Early warning indicators of grassland degradation in inner Mongolia

Jie Qin [1] , **Guodong Han** [Corresp., 1] , **Zhongwu Wang** [1] , **Linxi Hu** [1] , **Jun Zhang** [1]

[1] College of Grassland, Resources and Environment Science, Inner Mongolia Agricultural University, Huhhot, China

Corresponding Author: Guodong Han
Email address: nmghanguodong@163.com

Backgroung: With the implementation of the Household Production Responsibility System in China almost 30 years ago, obvious spatial heterogeneity has developed over rangeland.

Methods: We examined lifeform functional groups over 5 years on household ranches in different grazing utilization rate (30%-95%) ecosystems in Inner Mongolia to identify the early warning indicators of grassland degradation.

Results: The results showed that a similar grassland utilization threshold occurred in different types of steppe, with 78-89% utilization for meadow steppe, 81-89% for typical steppe and 70-85% for desert steppe. The vegetation composition above these utilization thresholds did not show obvious signs of degradation; therefore, the risk of degradation was difficult to determine. The spatial threshold (WD: L) had a value of 31.40:100 for meadow steppe, 8.53:100 for typical steppe and 42.21:100 for desert steppe.

Conclusion: Land managers cannot easily determine the risk of degeneration according to the vegetation composition or function group. So the spatial threshold is important for implemented strategies to prevent degradation, and our study provides new insights to improve the management and restoration of degraded grassland in Inner Mongolia.

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

Early warning indicators of grassland degradation in Inner Mongolia

Jie Qin[1], Guodong Han[1], Zhongwu Wang [1], Linxi Hu[1], Jun Zhang[1]

[1]College of Grassland, Resources and Environment Science, Inner Mongolia Agricultural University, Huhhot, China

Corresponding author:

Guodong Han

College of Grassland, Resources and Environment Science, No.29 Ordos East Street, Saihan Region, Hohhot city, Inner Mongolia. 010011, China

Email address: nmghanguodong@163.com

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

Abstract

Background: with the implementation of the Household Production Responsibility System in China almost 30 years ago, obvious spatial heterogeneity has developed over rangeland.

Methods: we examined lifeform functional groups over 5 years on household ranches in different grazing utilization rate (30%-95%) ecosystems in Inner Mongolia to identify the early warning indicators of grassland degradation.

Results: the results showed that a similar grassland utilization threshold occurred in different types of steppe, with 78-89% utilization for meadow steppe, 81-89% for typical steppe and 70-85% for desert steppe. The vegetation composition above these utilization thresholds did not show obvious signs of degradation; therefore, the risk of degradation was difficult to determine. The spatial threshold (WD: L) had a value of 31.40:100 for meadow steppe, 8.53:100 for typical steppe and 42.21:100 for desert steppe.

Conclusion: land managers cannot easily determine the risk of degeneration according to the vegetation composition or function group. So the spatial threshold is important for implemented strategies to prevent degradation, and our study provides new insights to improve the management and restoration of degraded grassland in Inner Mongolia.

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

1. Introduction

Rangeland plays important ecological and social roles (Wrage et al., 2011) and provides direct products, such as meat, milk, leather, and wool, for human consumption (O'Mara, 2012), as well as indirect ecological services, such as water conservation, carbon pools and climate stability (White, Murray & Rohweder, 2000; Huyghe, 2008). China has the third largest grassland area in the world, with nearly 400 million hm^2 (accounting for approximately 41.7% of China's total land area) (Schweiger et al., 2015). More than 70% of the native rangelands are located in the arid and semi-arid regions of Inner Mongolia, where meadow, typical, and desert steppe account for 11%, 34% and 39% of the total area, respectively (Han et al., 2008; Li et al., 2008; Liang et al., 2009). Grassland is a major production base in Inner Mongolia for raising livestock and an important component of Eurasian continental grassland ecosystems.

Livestock grazing represents an important historical use of rangelands (Mekuria, 2013). Grazing offers a management tool for maintaining primary production (Briske et al., 2015), biodiversity (Liu et al., 2015) and habitats (Ansell et al., 2016). China has a long nomadic history of approximately 7000 years; however, land management practices changed significantly after the Chinese government encouraged the Household Production Responsibility System (HPRS) in 1980. According to the HPRS, the state assigns long-term grassland use rights to individual households. Herders build fences to protect their leased rangelands, which blocks long-distance movements, and they also build shelters for livestock protection and human habitation. The use of grasslands for grazing is strongly influenced by watering points, and the intensity of biomass utilization increases with decreasing distance from watering points (Pickup & Chewings, 1994).

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

Increased utilization results in low productivity, poor soil fertility (Wang et al., 2016), and even desertification of grassland ecosystems (Lamchin et al., 2016; Sanderson et al., 2016), and these changes hinder the development of animal husbandry and the effective use of resources. Because the location of water points and shelters are fixed, spatial heterogeneity arises because of the interrupted and uneven utilization of permanent rangeland, and changes in grasslands are commonly observed within 1000 meters of watering points. In our study, the ultimate goal is to spatially identify early warning indicators of grassland degradation. Different grazing intensities should have divergent impacts on the spatial patterns of vegetation (Lin et al., 2010; Ren et al., 2016); therefore, our main objective was to quantify the grazing effects on grasslands.

Arid and semiarid rangelands often behave unpredictably in response to management actions and environmental stressors; therefore, ranchers may encounter difficulties when managing rangelands for long-term sustainability (Knapp & Fernandez-Gimenez, 2009). Grazing has a slight effect on grasslands that have self-regulating functions. Grazing-resistant plants have evolved over the long history of grazing in Inner Mongolia (Cui et al., 2005), and stable communities mainly consist of grazing-resistant vegetation. However, the influence of light grazing on functional groups is limited. We classified species into the following five plant functional groups (PFGs) primarily on the basis of life forms: perennial bunchgrasses (PB), perennial rhizome (PR), annuals and biennials (AB), shrubs and semi-shrubs (SS), and perennial forbs (PF) (Tilman, Isbell & Cowles, 2014). PFGs differ in plant stature, rooting depth, root-to-shoot ratio, water use efficiency, nutrient use efficiency and C:N:P stoichiometry. Worldwide, woody plants are replacing grasses in rangelands, and invasive species are becoming

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

more common (Reid, Fernández-Giménez & Galvin, 2014) because of heavy grazing or abandoned grazing lands. After grazing increases past a certain level, irreversible degradation of grasslands can occur. Beyond this threshold, the roles of functional groups change, with new functional group combinations arising because of competition for resources. A threshold represents a point in space and time at which primary ecological degradation is beyond the ability of self-repair (Petersen, Stringham & Roundy, 2009). Thus, a grassland community can shift to a state from which it can no longer self-recover to a healthy state, such as switching from an herbaceous to a shrub community. After such a transition, restoration requires a long time period and significant investments (Reid, Fernández-Giménez & Galvin, 2014). Therefore, the state transition threshold can be considered an early warning sign for grassland degradation.

