Jie Cheng[1]
Jimin Cheng[1,2]
Tianming Hu[1]
Hongbo Shao[3,4]
Jianming Zhang[1]

[1]Northwestern Sci-Tech University of Agriculture & Forestry, Yangling, P. R. China
[2]State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, Yangling, P. R. China
[3]CAS/Shandong Provincial Key Laboratory of Coastal Environmental Processes, Yantai Institute of Costal Zone Research, Chinese Academy of Sciences, Yantai, P. R. China
[4]Institute for Life Sciences, Qingdao University of Science & Technology, Qingdao, P. R. China

Research Article

Dynamic Changes of *Stipa bungeana* Steppe Species Diversity as Better Indicators for Soil Quality and Sustainable Utilization Mode in Yunwu Mountain Nature Reserve, Ningxia, China

Due to serious degradation of typical *Stipa bungeana* steppe community on the Loess Plateau, a 26-year (1982–2007) experiment has been carried out by methods of forbidden grazing, cutting, and rotational grazing. Our results show that the process of succession of long-term enclosed *S. bungeana* community can be divided into two stages: 1980–1996, the forward succession stage, when the species diversity and biomass reach the peak (33.7 species/m^2 and 1349.41 g/m^2, respectively); 1997–2007, the slow succession stage, when the gradually thickening of litter layer (litter depth reaches 3–5 cm) directly causes the reduction of species diversity and biomass to 19.1 species/m^2 and 863.19 g/m^2, respectively. While under the cutting and rotational grazing methods, grassland succession can be divided into four stages: 1st–5th year, the continuing growth stage; 6th–9th year, the vigorous competing stage; 10th–15th year, the aggregation growth stage of constructive species with biomass reaching the peak (1444.19 g/m^2); and 16th–23rd year, stable growth stage of constructive species, which form sub-climax and are eventually dominated by *S. bungeana*, with the species diversity and biomass of 25–27 species/m^2 and 956.76–1165.35 g/m^2, respectively. The constructive species suddenly change in the 24th year, and the population of *S. grandis* increases rapidly to 21 m^{-2} accounting for 25% of the total plant population. Long-term enclosure leads to decreased species diversity and biomass and is not beneficial for grassland renewing. The species diversity and biomass of degraded grassland continuously decrease to 10 species/m^2 and 392.1 g/m^2 due to long-term artificial failure and transitionally grazing, leading to harden soil with slow rainfall infiltration, where plants can only sustain life under the drought condition. Therefore, reasonable cutting and rotational grazing are the methods of choice for the gradual increase of species diversity and promotion of the natural renewal and forward succession of the grassland on Loess Plateau. These results provide reliable information for the diversity dynamic change as better indictors of soil quality and sustainable utilization mode.

Keywords: Nature reserve; Soil quality; Species diversity dynamics; *Stipa bungeana* steppe; Sustainable utilization mode

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1 Introduction

Grassland is one of the globally important terrestrial ecosystems, and the increase in species diversity and productivity of grassland community depends greatly on the long-term management [1–7]. More research indicates that the species diversity of grassland has important ecology functions [8–12], species diversity is positively related to productivity, especially aboveground biomass [13–15]. *Stipa bungeana* steppe is a major community of middle temperate semi-arid typical grassland in the Eurasian section, widely distributes in western China and Loess Plateau region, and is mainly used for grazing and cutting. Typical grassland has important position in the temperate steppe in China; all the ecological and geographic characters, species composition, community structure, and functions of typical grassland are demonstrated to be unique in ecology [16–19]. *S. bungeana*, one of the major typical grassland plants, has many characters, such as strong adaptability, wide distribution, suitable for domestic animals, strong root system, and with strong ability of stabilization. *S. bungeana* steppe is not only the main pasture on Loess Plateau, but also plays an important role in soil and water conservation and environment purification.

