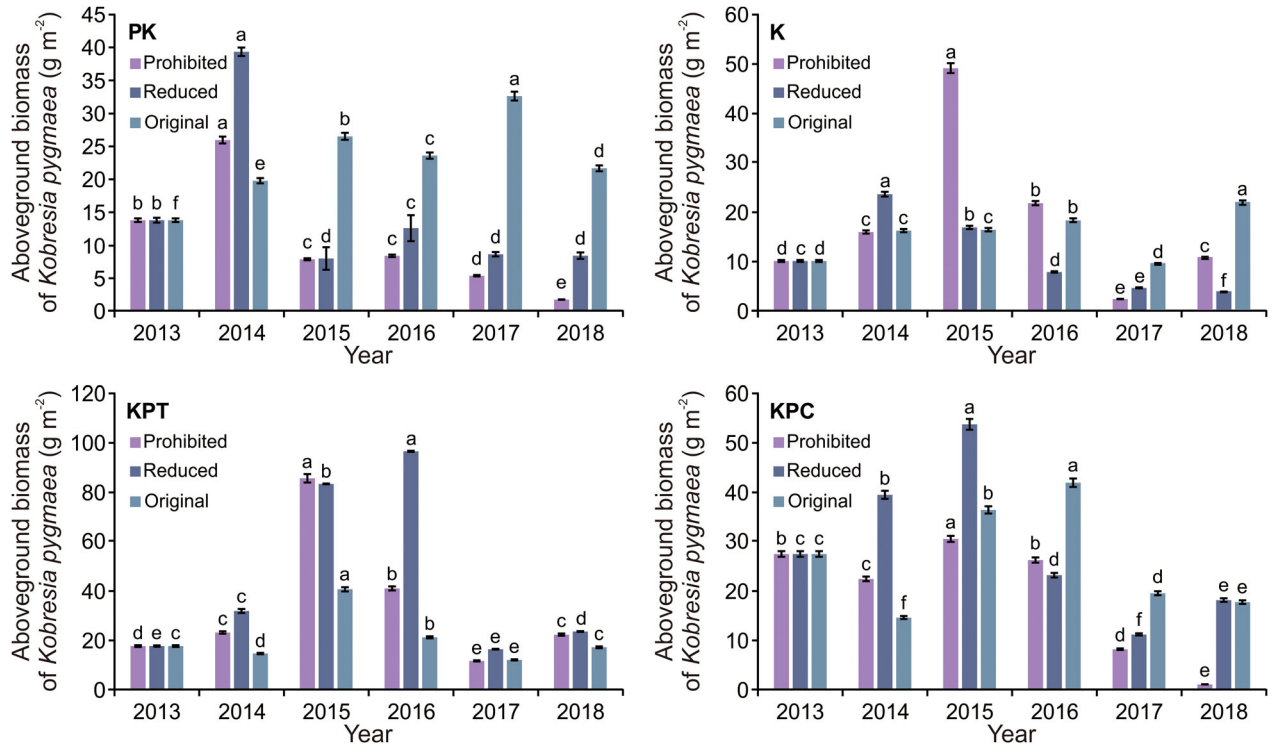


FIGURE 4 Aboveground biomass of the *Kobresia pygmaea* plant functional group (PFG) in different steady stages under different grazing intensities. "PK" denotes the "Poaceae + *Kobresia humilis*" stage, "K" denotes the "*K. humilis*" stage, "KPT" denotes the "thickening mattic epipedon in the *K. pygmaea*" stage, and "KPC" denotes the "cracking mattic epipedon in the *K. pygmaea*" stage. "Prohibited" denotes grazing prohibition treatment, "Reduced" denotes the treatment in which the grazing intensity is half of that under Original, and "Original" denotes the original grazing intensity in the pasture. All signifcant diferences were tested at $p < 0.05$ level.

shift, the aboveground biomass significantly decreased. The second regime shift occurred at K/(K + P) ratios greater than 37%; after that, it was stable at a level of aboveground biomass lower than those in PK and K steady stages (Figure 4).

Response of the Fabaceae PFG under different recovery treatments and steady stages

The biomass of Fabaceae was not sensitive in the original grazing treatments but showed a fluctuation trend in the other steady stages over time under prohibited or reduced grazing treatments. Moreover, the degree of variation of Fabaceae biomass under reduced grazing was higher than that under the original grazing treatments in all steady stages (Figure 5). Therefore, the stabilization ability of Fabaceae biomass was less in the recovery treatments than that in the original grazing treatments.

Response of the forb PFG under different recovery treatments and steady stages

The aboveground biomass of forbs was not sensitive to prohibited or reduced grazing, particularly in the KPC and KPT steady stages. Moreover, in this study, the forbs were a large group and showed a stronger biomass fluctuation than the other PFGs under both prohibited and reduced grazing treatments. The characteristics of forbs differed from those of the Fabaceae PFG. The biomass of forbs increased unsteadily over the first 3–4 years after prohibited or reduced grazing. After the first 4 years of prohibited grazing, the forb biomass decreased in the PK steady stages but continuously fluctuated in the K, KPC, and KPT steady stages (Figure 6).

Biomass recovery efficiencies in different steady stages under the prohibited grazing treatments

Based on the previous analysis, the structure and components of plant communities between the K and KPC steady stages were different, and original grazing intensities were different too. However, the two pastures, with the same geographical and climatic environmental factors and no fence for physical segmentation, belonged to the same herder before 1995; therefore, we inferred that the characteristics of the two pastures might be in the same steady stage with the same grazing intensity, but the grazing intensities were different after assigning plots to different herders since 1995. Hence, we took the two stages as representatives of steady stages under light and heavy grazing intensities (Table 1). In this research, there was little difference in the response trends of the steady stages to prohibited and reduced grazing treatments, so we used the aboveground biomass under the prohibited grazing treatment as a reference.