Many scientists have developed indexes for degradation based on soil microorganisms (Patra et al., 2008) or plant physiology (Wang et al., 2014a); however, a simple degradation index is required for use by grassland managers (herdsman). Therefore, early warning indicators of grassland degradation that are simple to operationalize must be identified (Zweig & Kitchens, 2009; Kachergis et al., 2013), which requires the resolution of three critical issues: 1) is there a threshold at which the composition of functional groups changes; 2) does the threshold have obvious characteristics in terms of vegetation or functional groups; and 3) how can the threshold be defined in spatial scales for grassland management. Thus, the objective of this research was to explore the impact of grassland utilization on functional groups in three types of steppe in Inner Mongolia and identify the early warning indicators of grassland degradation.

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

2. Materials and methods

2.1 Site description

(1) The meadow steppe (MS) ecosystem is located in Xiwuzhumuqin Banner in northeastern Inner Mongolia (E: 117°45′, N: 43°40′). The site has an elevation of 1090 m. The area has a sub-humid and semi-arid warm temperate continental climate, and the average annual precipitation from 1959 to 2006 was 325.1 mm, and it was mostly concentrated between June and August. The mean annual temperature is 1°C, and the frost-free period is 106 d (Tang et al., 2013). The average annual evaporation is 1600 mm, and the aridity index is 4.1. The community coverage is 78~86%, and the aboveground biomass is 148~164 $g \cdot m^{-2}$. The soil type is mainly typical kastanozems (FAO soil classification). The steppe is a *Stipa baicalensi-Leymus chinensis* meadow steppe, and *Stipa baicalensi*, *Leymus chinensis* and *Cleistogenes squarrosa* are the dominant species.

(2) The typical steppe (TS) ecosystem is located in Keshikten Banner in central Inner Mongolia (E: 116°33′, N: 43°26′) at an elevation of 1370 m. This area has a semi-arid warm temperate continental climate, with a cold and windy winter. The average annual precipitation from 1953 to 2000 was 282.4 mm, and it was mostly concentrated between June and August. The average annual temperature is 1.5°C, and the frost-free period is 100 days (Liang et al., 2009). The average annual evaporation is 1643 mm, and the aridity index is 4.7. The community coverage is 71~81%, and the above-ground biomass is 133~151 $g \cdot m^{-2}$. The soil type is kastanozem with a loamy sand texture. The experimental site is a typical *Stipa grandis-Leymus chinensis* steppe, and *Stipa grandis*, *Leymus chinensis* and *Cleistogenes squarrosa* are the dominant species.

(3) The desert steppe (DS) ecosystem is located in Siziwang Banner in the midwestern region of Inner Mongolia (E: 111°53′, N: 41°47′) at an elevation of 1450 m. The climate is dry and semi-arid warm temperate continental and characterized by a short growing season and a long cold winter. The average annual precipitation from 1954 to 2000 was 203.1 mm, and it was mostly concentrated between June and August. The average annual temperature is 3.5°C, and the frost-free period is 105 days. The average annual evaporation is 2947 mm, and the aridity index is 11.9. The community coverage is 25~29%, and the aboveground biomass is 42~46 $g \cdot m^{-2}$. The dominant soil type is kastanozem with a loamy sand texture (Li et al., 2008). The steppe is a *Stipa breviflora* desert steppe, and *Stipa breviflora*, *Cleistogenes songorica* and *Artemisia scoparia* are the dominant species.

2.2 Experimental design

The HPRS was initially implemented in Inner Mongolia in the 1980s (Li et al., 2007). Households were allocated use rights to areas on the basis of family size (stocking $rate_{MS}$=0.75~1.50 sheep units$\cdot hm^{-2}$, stocking $rate_{TS}$=0.60~1.50 sheep units$\cdot hm^{-2}$, and stocking $rate_{DS}$=0.50~0.75 sheep units$\cdot hm^{-2}$). After nearly 30 years of the HPRS program, grassland household ranches have developed a spatial pattern characterized by an outward radiation from a fixed settlement and a gradient from heavy to light grazing along the radius of the grazing areas (Pickup & Chewings, 1994). Flat plots with similar soil types and plant communities were selected for each of the three steppe types in 2004. Then, three ranches with similar family sizes and similar livestock breeds (e.g., sheep) and livestock numbers were selected in every plot.

On each ranch, we measured 20 cm×50 cm quadrats every 50 m along a transect from the center point (i.e., livestock water point or shelter) to the edge of the ranch. According to a cluster analysis of the vegetation composition, production and coverage in every quadrat, the grazing

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

intensity was divided into three levels (Pickup & Chewings, 1994): heavy grazing (H), moderate grazing (M), and light grazing (L). Control plots were selected using mown pasture with enclosures that had experienced no interference since 2004 (CK) (Han et al., 2008; Tang et al., 2013). According to preliminary investigations and the data analysis, the plots were classified into L, M and H grazing intensities, which corresponded to the distance from the center points as follows: 740 m, 520 m and 240 m in MS plots, respectively; 420 m, 300 m and 180 m in TS plots, respectively (Fig. 1); and 2400 m, 1700 m and 600 m in DS plots, respectively. The plant utilization rates under L, M, H intensities were 24%~30%, 40%~44% and 65%~70%, respectively. Three repeated quadrats were located near the point (radius of 10 miles at the grazing intensity point) in different directions.