Due to many years of overgrazing, cutting, and other intensive human activities, serious degradation, desertification, decrease in

Correspondence: Prof. H. B. Shao, Institute for Life Sciences, Qingdao University of Science & Technology, Qingdao 266042, P. R. China.
E-mail: shaohongbochu@126.com

Additional correspondence author: Professor J. M. Cheng, cheng_jimin@163.com

steppe vegetation, species diversity, and reduction of forage quality and yield have appeared in blocks; the grassland is irregularly interlaced with farmland and forest land on the Loess Plateau [20]. This results in a series of ecological and environmental problems. Although there are many investigations of the influence on species diversity and productivity of grassland community by enclosure, cutting, and rotational grazing worldwide, little study has been done in China, especially those studies in cutting, rotational grazing, and the succession relationship and rule between enclosure and un-utilization with the species diversity of *S. bungeana* steppe [5–8]. Based on previous researches, we take *S. bungeana* steppe, the main grassland type of subzone of temperate typical steppe on the Loess Plateau, as representative to study 26-year enclosed steppe and steppes under cutting and rotational grazing [18, 19], survey the data, analyze the change pattern of species diversity and biomass under the artificial management and regulation, and take feasible measures that can renew species composition and species diversity, protect and reconstruct grassland community type, develop animal husbandry, and finally protect the ecological environment by providing better indicators for evaluating soil quality and sustainable utilization mode.

2 Materials and methods

2.1 Nature condition

The experiments were carried out in NingXia "YunWu Mountain Nature Reserve" where has a well protected *S. bungeana* population, and the total area is 6700 ha at E106°24′|106°28′|N36°13′|36°19′ with an altitude of 1800–2100 m and an average temperature of 6–7°C. The average rainfall in 26 years is 455 mm, and the rainfall from July to September accounts for 65–85% of the annual precipitation. The ≥10°C accumulated temperature is 2100–3200°C, and the annual sunshine hours are 2500 h with annual average frostless period of 137 days and aridity at 1.5–2.0. The soils are dark loessial soil and mountain grey cinnamon soil. It belongs to temperate semi-arid typical steppe. There are 182 species of seed plants belonging to 131 genera and 51 families in this nature reserve. The main plant is herb, and most of the plants are xerophytism and mid-xeric. The constructive species are *S. bungeana* and *S. grandis*, and the companion species are *Artemisia vestita*, *Thymus mongolicus*, *Agropyron dasystachys*, *Potentilla bifurca*, *Heteropappus altaicus*, etc.

2.2 Methods

The experiment was started from 1983, and the major species was *S. bungeana*. The experiments were divided into 4 plots: (1) Enclosed area (forbidden grazing), (2) cutting area, based on enclosure condition, cutting was carried out twice per year in mid-June and mid-September, respectively, (3) rotational grazing area, except rational grazing in mid-June, mid-August, and mid-October (grazed for 7–10 days each time and the grazing intensity was 1.5–3.0 sheep per hectare), grazing in other time was completely forbidden, (4) long-term grazing area, which was set as control group.

2.3 Measurement

A 10 ha of fixed sample plot was established in every treatment, and each treatment contains 3 fixed plots (1 m × 1 m) with ten replicate blocks. Investigations of the vegetation were carried out on April 10th, July 10th, and October 5th, respectively. The heights of fixed plants were measured; coverage was measured by projection method; abundance, frequency, individual quantity of population, total number of vegetation, number of regeneration were determined by coenology and statistic methods, biomass were measured by fresh weight.

2.4 Statistical analysis

The statistical analysis was performed with DNP software; the calculation of diversity index was derived from Chen [15] and Zhang's [16] methods. The formulae are as follows:

Important value = (relative height + relative coverage + relative abundance + relative frequency)/4.