The aboveground biomass reached its first peak value after 3.21 years under prohibited grazing treatment in the K steady stage, and maintained a slow biomass recovery rate within 4.17 years under prohibited grazing in the KPC steady stage, but biomass increased rapidly thereafter. Therefore, it needs more time to increase the aboveground biomass of alpine meadows under a relatively heavy grazing intensity than under light grazing intensity (Figure 7).

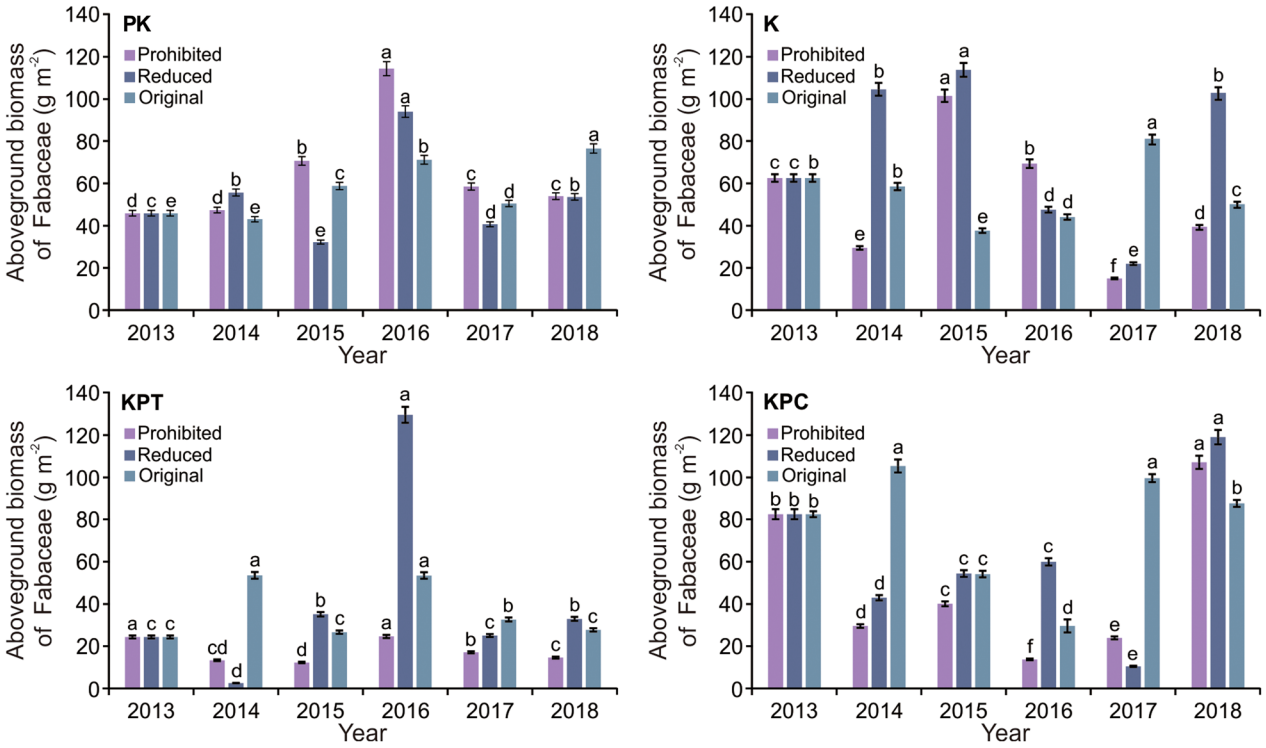


FIGURE 5 Aboveground biomass of the Fabaceae plant functional group (PFG) in different steady stages under different grazing intensities. "PK" denotes the "Poaceae + *Kobresia humilis*" stage, "K" denotes the "*K. humilis*" stage, "KPT" denotes the "thickening mattic epipedon in the *Kobresia pygmaea*" stage, and "KPC" denotes the "cracking mattic epipedon in the *K. pygmaea*" stage. "Prohibited" denotes the grazing prohibited treatment, "Reduced" denotes the treatment in which the grazing intensity is half of that under Original, and "Original" denotes the original grazing intensity in the pasture. All significant differences were tested at $p < 0.05$ level.