Quadrats of 0.2 m×0.5 m were sited every 20 m along the transect starting from the center point to the farthest radius in 2009, and 9 quadrats were located in non-grazing areas in each steppe (total of 829 quadrats in 3 sites (n_{MS}=200, n_{TS}=424, n_{DS}=205)).

The quadrats (1×1 m^2 and 0.2×0.5 m^2) were sampled in mid-August (i.e., the vigorous growth period) between 2005 and 2009 (Li et al., 2008) in each zone of grazing intensity. All plants were harvested at ground level, dried at 60°C to a constant mass and weighed to the nearest 0.1 g.

2.3 Analysis method

We used a multiple regression analysis to derive the relationships between the relative biomass of each functional group (i.e., functional group biomass/total biomass×100%) between the grazed and non-grazed plots as well as the grassland utilization. The model of the relationship between the functional groups and utilization rates was a cubic regression model with a high degree of fit. The analysis was conducted using the Statistical Package for the Social

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

Sciences (SPSS 20.0). According to the model, grassland utilization thresholds are observed in locations where a number of functional groups cross a certain utilization range.

Utilization rate=(CK quadrat biomass–grazing quadrat biomass)/CK quadrat biomass *100%,

where grazing quadrats represent the quadrats in the L, M or H grazing areas.

Relative biomass of functional group=functional group biomass/total biomass×100%.

Spatial threshold=WD/LL,

where WD represents the warning distance, which is the distance from a water point to a point, with the point presenting the same utilization threshold according to the long line transect data of 2009; and LL represents the line length, which is the distance from the water point to fences (Fig. 2).

3. Analysis of the results

Different types of steppe have different thresholds. The meadow steppe threshold occurred at grassland utilization rates between 78% and 89% (Fig. 3). The optimal state of the functional groups always occurred in the light grazing area. At this stage, the biomass was ordered as follows: PB>PF>PR>SS>AB. Functional groups presented different responses to increasing grazing stress, which resulted in a change in the order of biomass as follows: PF>AB>SS>PR>PB. When the utilization rate reached 89%, changes in the functional group pattern led to grassland degradation.

The threshold of the typical steppe was more concentrated for grassland utilization rates between 80% and 89% (Fig. 4). Similar to the meadow steppe, the biomass of functional groups in the typical steppe had an order of PB>PF>AB>SS>PR, although in the H plots, the order

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

changed to PF>PB>PR>SS>AB. Once the utilization rate reached 89%, changes in the functional group pattern led to degradation. The desert steppe threshold is shown in Fig. 5 (70%-85% utilization rate). Once the maximum utilization rate was reached, then the functional group biomass changed from PB>SS>PF>AB>PR to SS>PF>AB>PB>PR, which indicated that degradation occurred.

Different types of steppe had different functional group compositions in the threshold state (Fig. 6). The total aboveground biomass of the threshold state was 50.68 g/m^2 in meadow steppe, of which the biomass of grass (PB and PR) accounted for more than half the total biomass and the relative biomass of PF accounted for 25.18%. The biomass of AB and SS had low values of 2.57 and 1.78 g/m^2, respectively.

In the typical steppe, the total aboveground biomass of the threshold state was over 51.09 g/m^2. The biomass of PB was 28.65 g/m^2, which accounted for 40.92% of the total biomass, and the biomass of grass (PB and PR) accounted more than half the total biomass. The relative biomass of PF was 39.04% in total at 12.94 g/m^2. SS and AB had low values of 6.84 and 1.47 g/m^2, respectively.

In the desert steppe the total aboveground biomass of the threshold state was 23 g/m^2, and AB accounted for 44.38% (8.17 g/m^2), PF accounted for 29.67%, and SS accounted for 22%. The biomass of grass (PB and PR) accounted for less than a fifth of the total at 3.15 g/m^2 for PB and 0.39 g/m^2 for PR.

The dominant species presented different compositions at the threshold states (Table 1). The dominant species at the threshold state consisted of three functional groups in the meadow

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

steppe: *Leymus secalinus* and *Leymus chinensis* (rhizome grass) accounted for over 59% of the total biomass (42.33% and 17.21%, respectively), and *Cleistogenes squarrosa*, which was sub-dominant to the bunchgrasses, and other bunchgrasses, including *Festuca ovina*, accounted for 10.3% of the total biomass. *Potentilla tanacetifolia*, *Plantago asiatica*, *Potentilla bifurca* and *Iris dichotoma* accounted for over 10% of the relative biomass (17.39%, 14.91%, 11.31% and 10.84%, respectively).

Eight plants had a relative biomass over 10% in the typical steppe threshold state, and they belonged to five functional groups. Bunchgrass (including *Cleistogenes squarrosa* and *Stipa grandis*) had the largest relative biomass (55.93 and 15.88%, respectively). *Potentilla acaulis* was the second most dominant species (39.46%). Another forb, *Oxytropis hirta*, accounted for 11.86% of the total biomass. The sum of the relative biomass of *Convolvulus ammanii* and *Ixeris denticulata* was over 30% (25.24% and 10.17%, respectively). Among the semi-shrubs, one species (*Artemisia frigida* Willd at 18.39%) represented a dominant species. The common rhizome grass (*Leymus chinensis*) also had a relatively high biomass (16.52%).

In the threshold state in the desert steppe, 7 dominant species belonged to 5 functional groups. *Stipa breviflora Griseb* and *Leymus chinensis* (37.91% and 11.24%, respectively) accounted for 50% of the total biomass. Two annual and biennial grasses, *Convolvulus ammanii* and *Salsola collina,* had a relative biomass over 20% (27.75% and 21.64%, respectively). *Artemisia frigida* Willd accounted for 25.03% of total biomass, and *Caragana microphylla* Lam (semi-shrubs) accounted for 10.21% of the total biomass. *Cymbaria dahurica* was the only perennial forb, and it accounted for 14.88% of total biomass.

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

The WD/LL was 31.40:100 for the meadow steppe, 8.53:100 for the typical steppe and 42.21:100 for the desert steppe (Table 2).