Abundance index:

$$\text{Margalef index}: R = \frac{S-1}{\ln(N)}$$

Diversity index:

$$\text{Corrected Simpson index}: D_1 = -\ln\left[\sum_{i=1}^{S}\left(\frac{N_i}{N}\right)^2\right]$$

$$\text{Shannon-wiener index}: H = -\sum_{i=1}^{S}(P_i \ln P_i)$$

$$\text{Audair \& Goff index}: D_2 = 1 - \sqrt{\sum P_i^2}$$

Evenness index:

$$\text{Pielou evenness index}: E_1 = \frac{H}{\ln(S)}$$

$$\text{Similarity coefficient}: Is = \frac{2C}{A+B}$$

where S total species number of the community, N total individual number of all species in the community, N_i sum of each species, P_i ratio of the ith species' number to all, C species number of the community in enclosed and unenclosed plots, A species number in enclosed area, and B species number in unenclosed area.

3 Statistics and analysis

3.1 Effects of grassland utilization on composition of plant density

Figure 1 and Tab. 1 show significant differences in variations of species diversity among different treatments in 26-year experiment with *S. bungeana* grassland. In district A, plants grow luxuriantly with increased species diversity after the long-term enclosure; the growth and development of plant are normal. The vegetation coverage increases, and the structure of plant is significantly improved. Because the community structure has not been destroyed by human and grazing and not been trampled by live stock, the 26 years change of the succession process of species diversity shows polynomial parabolic. In enclosure period from 1982 to 1996, the number of plant population has reached the highest value (33.7 species/m^2) with increased plant circumference, and the coverage has increased from 10–25% to 85–95%. As a result, an intense upper-layer

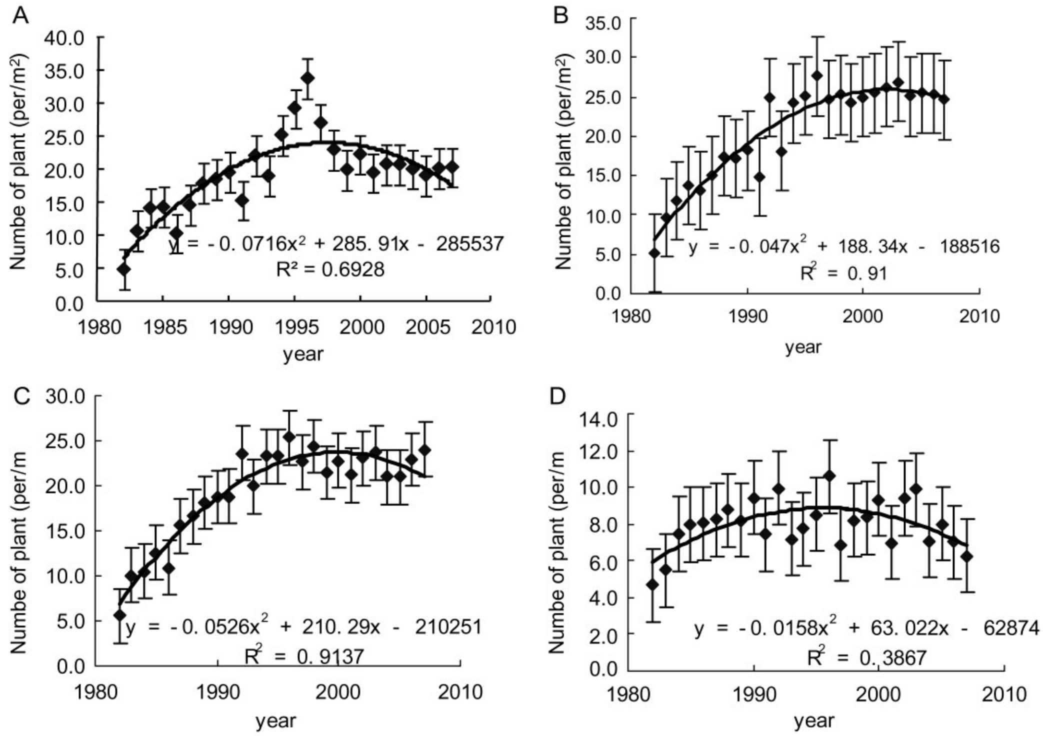

Figure 1. The change of species diversity under different types of grassland utilization of *S. bungeana* steppe; (A) enclosed area; (B) cutting area; (C) rotational grazing area; (D) control area.