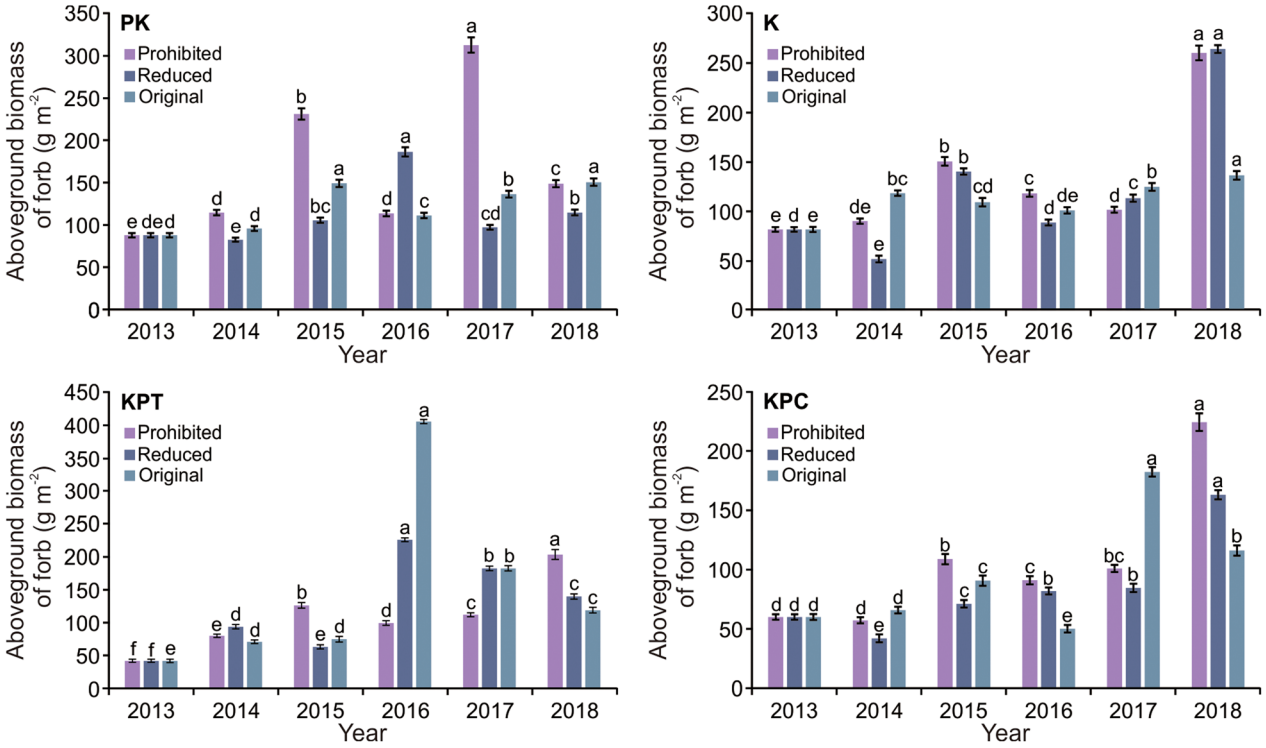


FIGURE 6 Aboveground biomass of the forb plant functional group (PFG) in different steady stages under different grazing intensities. "PK" denotes the "Poaceae + *Kobresia humilis*" stage, "K" denotes the "*K. humilis* stage," "KPT" denotes the "thickening mattic epipedon in the *Kobresia pygmaea*" stage, and "KPC" denotes the "cracking mattic epipedon in the *K. pygmaea*" stage. "Prohibited" denotes the grazing prohibited treatment, "Reduced" denotes the treatment in which the grazing intensity is half of that under Original, and "Original" denotes the original grazing intensity in the pasture. All significant differences were tested at $p < 0.05$ level.

Relationships between plant communities and soil nutrients

We estimated the relationships between soil nutrients and plant communities using structural equation models (SEMs). The plant community structure had the highest path coefficient toward the aboveground biomass of the plant community (Figure 8). The biomass of Poaceae and forb PFGs had the highest path coefficients toward the plant community structure.

Compared with the plant community structure, aboveground biomass had lower path coefficients toward soil nutrient concentrations. Moreover, the path coefficients from the different concentrations of soil physicochemical properties toward aboveground biomass differed from each other. Among the total soil nutrients, soil OM concentration had the highest path coefficients toward aboveground biomass and plant community structure. Among the soil available nutrients, NH_4^+ and NO_3^- influenced aboveground biomass and plant community structure the most, respectively. In addition, the highest path coefficient in the SEM was plant community structure to aboveground biomass, which indicated that plant community structure determined the primary biomass in those pastures (Figure 8). Therefore, plant community structure was the core factor influencing the components in the ecosystem under the prohibited and reduced grazing treatments in alpine meadows.

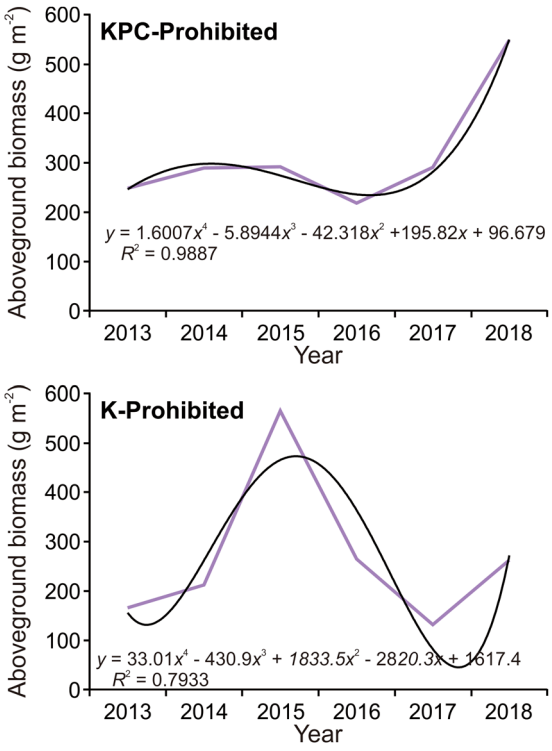


FIGURE 7 Turning points in the steady stage over the monitoring period. "K" denotes the "*Kobresia humilis*" stage, "KPC" denotes the "cracking mattic epipedon in *Kobresia pygmaea*" stage, and "Prohibited" denotes the absence of grazing in the plot.

DISCUSSION

Plant community structure as the core factor influencing soil nutrient accumulation and aboveground biomass

The ability of grasslands to produce forage has received considerable attention worldwide (Abdalla et al., 2018; Harris, 2010; Liu et al., 2018; Zhou et al., 2005). Overgrazing may decrease the yield of grasslands and reduce the stability and serviceability of this ecosystem (Briones et al., 2009; Cheng et al., 2007; Dong et al., 2012;