4. Discussion

Vegetation changes that occur before the onset of degradation appear slight when observed at small scales. Therefore, degradation indicators are difficult to detect. The key issues for detecting these indicators are to identify where, when, and under what circumstances undesirable transitions may occur (Bestelmeyer, Goolsby & Archer, 2011). Scientists who study grassland degradation focus on degradation indicators (e.g., soil, toxic weeds, etc.). Compared with traditional thresholds, spatial thresholds allow natural resource professionals to better understand transition mechanisms (e.g., soil indices). Hence, spatial thresholds are used more often for assessments, monitoring and forecasting. The Chinese government strengthened the investment and management of grassland construction to restore grassland vegetation based on the spatial threshold strategy.

The vegetation and functional group compositions of the steppe ecosystems of Inner Mongolia were well under the threshold for degradation, and obvious degradation traces (i.e., dominance of short drought-tolerant plants) were not observed. Therefore, determine the risk level is difficult. Based on the threshold analysis for the three types of grasslands, we found that rhizomatous grass and bunchgrass represented more than half of the total biomass at the threshold, which suggested that grass was the dominant functional group in the three types of steppe. We also found that *Cleistogenes squarrosa*, the index vegetation of light degradation, was the dominant species in the meadow steppe and the typical steppe ecosystems. Although the

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

dominant species were still grass, the proportion of original constructive grasses was reduced. For example, in the meadow steppe, the biomass of *Stipa baicalensis* (original constructive species of meadow steppe) was less than 10% of the total biomass at the threshold; and in the typical steppe, the biomass of *Stipa grandis* (original constructive species of typical steppe) was less than 16% of the total biomass at the threshold. The proportion of high grass with good palatability for livestock decreased, whereas the proportion of *Cleistogenes*, which presents a strong asexual reproduction ability, increased. Four kinds of perennial forb were observed, and they each represented more than 10% of the total biomass in the meadow steppe. Perennial forbs are likely to become the new dominant functional group under more intensive grassland utilization; moreover, these plants are hard to remove because they have a strong underground vegetative propagation system and can regenerate and expand because of their rich buds, stored food, vegetative propagules, and long lifespans (Yan et al., 2015). Therefore, these plants can rapidly occupy beneficial land and underground areas. Shrubs represent another main functional group and include *Artemisia frigida*, especially in desert steppe (25% of the relative biomass was *Artemisia frigida*). Shrubs and semi-shrubs can adapt to harsh environments because of their strong root systems, drought tolerance and grazing resistance (Liang et al., 2009). Shrubs such as *Artemisia frigida* can regenerate a large number of stolons, and when stolon fractures are trampled or eaten by animals, they become buried in the soil and can produce new plants (Wang et al., 2014b); therefore, these plants have strong grazing tolerance. This type of shrub would become the main functional group in a severe environment, especially in the desert steppe.

According to the study by Bestelmeyer et al. (2003), the elimination of shrubs and semi-shrubs

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

requires the long-term exclusion of grazing.

Managers consider a threshold to act as a boundary, and as values progress beyond the threshold, the ability to regain the original productive potential of the land diminishes (Kachergis et al., 2013). The composition of functional groups changes positions beyond the threshold. Therefore, the threshold could be considered an early warning indicator of degradation. Under such conditions, efficient measures should be implemented to prevent grasslands from degradation. Our study suggests that the studied grasslands were healthy at the threshold. Based on this result, determining the degradation crisis point was difficult, which could lead to wrong decisions. Many studies have focused on indicator species of degeneration (Ansell et al., 2016; Lv et al., 2016; Veldman, 2016), such as *Stellera chamaejasme*, *Potentilla anserina*, and *Artemisia frigida*. However, once these species are found, the grassland has already degraded and presents a limited capacity to recover in a short time. Thus, dominant functional groups that are well adapted to severe environments will remain dominant. As a result, degraded grasslands cannot easily return to their original state. Grassland degeneration is an ecological issue that draws substantial attention. Restoration measures have been studied, including tillage, resowing, irrigation and suspending grazing; however, these measures involve considerable time and funding. Restoring grasslands is always difficult; therefore, preventing grassland degradation is important.

To ensure that early warning indicators are applied to the practical management of rangelands, the spatial threshold for a household should be identified. Although the thresholds of utilization were similar in the three steppes, the spatial thresholds derived from the threshold of

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

utilization were significantly different among the different steppe ecosystems. Therefore, the strategies for preventing degradation will vary in the three steppes. Grassland degradation would occur at a spatial threshold of 3:10 in the meadow steppe, 1:10 in the typical steppe, and 4:10 in the desert steppe. When these values are observed, measures should be implemented to prevent grassland degradation. The results show that improved sustainability was observed in the typical steppe, which had a greater portion of healthy grassland than the meadow and desert steppe. In the desert and meadow steppe, the area in a dangerous state was large. Therefore, measures to protect grassland should be implemented in 30%-20% circular regions in the desert and meadow steppe. The threshold could move closer to the central point over time, and the area of healthy grassland would increase. Further studies are required to identify effective and low cost mitigation methods for different types of steppe.

5. Conclusions

1) In our study, different thresholds were observed in the different steppe ecosystems. The thresholds of grassland utilization were 78-89% for meadow steppe, 80-89% for typical steppe and 70-85% for desert steppe.
2) Significant degradation characteristics were not observed for the plants or functional groups in the threshold state. Therefore, managers cannot easily determine the risk of degeneration according to the vegetation composition.
3) Spatial thresholds (as defined in the materials and methods) were 3:10 for meadow steppe, 1:10 for typical steppe and 4:10 for desert steppe. Managers have implemented strategies to prevent degradation using the spatial threshold method.

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

Acknowledgements

We are grateful to the hard work of the 2005-2009 research teams, which included undergraduate students and teacher from The Agricultural Inner Mongolia University who helped in all aspects of field research. Special thanks to the dedication of Chenjie Wang, Mingjun Wang, Chunli Li, Shuying Jiao and Chunyang Wu who assisted tirelessly with both field and laboratory work. We also thank the reviewers and editors for their insightful comments. The manuscript benefited from comments from Gary Zhiming Wang on an earlier draft of the manuscript.

Funding

This study was supported by National Natural Science Foundation of China (Grant No. 31270502).

Competing Interests

The authors declare there are no competing interests.

Author Contributions

Guodong Han designed the study and processed the data.