forms with obviously differentiated community hierarchy. The first hierarchy is *S. bungeana*, the forage grass, the second hierarchy is mainly composed of *H. altaicus* and *Artemisia*, and the composition of the third hierarchy is *Potentilla sifarca*, *P. acaulis*, and *Thymus serpyllum*. Fifteen years later, with the lapse of enclosing time, species diversity has decreased by 38.8% from 1996 (20.7 species/m^2) to 2007 with $R^2 = 0.6928$; on the other hand, the depth of community litter-cover increases. Numerous seeds of forage grass hang on the litter-cover after maturation and cover the ground with the thickness of 3–5 cm; due to long-term enclosure, seeds are hard to reach the soil directly. Although the seeds can germinate and form seedling under the condition of proper water and heat, weak roots of seedling are difficult to grow into the soil and cannot get enough water and nutrient. Half of seedlings are dead after germination. The seedlings grow and develop slowly and dead earlier because of interspecies competition. This is a crucial problem influencing the community species and diversity.

Under the conditions of cutting and rotational utilization, the variation of the species diversity is relatively stable. By the 23rd year of cutting and grazing, species diversity has declined, but the amplitude is small with a stable value of 23–25 species/m^2. The corresponding R^2 is between 0.9100 and 0.9137. Among the continuously increasing brunches, the number of new brunches, which are mainly reproduced by seed, increases greatly; while the number of new brunches reproduced by sprouting is less. The distributions of individual species are stable, and the sub-climax community that is mainly composed of *S. bungeana* population appears eventually. In district D, due to long-term overgrazing, the individual number of population decreases, and the plants grow low with even distribution. *S. bungeana* is dominant, but the composition of plant structure is unique. The ground barrens have no regenerating seedlings; the grassland usually deteriorates severely. The result demonstrates that under different managements and use of the grassland, time prolongation has significantly affected the species diversity.

Table 1. The change of species diversity under different types of grassland uses (species/m^2)*

Utilization years (Y)	Enclosed area	Cutting area	Rotational area	Control area
1 (1982)	5.050 ± 2.025	5.133 ± 1.224	5.533 ± 1.525	4.667 ± 1.446
5 (1986)	10.230 ± 2.318	13.200 ± 0.714	10.900 ± 2.155	7.967 ± 1.974
10 (1991)	15.090 ± 2.248	14.700 ± 0.988^{G}	18.933 ± 1.337^{lF}	7.333 ± 1.213^{gG}
15 (1996)	33.740 ± 3.621^{aA}	27.667 ± 1.748^{aA}	25.267 ± 1.701^{aA}	10.533 ± 1.592^{aA}
20 (2001)	19.497 ± 1.909^{l}	25.533 ± 1.432^{dC}	20.767 ± 1.547^{fG}	7.000 ± 1.640l
26 (2007)	20.693 ± 1.883^{fG}	24.633 ± 1.629^{fG}	23.166 ± 2.036^{dC}	6.267 ± 1.874

*Lower case indicates significant on the 0.05 level; capital letter indicates very significant on the 0.01 level. All data are presented as mean ± standard deviation.