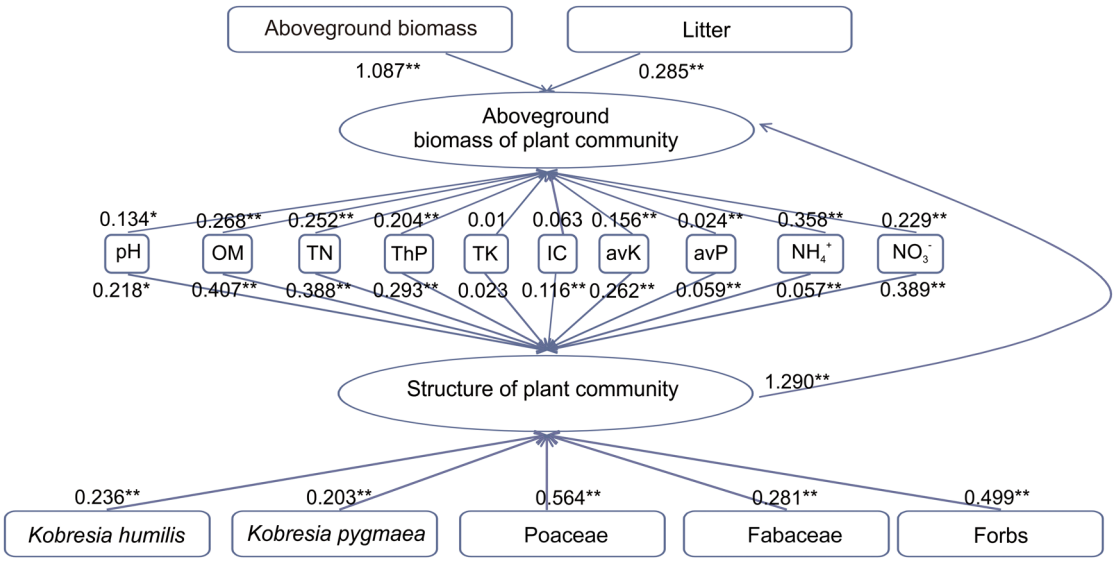


FIGURE 8 Path analysis results of the plant–soil system. The latent variables "structure of plant community" and "aboveground biomass of plant community" were structured based on the aboveground biomass of *Kobresia humilis*, *Kobresia pygmaea*, Poaceae, Fabaceae, and the forb plant functional group (PFG), and the biomass of living aboveground biomass and litter, respectively. The variable names pH, OM, TN, ThP, TK, IC, avK, avP, NH_4^+, and NO_3^- refer to pH, the concentration of soil organic matter, the concentration of total soil nitrogen, the concentration of total soil phosphorus, the concentration of total soil potassium, the concentration of soil inorganic carbon, the concentration of soil available potassium, the concentration of soil available phosphorus, the concentration of soil ammoniacal nitrogen, and soil nitrate nitrogen in 0–40 cm soil layers, respectively. *Path coefficients significant at $p < 0.05$; **Path coefficients significant at $p < 0.01$.

Harris, 2010; Li et al., 2014). Our research demonstrated that plant community structure was the core factor influenced by soil nutrient concentrations (including soil OM, TN, ThP, NH_4^+, NO_3^-, and avP) and that influenced aboveground biomass production under prohibited and reduced grazing treatments. The Poaceae, forb, and Cyperaceae PFGs were the main components influencing aboveground biomass production by affecting plant community structure, and soil nutrient accumulation under varying grazing intensities, presumably related to the different responses of the plant community structure and aboveground biomass production to prohibited or reduced grazing in alpine meadows. These differences between the responses could be summarized as follows: first, among plant communities, the forb PFG is the largest group influencing aboveground biomass formation (Lin, 2017). It contains over 10 species located in different vertical spaces in the plant community and mixes with annual and perennial plants in alpine meadows (Harris, 2010; S. He & Richards, 2015; Pando-Moreno et al., 2004; Wen et al., 2018; Zhou et al., 2005). Therefore, the forb PFG could resist a large range of grazing intensities to maintain the stability of PFG biomass. Moreover, the forb biomass accounts for the largest biomass proportion in the plant community (Lin, 2017), and thus, the group strongly contributes to biomass stabilization under varying grazing intensities. Therefore, we categorized this PFG as the overgrazing-insensitive group. However, most of the time, the group showed no or little contribution to livestock husbandry production, particularly in winter pastures.

Second, the aboveground biomass of the Poaceae located at a higher level in the vertical space in the plant community, rapidly increased in the first 3 years under reduced or prohibited grazing treatments in the steady stages with Poaceae as dominant species, while it decreased afterward. The reason for this might have been that the presence of litter and higher plants in the ecosystem reduced the light supplied to the plant community, which resulted in shading and other detrimental effects on the growth or germination of Poaceae under continued reduced or prohibited grazing (Kleyer, 2002; Lang, 2022). Consequently, under prolonged duration of prohibited grazing, the total biomass of the pasture decreased. Therefore, Poaceae were categorized as highly sensitive to grazing intensity.

Third, *K. pygmaea*, which occupied the lower vertical space in the plant community, was a dominant species in the KPT and KPC steady stages, but it was the PFG with the lowest path coefficient compared with other PFGs in the path analysis. This indicated that this PFG was less sensitive to changes in grazing intensity than the Poaceae PFG.

Based on the above discussion, Poaceae and Cyperaceae, which are considered as the main body of edible forage in winter pastures, were divided into two categories according to their sensitivity and response speed to changed grazing intensity. The Poaceae reacted rapidly to changes in grazing intensity, while the *Kobresia* PFGs reacted slowly. This might explain why the steady stage with *K. pygmaea* as dominant species needed more time to recover the yield of the plant community. Furthermore, the biomass of the *Kobresia* PFGs was less than that of the Poaceae and it was also more stable than that of the Poaceae. Therefore, increasing the biomass of *Kobresia* in a short time did not affect the forage yield of the pastures, whereas changes of the Poaceae could do so. Thus, we suggest that the biomass ratio of K/(P + K) could reflect ecosystem regime shifts and stabilization under grazing intensity change, and decreasing the ratio or adding Poaceae could be effective for biomass recovery in a degraded pasture.