Jie Qin gave comments on the manuscript. All authors Contributed to the results, related discussions and manuscript writing.

Jun Zhang, Zhongwu Wang and Linxi Hu prepared figures, reviewed drafts of the paper.

References

Ansell D, Fifield G, Munro N, Freudenberger D, Gibbons P. 2016. Softening the agricultural matrix: a novel agri-environment scheme that balances habitat restoration and livestock grazing. *Restoration Ecology* 24:159-164. DOI: 10.1111/rec.12304.

Bestelmeyer BT, Brown JR, Havstad KM, Alexander R, Chavez G, Herrick JE. 2003. Development and use of state-and-transition models for rangelands. *Journal of Range Management* 56:114. DOI: 10.2307/4003894.

Bestelmeyer BT, Goolsby DP, Archer SR. 2011. Spatial perspectives in state-and-transition models: a missing link to land management? *Journal of Applied Ecology* 48:746-757. DOI: 10.1111/j.1365-2664.2011.01982.x.

Briske DD, Zhao M, Han G, Xiu C, Kemp DR, Willms W, Havstad K, Kang L, Wang Z, Wu J, Han X, Bai Y. 2015. Strategies to alleviate poverty and grassland degradation in Inner Mongolia: intensification vs production efficiency of livestock systems. *Journal of Environmental Management* 152:177-182. DOI: 10.1016/j.jenvman.2014.07.036.

Cui X, Wang Y, Niu H, Wu J, Wang S, Schnug E, Rogasik J, Fleckenstein J, Tang Y. 2005. Effect of long-term grazing on soil organic carbon content in semiarid steppes in Inner Mongolia. *Ecological Research* 20:319-527. DOI: 10.1007/s11284-005-0063-8.

Han G, Hao X, Zhao M, Wang M, Ellert BH, Willms W, Wang M. 2008. Effect of grazing intensity on carbon and nitrogen in soil and vegetation in a meadow steppe in Inner Mongolia. *Agriculture, Ecosystems & Environment* 125:21-32. DOI: 10.1016/j.agee.2007.11.009.

Huyghe C. 2008. Multi-function grasslands in France: I. production functions. *Cahiers Agricultures* 17:427-435

Kachergis EJ, Knapp CN, Fernandez-Gimenez ME, Ritten JP, Pritchett JG, Parsons J, Hibbs W, Roath R. 2013. Tools for resilience management: multidisciplinary development of state-and-transition models for northwest Colorado. *Ecology and Society* 18. DOI: 10.5751/es-05805-180439.

Knapp CN, Fernandez-Gimenez ME. 2009. Understanding change: integrating rancher knowledge into state-and-transition models. *Rangeland Ecology & Management* 62:510-521. DOI: 10.2111/08-176.1.

Lamchin M, Lee J-Y, Lee W-K, Lee EJ, Kim M, Lim C-H, Choi H-A, Kim S-R. 2016. Assessment of land cover change and desertification using remote sensing technology in a local region of Mongolia. *Advances in Space Research* 57:64-77. DOI: 10.1016/j.asr.2015.10.006.

Li C, Hao X, Zhao M, Han G, Willms WD. 2008. Influence of historic sheep grazing on vegetation and soil properties of a desert steppe in inner Mongolia. *Agriculture, Ecosystems & Environment* 128:109-116. DOI: 10.1016/j.agee.2008.05.008.

Li G, Jiang G, Li Y, Liu M, Peng YU, Li L, Han X. 2007. A new approach to the fight against desertification in Inner Mongolia. *Environmental Conservation* 34:95. DOI: 10.1017/s0376892907003864.

Liang Y, Han G, Zhou H, Zhao M, Snyman HA, Shan D, Havstad KM. 2009. Grazing intensity on vegetation dynamics of a typical steppe in northeast inner Mongolia. *Rangeland*

Ecology & Management 62:328-336. DOI: 10.2111/08-167.1.

Lin Y, Hong M, Han G, Zhao M, Bai Y, Chang SX. 2010. Grazing intensity affected spatial patterns of vegetation and soil fertility in a desert steppe. *Agriculture, Ecosystems & Environment* 138:282-292. DOI: 10.1016/j.agee.2010.05.013.

Liu J, Feng C, Wang D, Wang L, Wilsey BJ, Zhong Z, Firn J. 2015. Impacts of grazing by different large herbivores in grassland depend on plant species diversity. *Journal of Applied Ecology* 52:1053-1062. DOI: 10.1111/1365-2664.12456.

Lv X, Zhou G, Wang Y, Song X. 2016. Sensitive indicators of zonal stipa species to changing temperature and precipitation in inner Mongolia grassland, China. *Frontiers in Plant Science* 7:73. DOI: 10.3389/fpls.2016.00073.

Mekuria W. 2013. Changes in regulating ecosystem services following establishing exclosures on communal grazing lands in Ethiopia: a synthesis. *Journal of Ecosystems* 2013:1-12. DOI: 10.1155/2013/860736.

O'Mara FP. 2012. The role of grasslands in food security and climate change. *Annals of Botany* 110:1263-1270. DOI: 10.1093/aob/mcs209.

Patra AK, Le Roux X, Grayston SJ, Loiseau P, Louault F. 2008. Unraveling the effects of management regime and plant species on soil organic carbon and microbial phospholipid fatty acid profiles in grassland soils. *Bioresource Technology* 99:3545-3551. DOI: 10.1016/j.biortech.2007.07.051.

Petersen SL, Stringham TK, Roundy BA. 2009. A process-based application of state-and-transition models: a case study of Western Juniper (Juniperus occidentalis) encroachment. *Rangeland Ecology & Management* 62:186-192. DOI: 10.2111/06-171.1.

Pickup G, Chewings VH. 1994. Grazing gradient approach to land degradation assessment in arid areas from remotely-sensed data. *International Journal of Remote Sensing* 15:597-617

Reid RS, Fernández-Giménez ME, Galvin KA. 2014. Dynamics and resilience of rangelands and pastoral peoples around the globe. *Annual Review of Environment and Resources* 39:217-242. DOI: 10.1146/annurev-environ-020713-163329.