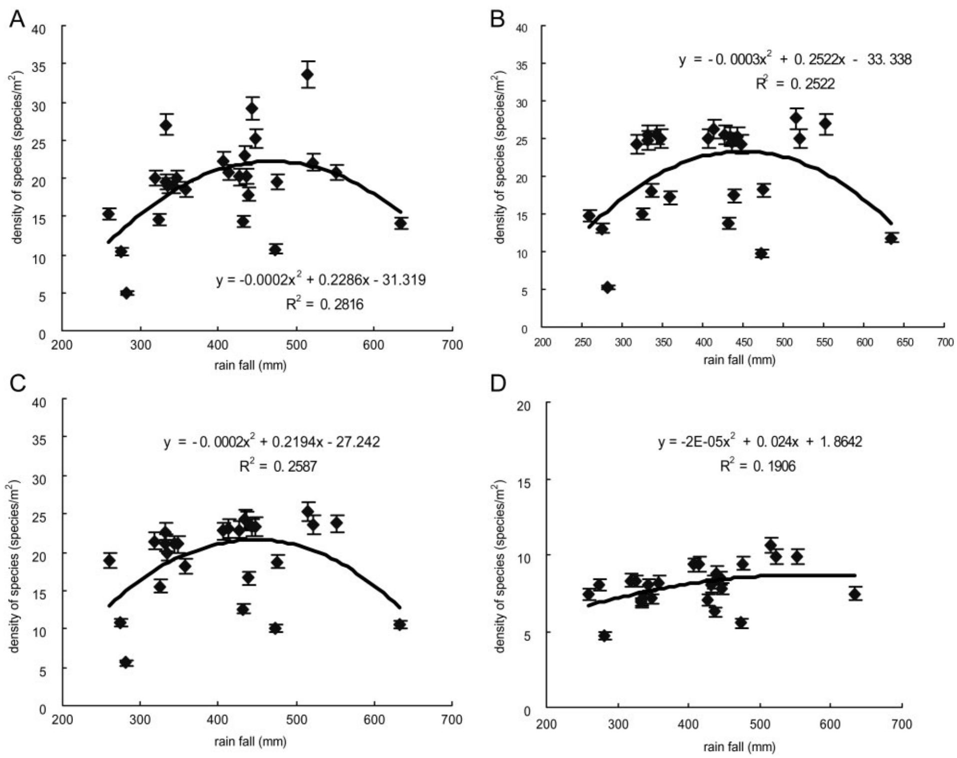

Figure 2. The relationship between different types of grassland utilization, rainfall, and species diversity of *S. bungeana* steppe; (A) enclosed area; (B) cutting area; (C) rotational grazing area; (D) control area.

3.2 Effects of rainfall on the species diversity of grassland

Figure 2 shows the fitting results of rainfall and species diversity through 26-year experiment of *S. bungeana* steppe; the effect of rainfall on species diversity shows a trend of parabolic changes. There are little differences among the fitting curves of enclosed, cutting, and rotational grazing areas with corresponding R^2 of 0.2816, 0.2522, and 0.2587, respectively. However, significant differences are found between the three treated areas and the control group, which has a R^2 of 0.1906. Under different managements and utilization, species diversity should change correspondingly along with different rainfall environmental gradients, indicating although rainfall has effect on species diversity, the seasonal variances in precipitation distribution lead to little change. Spring is the key period for plant germination and seedling emergence, but under the arid and rainless condition, only perennial that can use water in deep layer maintains life under water-stress; while other seedlings are difficult to form. After 15 years of experiment, affected by the thickening of litter layer, the species diversity and biomass decrease significantly with individual seedling dysplasia; the grassland community is in a degraded trend, especially during the time from July to September. The grass is in a semi-perishing status with simple community structure and scarcity of renewal seedlings; natural renewal of grassland is directly inhibited.