Why was the recovery time span in *K. pygmaea* meadows longer than in others? Previous studies have shown that the key factor driving the recovery of the *K. pygmaea* meadow is the imbalance between the resource supply capacity of the ecosystem and the demand of plant communities (Cao et al., 2007). Therefore, in the steady stages with *K. pygmaea* as the dominant PFG, a slow increase rate in biomass was maintained over a longer time (more than 5 years) under prohibited grazing. To accurately explain the relationship between soil nutrient balance, plant community productivity, and changes in grazing intensity, longer-term field monitoring studies would be needed in the future.

In conclusion, different steady stages require different recovery methods, which should be considered in PFG construction and in determining the factors driving the degradation in forage production. In the steady stages with taller plant communities, biomass increased in a relatively short time. Therefore, under the prohibited grazing treatment, litter removal would be an important strategy to retain Poaceae species as the dominant species in alpine meadows and maintain biomass recovery. In the steady stages with lower plant community height, biomass increased more slowly. Therefore, in this kind of steady stage, prohibited or reduced grazing did not lead to biomass increase in a short time, which might be because the lower forage production was accompanied by lower limiting soil nutrient contents in those meadows (Cao et al., 2007).

Relationship between components in the plant-soil ecosystem and feedback to disturbance

The path coefficients between the plant community and soil nutrients (including total nutrients and available nutrients) were positive. The plant-soil system showed synergistic changes under prohibited and reduced grazing. The multisteady-stage theory holds that the negative feedback of ecosystem components to disturbance is the basis for maintaining system stability, while the positive feedback to disturbance is the basis for regime shift (Hu et al., 2018). However, in our research, all plots were under the same geographical and climatic conditions, which implied that the plots belonged to the same categories of soil types and had similar profile characteristics. The only difference between plots was the grazing intensity, which indicated that grazing intensity was a key factor driving ecosystem regime shifts.

The path coefficient between the plant community and soil nutrients was high. According to Liebig's minimum law, PFGs whose growth is sensitive to resource availability will be limited under limiting

resources (Lin et al., 2010). Lin (2017) reported that the current characteristics of alpine meadows in the QTP are determined by the groups insensitive to over-grazing, and the Poaceae PFG was sensitive to grazing intensity, which resulted in this PFG being reduced in the community under overgrazing conditions. Therefore, in the condition of overgrazing, the risk of replacement between Poaceae and Cyperaceae could increase and a replacement among dominant PFGs could affect the structure and the yield of the plant communities. The plant community structure had the highest path coefficient with soil OM and NO_3^-, which can be considered as nutrient reservoirs or limited resources in northern ecosystems (Miehe, Kerstin, et al., 2011; Y. Wang et al., 2021). Previous studies showed that *K. pygmaea* has a low aboveground biomass production but a high belowground biomass production, and that the root biomass is positively related to soil OM accumulation (Lin et al., 2010). Therefore, the plant community structure and yield changes might exert a positive feedback by soil nutrient content and accumulation (Lin et al., 2010).

Besides the above, the response of soil nutrients to regime shifts in plant communities was not synchronized, and limiting nutrients had higher correlations with the structure and biomass of the plant community than with other factors in the regime shift processes. For example, plant community structure and aboveground biomass were positively related to the concentrations of soil OM, soil TN, and NO_3^-, and the path coefficients were higher than those with phosphorus. Compared with NH_4^+, the plant community is more likely to absorb NO_3^- as the available nitrogen, while soil microorganisms are more likely to absorb NH_4^+ as the available nitrogen (Kuzyakov & Xu, 2013). NO_3^- is the core of the nitrogen cycle (K. Yang et al., 2020). In the steady stages of the alpine meadow with lower aboveground biomass, the concentration of available nitrogen (mainly NO_3^- and NH_4^+) is not higher, but the biomass of soil microorganisms is higher than that of the steady stage with higher aboveground biomass (Lin, Cao, Xu, et al., 2022; Miller, 2005; Kuzyakov & Xu, 2013), which could increase the gap between nitrogen supply and plant community demand.

We proposed that in the process of the described plant community regime shift due to overgrazing, the structure of the plant community was changed first because of the coupling relationship between characteristics of the plant community and the distribution and accumulation of soil nutrients and OM. This would then have led to a changed synergy between soil nutrient content and the plant community and altered characteristics of the ecosystem, thus completing the regime shift among steady stages.

CONCLUSIONS

Grazing intensity was one of the factors driving ecosystem stabilization or regime shift, and Poaceae and *Kobresia* were sensitive to grazing intensity. In the meadows with Poaceae as the dominants, aboveground biomass rapidly increased under prohibited or reduced grazing over about 3 years. In the meadows with *Kobresia pygmaea* as the dominants, aboveground biomass production was relatively steady for a long time under prohibited or reduced grazing. The PFGs and soil nutrients positively responded to the increase or decrease in grazing intensity, and among the ecosystem components, the biomass of Poaceae and *Kobresia*, the contents of soil OM, TN, and available nitrogen had higher path coefficients in establishing alpine meadow structure and maintaining its stability under disturbance. Poaceae, *Kobresia*, and forb PFGs played different roles in ecosystem stabilization and regime shifts under prohibited or reduced grazing. Specifically, the Poaceae increased their biomass production, while *Kobresia* maintained its biomass production over a long time and the forbs also maintained their biomass production under a wide range of grazing intensities. Therefore, under prohibited grazing, in the meadow with *Kobresia* as the dominant PFGs, biomass took a longer time to increase, suggesting that this kind of meadow may be the rate-limiting step (e.g., to replenish soil nutrients) in biomass recovery during steady stage regime shifts. In summary, our study suggests that different steady stages of alpine meadows in the QTP require different methods to increase the efficiency and speed in biomass recovery.

AUTHOR CONTRIBUTIONS

Li Lin: Formal analysis; funding acquisition; investigation; writing—original draft. **Xingliang Xu**: Methodology; supervision; writing—review and editing. **Guangmin Cao**: Conceptualization; project administration; writing—review and editing. **Fawei Zhang**: Investigation. **Yikang Li**: Investigation; **Junjie Huang**: Methodology.