Ren H, Han G, Schönbach P, Gierus M, Taube F. 2016. Forage nutritional characteristics and yield dynamics in a grazed semiarid steppe ecosystem of Inner Mongolia, China. *Ecological Indicators* 60:460-469. DOI: 10.1016/j.ecolind.2015.07.027.

Sanderson MA, Liebig MA, Hendrickson JR, Kronberg SL, Toledo D, Derner JD, Reeves JL. 2016. A century of grazing: the value of long-term research. *Journal of Soil and Water Conservation* 71:5A-8A. DOI: 10.2489/jswc.71.1.5A.

Schweiger AK, Risch AC, Damm A, Kneubühler M, Haller R, Schaepman ME, Schütz M, Rocchini D. 2015. Using imaging spectroscopy to predict above-ground plant biomass in alpine grasslands grazed by large ungulates. *Journal of Vegetation Science* 26:175-190. DOI: 10.1111/jvs.12214.

Tang S, Wang C, Wilkes A, Zhou P, Jiang Y, Han G, Zhao M, Huang D, Schönbach P. 2013. Contribution of grazing to soil atmosphere CH4 exchange during the growing season in a continental steppe. *Atmospheric Environment* 67:170-176. DOI: 10.1016/j.atmosenv.2012.10.037.

Tilman D, Isbell F, Cowles JM. 2014. Biodiversity and ecosystem functioning. *Annual Review of*

Ecology, Evolution, and Systematics 45:471-493. DOI: 10.1146/annurev-ecolsys-120213-091917.

Veldman JW. 2016. Clarifying the confusion: old-growth savannahs and tropical ecosystem degradation. *Philosophical Transactions of the Royal Society of London Series B, Biological Sciences* 371. DOI: 10.1098/rstb.2015.0306.

Wang X, Dong S, Yang B, Li Y, Su X. 2014a. The effects of grassland degradation on plant diversity, primary productivity, and soil fertility in the alpine region of Asia's headwaters. *Environmental Monitoring and Assessment* 186:6903-6917. DOI: 10.1007/s10661-014-3898-z.

Wang Z, Jiao S, Han G, Zhao M, Ding H, Zhang X, Wang X, Ayers EL, Willms WD, Havsatad K, A L, Liu Y. 2014b. Effects of stocking rate on the variability of peak standing crop in a desert steppe of Eurasia grassland. *Environmental Management* 53:266-273. DOI: 10.1007/s00267-013-0186-6.

Wang Z, Johnson DA, Rong Y, Wang K. 2016. Grazing effects on soil characteristics and vegetation of grassland in northern China. *Solid Earth* 7:55-65. DOI: 10.5194/se-7-55-2016.

White R, Murray S, Rohweder M. 2000. *Pilot analysis of global ecosystems: grassland ecosystems*. Washington, D.C.: World Resources Institute.

Wrage N, Strodthoff J, Cuchillo HM, Isselstein J, Kayser M. 2011. Phytodiversity of temperate permanent grasslands: ecosystem services for agriculture and livestock management for diversity conservation. *Biodiversity and Conservation* 20:3317-3339. DOI:

10.1007/s10531-011-0145-6.

Yan R, Xin X, Yan Y, Wang X, Zhang B, Yang G, Liu S, Deng Y, Li L. 2015. Impacts of differing grazing rates on canopy structure and species composition in Hulunber Meadow Steppe. *Rangeland Ecology & Management* 68:54-64. DOI: 10.1016/j.rama.2014.12.001.

Zweig CL, Kitchens WM. 2009. Multi-state succession in wetlands: a novel use of state and transition models. *Ecology* 90:1900-1909. DOI: 10.1890/08-1392.1.

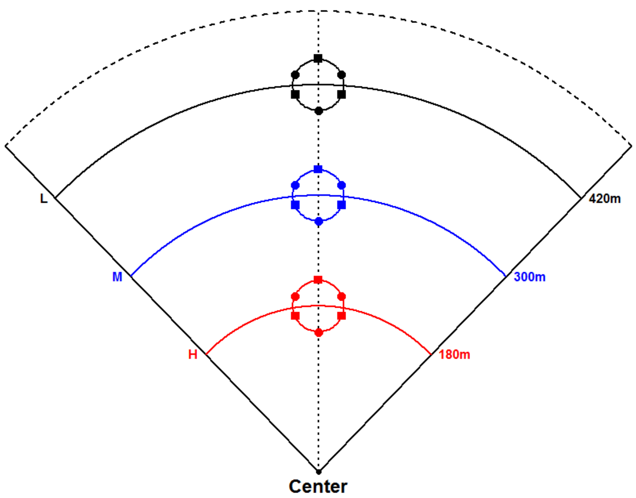


Figure 1. Schematic diagram of the grazing system (in the typical steppe).

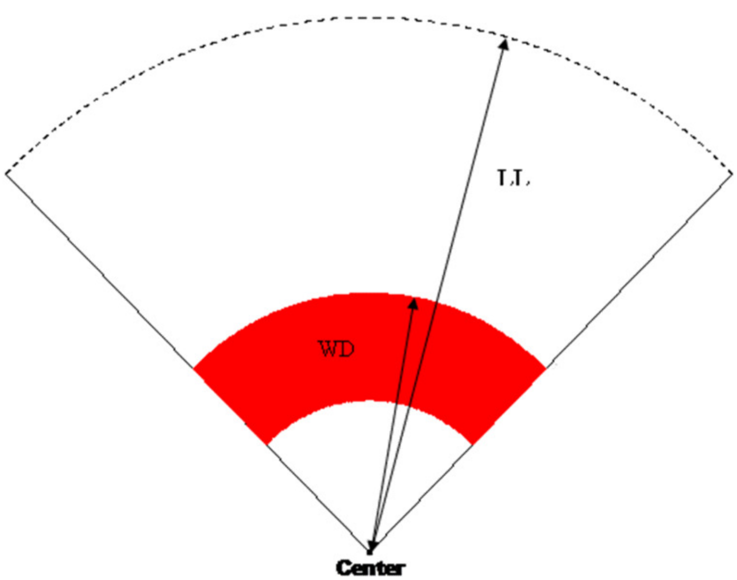


Figure 2. Schematic diagram of the spatial threshold.