3.3 Effects of grassland utilization on biomass

Figure 3 shows that there is significant difference in the grass biomass among the four treatments. For district A, the density of *S. bungeana* community increases gradually during 15-year enclosure; in 15th year, the species diversity, coverage, and biomass growth reach the maximum level. The plant heights are 40–50 cm, and the coverage reaches 80–90%. Species diversity and biomass linearly increase with time during the 26 years, and the correlation reaches extremely significant level with relative coefficient R^2 of 0.7468. In district B and C, with twice of cutting and three times of grazing in each year, the species diversity and biomass show linearly increasing trend; similarly, the correlations are also extremely significant but show little change with relative coefficient R^2 of 0.8421 and 0.9221, respectively. The average biomass in cutting area and grazing area increases 3.1–3.5 times and 3.3–4.8 times, respectively, indicating that reasonably protecting grassland and promoting development of animal husbandry are beneficial to the normal reproduction and renewal. In Fig. 3, the statistics by analysis of 3120 quadrats, four types of treatments, and 26-year experiment shows that the species richness, Simpson index, and Shannon index are linearly associated with the biomass with fitting coefficient r of 0.50, and the fitting results are significant ($p < 0.005$). The fitting coefficients of long-term enclosure and grazing are lower indicating that both long-term enclosure and grazing are against the sustainable development of grassland.

Figure 3 also shows that the peaks of biomass under four treatments all appear in the 15th year, and the biomass in every treatment is significantly higher than that in control. The rank of biomass is rotational grazing area > cutting area > enclosed area > control area. From 16th to 26th year, on the basis of 11 years of cutting and rotational grazing, their biomass has stabilized at 927.39–1165.35 g/m^2; while biomass in the enclosed area is only 863.19–950.06 g/m^2 but much higher than that in the control group. These results indicate

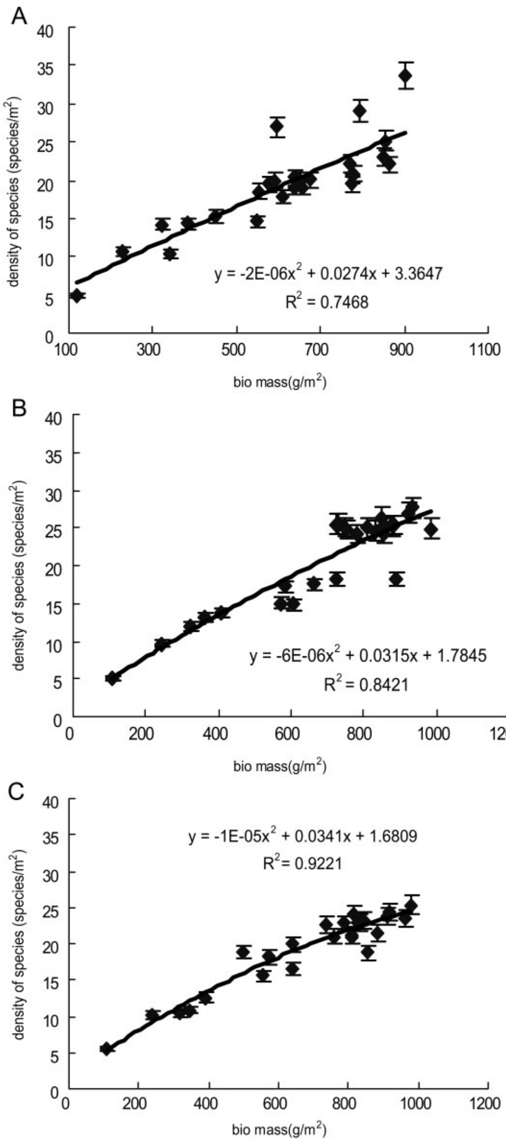

Figure 3. The change of biomass and species diversity under different types of utilization of *S. bungeana* steppe; (A) enclosed area; (B) cutting area; (C) rotational grazing area; (D) control area.

that reasonable utilization of grassland on Loess Plateau can effectively promote the natural renewal and regeneration and increase the biomass, but long-term enclosure and overgrazing, on the contrary, show retroaction.