ACKNOWLEDGMENTS

This research work was supported by the Natural Science Foundation of Qinghai (2020-ZJ-720).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Li Lin http://orcid.org/0000-0003-2531-0032

REFERENCES

Abdalla, K., Mutema, M., Chivenge, P., Everson, C., & Chaplot, V. (2018). Grassland degradation significantly enhances soil CO_2 emission. *Catena*, *167*, 284–292. https://doi.org/10.1016/j.catena.2018.05.010

Bloom, A. J., Chapin, F. S., & Mooney, H. A. (1985). Resource limitation in plants: An economic analogy. *Annual Review of Ecology and Systematics*, *16*(1), 363–392. https://doi.org/10.1146/annurev.es.16.110185.002051

Briones, M. J. I., Ostle, N. J., McNamara, N. P., & Poskitt, J. (2009). Functional shifts of grassland soil communities in response to soil warming. *Soil Biology and Biochemistry*, *41*, 315–322. https://doi.org/10.1016/j.soilbio.2008.11.003

Cao, G. M. (2010). *Soil-biology process and mechanism during alpine Kobresia meadow degradation in the Qinghai-Tibetan*

Plateau [Doctoral dissertation, Gansu Agricultural University]. Gansu Agricultural University.

Cao, G. M., Lin, L., Zhang, F. W., Li, Y. K., Han, D. R., & Long, R. J. (2010). A review of maintenance, loss and recovery of stability of alpine *Kobresia humilis* meadow on Tibetan Plateau. *Pratacultural Science*, *27*(8), 34–38.

Cao, G. M., Du, Y. G., Wang, Q. L., Wang, C. H. T., & Liang, D. Y. (2007). Character of passive-active degradation process and its mechanism in alpine *Kobresia* meadow. *Journal of Mountain Science*, *25*(6), 641–648. https://doi.org/10.3969/j.issn.1008-2786.2007.06.001

Chen, S. H. Y., Liu, W. J., Ye, B. S. H., Yang, G. J., Yi, S. H. H., Wang, F. G., Qin, X., Ren, J. W., & Qin, D. H. (2011). Species diversity of vegetation in relation to biomass and environmental factors in the upper area of the Shule River. *Acta Pracaculturae Sinica*, *20*(3), 70–83. https://doi.org/10.11686/cyxb20110308

Cheng, X., An, S., Chen, J., Li, B., Liu, Y., & Liu, S. (2007). Spatial relationships among species, above-ground biomass, N, and P in degraded grasslands in Ordos Plateau, Northwestern China. *Journal of Arid Environments*, *68*(4), 652–667. https://doi.org/10.1016/j.jaridenv.2006.07.006

Dong, S. K., Wen, L., Li, Y. Y., Wang, X. X., Zhu, L., & Li, X. Y. (2012). Soil-quality effects of grassland degradation and restoration on the Qinghai-Tibetan Plateau. *Soil Science Society of America Journal*, *76*(6), 2256–2264. https://doi.org/10.2136/sssaj2012.0092

Gamfeldt, L., Hillebrand, H., & Jonsson, P. R. (2008). Multiple functions increase the importance of biodiversity for overall ecosystem functioning. *Ecology*, *89*(5), 1223–1231. https://doi.org/10.1890/06-2091.1

Harris, R. B. (2010). Rangeland degradation on the Qinghai-Tibetan Plateau: A review of the evidence of its magnitude and causes. *Journal of Arid Environments*, *74*(1), 1–12. https://doi.org/10.1016/j.jaridenv.2009.06.014

He, J., Bu, H., Hu, X., Feng, Y., Li, S., Zhu, J., Liu, G., Wang, Y., & Nan, Z. (2020). Close-to-nature restoration of degraded alpine grasslands: Theoretical basis and technical approach. *Chinese Science Bulletin*, *65*(34), 3898–3908. https://doi.org/10.1360/TB-2020-0405

He, S., & Richards, K. (2015). Impact of meadow degradation on soil water status and pasture management: A case study in Tibet. *Land Degradation & Development*, *26*(5), 468–479. https://doi.org/10.1002/ldr.2358

Hu, Z., Guo, Q., Li, S., Piao, S., Knapp, A. K., Ciais, P., Li, X., & Yu, G. (2018). Shifts in the dynamics of productivity signal ecosystem state transitions at the biome-scale. *Ecology Letters*, *21*, 1457–1466. https://doi.org/10.1111/ele.13126

Isbell, F., Calcagno, V., Hector, A., Connolly, J., Harpole, W. S., Reich, P. B., Scherer-Lorenzen, M., Schmid, B., Tilman, D., van Ruijven, J., Weigelt, A., Wilsey, B. J., Zavaleta, E. S., & Loreau, M. (2011). High plant diversity is needed to maintain ecosystem services. *Nature*, *477*, 199–202. https://doi.org/10.1038/nature10282

Kiaer, L. P., Weisbach, A. N., & Weiner, J. (2013). Root and shoot competition: A meta-analysis. *Journal of Ecology*, *101*, 1298–1312. https://doi.org/10.1111/1365-2745.12129

Kleyer, M. (2002). Validation of plant functional types across two contrasting landscapes. *Journal of Vegetation Science*, *13*, 167–178. https://doi.org/10.1658/1100-9233(2002)013[0167:VOPFTA]2.0.CO;2

Kuzyakov, Y., & Xu, X. (2013). Competition between roots and microorganisms for nitrogen: Mechanisms and ecological relevance. *New Phytologist*, *198*, 656–669. https://doi.org/10.1111/nph.12235

Lang, P. (2022). *Effects of different disturbance modes on grassland ecological characteristics: A case study of Altai* [Master's thesis, Xinjiang Normal University]. Xinjiang Normal University.