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

Spatial threshold=WD/LL, where WD represents the warning distance, which is the distance from a center point to one point, with the point presenting the same utilization threshold according to the long line transect data of 2009; and LL represents the line length, which is the distance from the center point to fences

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

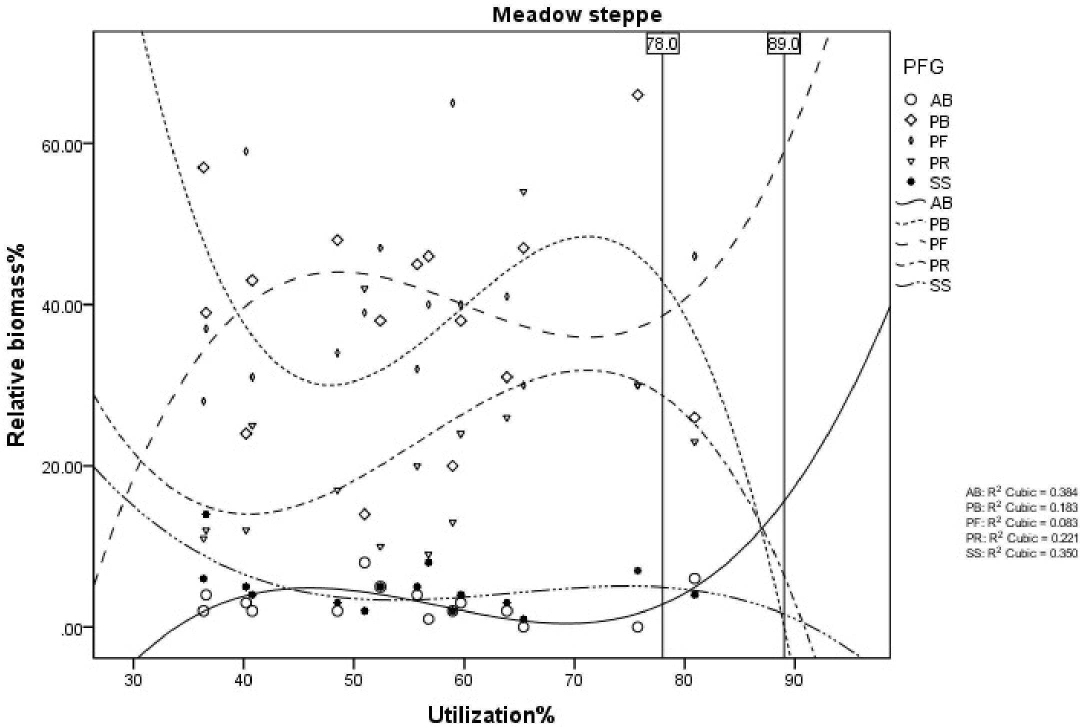


Figure 3. Model of the functional groups with the utilization percentage in the meadow steppe. perennial bunchgrass (PB); perennial rhizome (PR); annuals and biennials (AB); shrubs and semi-shrubs (SS); perennial forbs (PF).

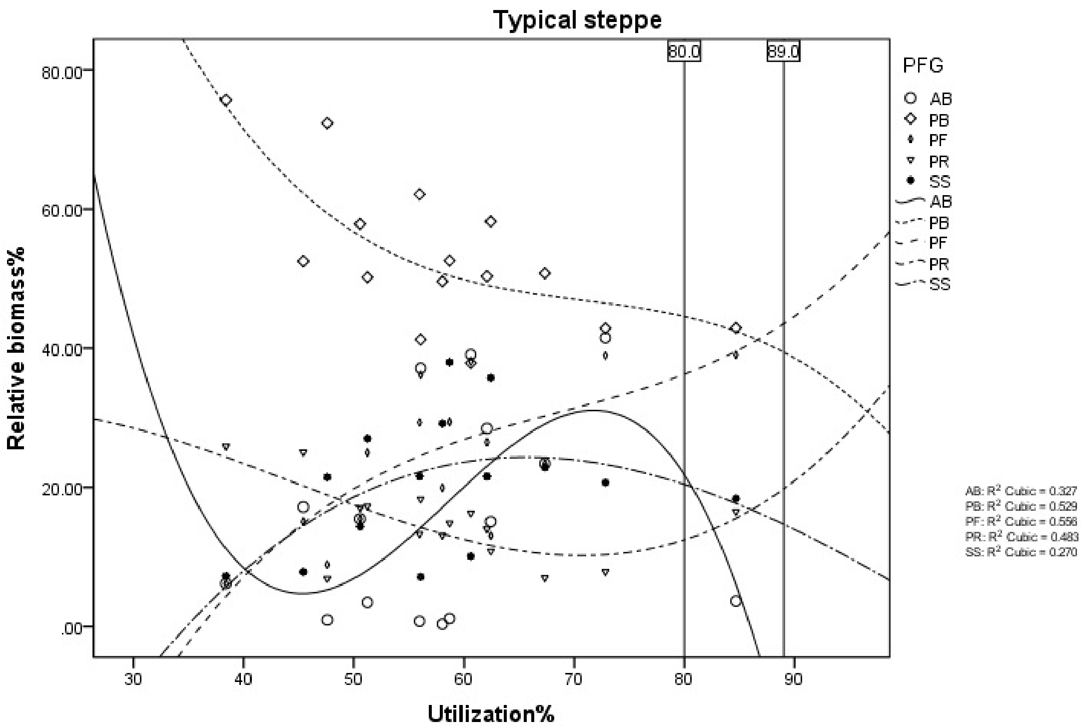


Figure 4. Model of the functional groups with the utilization percentage in the typical steppe. perennial bunchgrass (PB); perennial rhizome (PR); annuals and biennials (AB); shrubs and semi-shrubs (SS); perennial forbs (PF).