3.4 Effects of grassland utilization on changes of species diversity index

Tables 2 and 3 show the obvious changes in species diversity of *S. bungeana* community under different treatments. Species richness index *R*, species diversity index, modified Simpson index, Shannon-winner index, Audair and Groff index, and evenness index of enclosed area, cutting area, and rotational grazing area are much greater than that of control area. Therefore, long-term enclosure, reasonable cutting, and rotational grazing of grassland improve vegetation biotope and promote generation and proliferation of new species leading to significant enhancement of the species abundance and the diversity of grassland community. The increase of new species is not because of the increase of individual number, but because of the appearance of individual. However, the invasion, competition, and settlement are a long-term process, which is always necessary for the appearance of a new species. At the beginning, the space occupied by new species is relatively less, and the number of species in control grassland community is stable. Therefore, the evenness index is relatively higher. Change of species diversity, species richness index, evenness index, and species diversity index are all greater in cutting area and rotational grazing area than in enclosed area, indicating that only reasonable cutting and rotational grazing can effectively promote natural renewal and regeneration; long-term enclosure, on the contrary, goes against the grassland natural renewal.

4 Discussion

The restoration of grassland by enclosure is the process of subsequent evolution of the degraded grassland that had been interfered by non-fence grazing and human activities. Following the enclosure of grassland, vegetation community and species composition have been obviously changed; one community has been replaced by another. In this study, we report after 26-year enclosure of degraded grassland in Loess Plateau, *S. bungeana* community has formed through the evolution process (Tabs. 1–3), and the vegetation succession has reached sub-climax. Numerous mesophytic shrubs and herbages appear too. However, long-term enclosure can also inhibit the forage growth and development; the litter can inhibit the plant regeneration and decrease the species diversity. The regeneration ability of grassland becomes weak, and the coverage declines with reduced grass production by 18–26%. Previous study has shown that in the long-term enclosure, grassland soil has the properties of low bulk density, high porosity, abundant organic matter, and thick litter layer. But for the reason of existence of litter layer, present biomass is few, and sediment is plenty. The grass production has reduced by 29% [13]. The objective of uniformed distribution and

Table 2. Temporal and spatial variation of biomass under different types of utilization of *S. bungeana* steppe ($g\,m^{-2}$)*

Year (Y)	Enclosed area	Cutting area	Rotational area	Control area
1 (1982)	174.45 ± 17.24	159.33 ± 7.62	162.05 ± 10.18	83.69 ± 3.52
5 (1986)	510.33 ± 38.72	544.74 ± 13.04	520.57 ± 12.24	160.55 ± 15.72^{m}
10 (1991)	673.51 ± 80.88	792.50 ± 80.64	749.74 ± 120.06^{c}	101.21 ± 12.18^{o}
15 (1996)	1349.41 ± 170.94^{aA}	1394.24 ± 104.10^{bB}	1444.19 ± 59.90^{aA}	392.10 ± 14.90^{aA}
20 (2001)	863.19 ± 102.88^{hG}	956.76 ± 30.68^{k}	927.39 ± 44.46^{l}	174.32 ± 14.64^{l}
26 (2007)	950.06 ± 89.60^{eD}	1165.35 ± 31.76^{fF}	996.90 ± 47.32^{gG}	181.60 ± 10.94^{jk}

*Lower case indicates significant on the 0.05 level; capital letter indicates very significant on the 0.01 level. All data are presented as mean ± standard deviation.

Table 3. The changes of species diversity of *S. bungeana* grassland community*

Treatment	Richness index (*R*)	Evenness index (*E*)	Species diversity index		
			*D*1	*H*	*D*2
Enclosed area	14.23 ± 1.35^{a}	0.74 ± 0.02^{c}	5.32 ± 0.16^{a}	3.16 ± 0.42^{cB}	0.93 ± 0.26^{aB}
Cutting area	17.26 ± 2.12^{aA}	0.93 ± 0.09^{aA}	5.68 ± 0.43^{aA}	3.85 ± 0.28^{aC}	0.94 ± 0.21^{aB}
Rotational area	16.84 ± 2.81^{aA}	0.91 ± 0.13^{aA}	5.72 ± 0.54^{aA}	3.79 ± 0.62^{aA}	0.96 ± 0.35^{aA}
Control area (CK)	4.24 ± 1.32^{b}	0.52 ± 0.33^{b}	2.21 ± 0.47^{cB}	2.42 ± 0.22^{bC}	0.54 ± 0.03^{bB}