Li, Y. Y., Dong, S. K., Wen, L., Wang, X. X., & Wu, Y. (2014). Soil carbon and nitrogen pools and their relationship to plant and soil dynamics of degraded and artificially restored grasslands of the Qinghai-Tibetan Plateau. *Geoderma*, *213*, 178–184. https://doi.org/10.1016/j.geoderma.2013.08.022

Lin, L. (2017). *Response and adaptation of plant-soil system of alpine meadows in different successional stages to grazing intensity* [Doctoral dissertation, Gansu Agricultural University] Gansu Agricultural University.

Lin, L., Cao, G. M., Li, Y. K., Zhang, F. W., Guo, X. W., & Han, D. R. (2010). Effects of human activities on organic carbon storage in the *Kobresia humilis* meadow ecosystem on the Tibetan Plateau. *Acta Ecologica Sinica*, *30*(15), 4012–4018. https://stxb/article/abstract/stxb200907291006

Lin, L., Cao, G. M., Guo, X. W., Li, Q., Qian, D. W., Du, Y., Huang, J., Fan, B., Li, B. C., Lan, Y., & Si, M. K. (2022). The process of soil nutrient stabilization in micro-patches in alpine *Kobresia* meadows. *Diversity*, *14*(8), 656. https://doi.org/10.3390/d14080656

Lin, L., Cao, G. M., Xu, X. L., Li, C. L., Fan, B., Li, B. C., Lan, Y. T., Si, M. K., & Dai, L. C. (2022). Changes and relationships between components in the plant-soil system and the dominant plant functional groups in alpine *Kobresia* meadows due to overgrazing. *Diversity*, *14*(3), 183. https://doi.org/10.3390/d14030183

Lin, L., Li, B. C., Fan, B., Lan, Y. T., & Si, M. K. (2022). Response and adaption of plant community in *Kobresia* meadow to different grazing intensity. *Chinese Journal of Grassland*, *44*(9), 19–30. https://doi.org/10.16742/j.zgcdxb.20220018

Liu, S., Zamanian, K., Schleuss, P. M., Zarebanadkouki, M., & Kuzyakov, Y. (2018). Degradation of Tibetan grasslands: Consequences for carbon and nutrient cycles. *Agriculture, Ecosystems & Environment*, *252*, 93–104. https://doi.org/10.1016/j.agee.2017.10.011

Ma, H. W., Yang, Y. H., He, J. S., Zeng, H., & Fang, J. (2008). Above- and belowground biomass in relation to environmental factors in temperate grasslands, Inner Mongolia. *Science in China Series C: Life Sciences*, *51*(3), 263–270. https://doi.org/10.1007/s11427-008-0029-5

Miehe, G., Kerstin, B., Miehe, S., Kluge, J. Y. Y., La Duo, S. C., & Wesche, K. (2011). Alpine steppe plant communities of the Tibetan highlands. *Applied Vegetation Science*, *14*(4), 547–560. https://doi.org/10.1111/j.1654-109X.2011.01147.x

Miehe, G., Miehe, S., Bach, K., Nölling, J., Hanspach, J., Reudenbach, C., & Ma, Y. M. (2011). Plant communities of central Tibetan pastures in the Alpine Steppe/*Kobresia pygmaea* ecotone. *Journal of Arid Environments*, *75*(8), 711–723. https://doi.org/10.1016/j.jaridenv.2011.03.001

Miller, D. J. (2005). The Tibetan steppe. Plant production and protection series No. 34. In J. M. Suttie, S. G. Reynolds, & C. Batello (Eds.), *Grasslands of the world* (pp. 305–342). UN Food and Agriculture Organization.

Mokany, K., Raison, R. J., & Prokushkin, A. S. (2006). Critical analysis of root : shoot ratios in terrestrial biomes. *Global Change Biology*, *12*(1), 84–96. https://doi.org/10.1111/j.1365-2486.2005.001043.x

Niu, K., Luo, Y., Choler, P., & Du, G. (2008). The role of biomass allocation strategy in diversity loss due to fertilization. *Basic and Applied Ecology*, *9*(5), 485–493. https://doi.org/10.1016/j.baae.2007.06.015

Pando-Moreno, M., Jurado, E., Manzano, M., & Estrada, E. (2004). The influence of land use on desertification processes. *Journal of Range Management*, *57*, 320–324. https://doi.org/10.2111/1551-5028(2004)057[0320:TIOLUO]2.0.CO;2

Peng, F., Xue, X., You, Q., Huang, C., Dong, S., Liao, J., Duan, H., Tsunekawa, A., & Wang, T. (2018). Changes of soil properties regulate the soil organic carbon loss with grassland degradation on the Qinghai-Tibet Plateau. *Ecological Indicators*, *93*, 572–580. https://doi.org/10.1016/j.ecolind.2018.05.047

Qinghai Agricultural Resources Zoning Office. (1997). *Qinghai Soil*. China Agricultural Press.

Rong, X. S., He, M., Wang, C. Y., Li, Y., Dai, Z. C., Liang, Z. S., Wan, L. Y., Gao, Z. Y., Jiang, K., Wu, B. D., Zhang, L., & Zhou, J. W. (2018). Analysis on the diversity of soil bacterial and fungal communities in the degraded alpine grassland in northern Tibet Plateau. *Ecology and Environmental Sciences*, *27*(9), 1646–1651. https://doi.org/10.16258/j.cnki.1674-5906.2018.09.009

Sang, Z. H. H. (2006). *Studies on soil seed bank and regeneration of degraded alpine grassland in the headwater of Yangtze and Yellow*

rivers on Tibetan Plateau [Doctoral dissertation, Gansu Agricultural University] Gansu Agricultural University.

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, *413*, 591–596. https://doi.org/10.1038/35098000

Shao, W., & Cai, X. B. (2008). Grassland degradation and its formation causes analysis in Tibetan Plateau. *Science of Soil and Water Conservation*, *6*(1), 112–116. https://doi.org/10.16843/j.sswc.2008.01.020

Sun, J., Ma, B. B., & Lu, X. Y. (2018). Grazing enhances soil nutrient effects: Trade-offs between aboveground and belowground biomass in alpine grasslands of the Tibetan Plateau. *Land Degradation & Development*, *29*, 337–348. https://doi.org/10.1002/ldr.2822

Sun, J., Qin, X., & Yang, J. (2016). The response of vegetation dynamics of the different alpine grassland types to temperature and precipitation on the Tibetan Plateau. *Environmental Monitoring and Assessment*, *188*(1), 20. https://doi.org/10.1007/s10661-015-5014-4

Wang, X. X., Dong, S. K., Yang, B., Li, Y. Y., & Su, X. K. (2014). The effects of grassland degradatoin on plant diversity, primary productivity, and soil fertility in the alpine region of Asia's headwaters. *Environmental Monitoring & Assessment*, *186*, 6903–6917. https://doi.org/10.1007/s10661-014-3898-z

Wang, Y., & Wesche, K. (2016). Vegetation and soil responses to livestock grazing in Central Asian grasslands: A review of Chinese literature. *Biodiversity and Conservation*, *25*, 2401–2420. https://doi.org/10.1007/s10531-015-1034-1

Wang, Y. F., Lv, W. W., Xue, K., Wang, S. H. P., Zhang, L. R., Hu, R. H., Zeng, H., Xu, X. L., Li, Y. M., Jiang, L. L., Hao, Y. B., Du, J. Q., Sun, J. P., Dorji, T., Piao, S. H. L., Wang, C. H. H., Luo, C. Y., Zhang, Z. H. H., Chang, X. F., … Niu, H. S. H. (2022). Grassland changes and adaptive management on the Qinghai–Tibetan Plateau. *Nature Reviews Earth & Environment*, *3*, 668–683. https://doi.org/10.1038/s43017-022-00330-8

Wang, Y., Pei, W., Cao, G., Guo, X., Zhou, H., & Du, Y. (2021). Moderate grazing increases water use efficiency for environmental health in alpine meadows of the Tibetan plateau. *Frontiers in Ecology and Evolution*, *9*, 684321. https://doi.org/10.3389/fevo.2021.684321

Wen, L., Dong, S., Li, Y., Wang, X., Li, X., Shi, J., & Dong, Q. (2013). The impact of land degradation on the C pools in alpine grasslands of the Qinghai-Tibet Plateau. *Plant and Soil*, *368*(1–2), 329–340. https://doi.org/10.1007/s11104-012-1500-4

Wen, L., Dong, S. K., Zhu, L., Li, X. Y., Shi, J. J., Y.L.Wang, Y. L., & Ma, Y. S. (2010). The construction of grassland degradation index for alpine meadow in Qinghai–Tibetan Plateau. *Procedia Environmental Sciences*, *2*, 1966–1969. https://doi.org/10.1016/j.proenv.2010.10.210

Wen, L., Jinlan, W., Xiaojiao, Z., Shangli, S., & Wenxia, C. (2018). Effect of degradation and rebuilding of artificial grasslands on soil respiration and carbon and nitrogen pools on an alpine meadow of the Qinghai-Tibetan Plateau. *Ecological Engineering*, *111*, 134–142. https://doi.org/10.1016/j.ecoleng.2017.10.013

Xu, C., Wang, H., Liu, Q., & Wang, B. (2020). Alternative stable states and tipping points of ecosystems. *Biodiversity Science*, *28*(11), 1417–1430. https://doi.org/10.17520/biods.2020233

Yang, K., Luo, S., Hu, L., Chen, B., Xie, Z., Ma, B., Ma, W., Du, G., Ma, X., & Le Roux, X. (2020). Responses of soil ammonia-oxidizing bacteria and archaea diversity to N, P and NP fertilization: Relationships with soil environmental variables and plant community diversity. *Soil Biology and Biochemistry*, *145*, 107795. https://doi.org/10.1016/j.soilbio.2020.107795

Yang, Y., Fang, J., Ji, C., & Han, W. (2009). Above- and belowground biomass allocation in Tibetan grasslands. *Journal of Vegetation Science*, *20*, 177–184. https://doi.org/10.1111/j.1654-1103.2009.05566.x

Yang, Y., Fang, J., Ma, W., Guo, D., & Mohammat, A. (2010). Large-scale pattern of biomass partitioning across China's grasslands: Biomass partitioning in grasslands. *Global Ecology and Biogeography*, *19*, 268–277. https://doi.org/10.1111/j.1466-8238.2009.00502.x

Zavaleta, E. S., Pasari, J. R., Hulvey, K. B., & Tilman, G. D. (2010). Sustaining multiple ecosystem functions in grassland communities requires higher biodiversity. *Proceedings of the National Academy of Sciences United States of America*, *107*(4), 1443–1446. https://doi.org/10.1073/pnas.0906829107

Zhao, G. F., Yu, C. Q., Wu, J. X., Luo, L. M., & Miao, Y. J. (2013). Research progress on restoration and management of degraded alpine meadow in Qinahai–Tibet Plateau. *Guizhou Agricultural Science*, *41*(5), 125–129. https://doi.org/10.3969/j.issn.1001-3601.2013.05.036

Zhou, H., Zhao, X., Tang, Y., Gu, S., & Zhou, L. (2005). Alpine grassland degradation and its control in the source region of the Yangtze and Yellow Rivers, China. *Grassland Science*, *51*(3), 191–203. https://doi.org/10.1111/j.1744-697X.2005.00028.x

How to cite this article: Lin, L., Xu, X., Cao, G., Zhang, F., Li, Y., & Huang, J. (2023). Self-stabilizing maintenance process in plant communities of alpine meadows under different grazing intensities. *Grassland Research*, *2*(2), 140–152. https://doi.org/10.1002/glr2.12046