*Lower case indicates significant on the 0.05 level; capital letter indicates very significant on the 0.01 level. All data are presented as mean ± standard deviation.

productivity improvement for species in grassland can be achieved only through rational enclosure. There is a significant quadratic function relationship between species diversity and biomass of *S. bungeana* grassland community in Loess Plateau; following the increasing of biomass, species diversity can be expressed in a single peak curve. Biomass and species diversity reach the peak in 15th year. Biomass reaches the peak when the number of plant population reaches the maximum, and the results are similar with that from ref. [9]. After enclosure for 15 years, species diversity and biomass decrease with time. Species composition, interaction between different species, and interaction between species and environmental factors determine the property, structure, and function of an ecosystem [17–24]. Because of the compensatory growth of plant and soil, species diversity and biomass are high during the first 1–15 years. After 15 years of enclosure, environmental factors and litter layer (litter thickness reaches 3–5 cm) lead to bad soil aeration which influences the renewal seedling, forage regeneration, and finally the stability of the system. Bad soil aeration directly inhibits the normal growth and development of grass and the formation of species diversity leading to the decline of natural regeneration of grassland and remarkable decrease in biomass [25–30].

Species composition of plant community is an important symbol of grassland community property, structure, and function. However, the change of environmental factors plays a crucial role in community evolution. Human activities, such as cutting and grazing, are considered as the most influential factors affecting grassland habitat by obviously influencing the composition and structure of grassland species diversity [18–30]. A seven-year research of short forage grassland shows that heavy grazing can reduce total grass production by about 40% in growth season from June to July, and the highest production can be obtained by heavy grazing in the late growth season [2, 3, 27, 28]. In this study, heavy grazing reduces total grass production by about 30–45% in semiarid area in growth season from June to July. The average production, not the highest, can be obtained by heavy grazing in the late growth season. *S. bungeana* whose tiller bud is under the ground belongs to dense clumping forage; its tiller bud cannot be easily damaged by sheep and can be promoted to regenerate under rational grazing condition. Therefore, grazing has both inhibition and promotion mechanisms [6], and the effect of reasonable cutting and grazing on species diversity of grassland communities follows the ''intermediate disturbance hypothesis''. Plant compensatory growth can be decided by the net effect of inhibition and promotion, which relates to the community type, stocking rate, environment condition, and grazing history [5]. Domestic and foreign studies on plant compensatory growth mostly focus on theory and model, and the study through comprehensive and systematic experiment is very much limited [15, 25–29].

5 Conclusion

- During the first 1–15 years of enclosure, species diversity and biomass reach the peak; however, species diversity, biomass, and natural regeneration ability of the grassland display a decreasing tendency thereafter.
- Under the rational cutting and rotational grazing, species diversity and biomass of *S. bungeana* steppe reach the peak in 15th year; it eventually reaches sub-climax community in four stages of succession. After 24 years of appropriate utilization, great changes have occurred, and individual number of *S. grandis* increases sharply showing a tendency of replacing the *S. bungeana*.
- The average biomass of 26-year enclosed grassland is 3–4.5 times more than that of control area, and biomass in rational cutting and rotational grazing area is 3.1–5.5 and 3.3–4.8 times more than that of control area, respectively. The rational cutting and grazing not only protect grassland, but also develop livestock industry and promote the normal regeneration of grassland. The above steppe dynamic changes can be better indicators for evaluating soil quality and referenced sustainable utilization mode in similar nature reserve in the world.

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