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

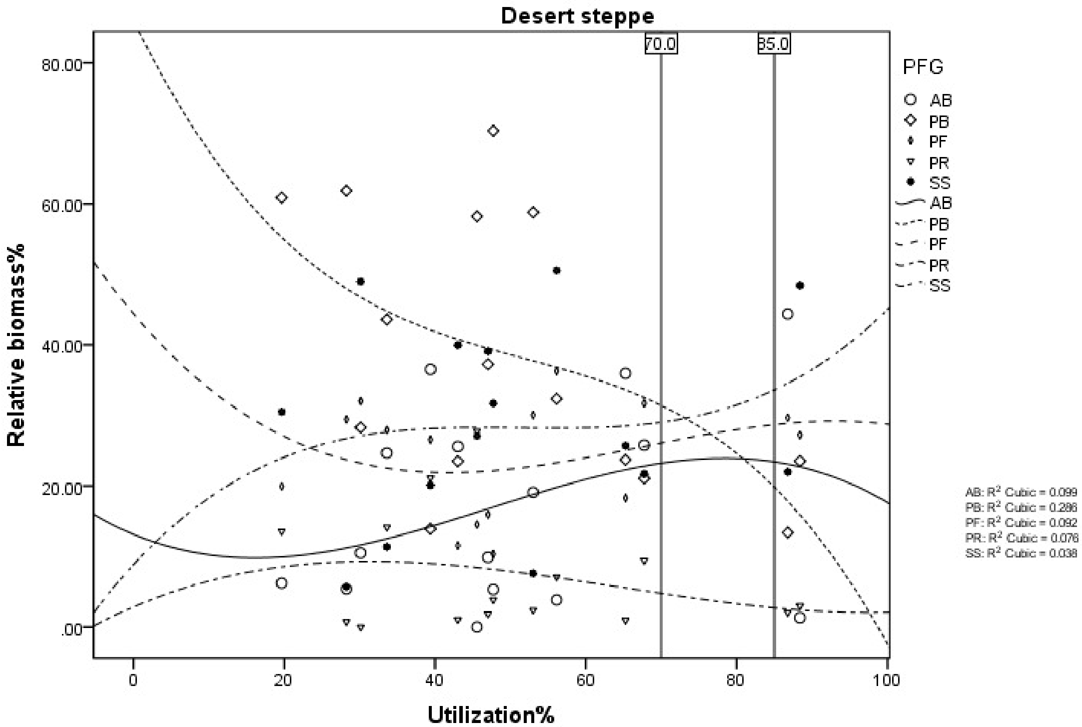


Figure 5. Model of the functional groups with the utilization percentage in the desert steppe. perennial bunchgrass (PB); perennial rhizome (PR); annuals and biennials (AB); shrubs and semi-shrubs (SS); perennial forbs (PF).

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

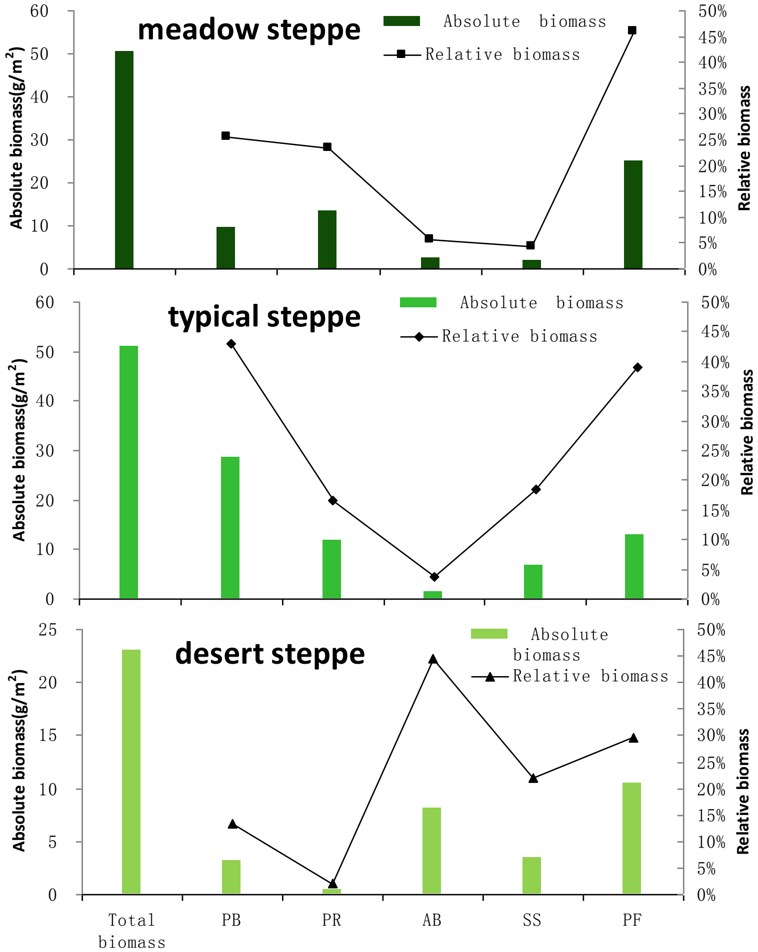


Figure 6. Composition of functional groups in the threshold state.

perennial bunchgrass (PB); perennial rhizome (PR); annuals and biennials (AB); shrubs and semi-shrubs (SS); perennial forbs (PF).

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

Table 1. Species composition of the thresholds of the three types of steppe

Steppe type	Species	PFG	Relative biomass (%)
Meadow steppe	*Leymus secalinus*	PR	42.33
	Cleistogenes squarrosa	PB	22.21
	Potentilla tanacetifolia	PF	17.39
	Leymus chinensis	PR	17.21
	Plantago asiatica	PF	14.91
	Potentilla bifurca	PF	11.32
	Iris dichotoma	PF	10.84
	Festuca ovina	PB	10.30
Typical steppe	*Cleistogenes squarrosa*	PB	55.93
	Potentilla acaulis	PF	39.46
	Convolvulus ammanii	AB	25.24
	Artemisia frigida Willd	SS	18.39
	Leymus chinensis	PR	16.52
	Stipa grandis	PB	15.88
	Oxytropis hirta	PF	11.86
	Ixeris denticulata	AB	10.17
Desert steppe	*Stipa breviflora* Griseb.	PB	37.91
	Convolvulus ammanii	AB	27.75
	Artemisia frigida Willd	SS	25.03
	Salsola collina	AB	21.64
	Cymbaria dahurica	PF	14.88
	Leymus chinensis	PR	11.24
	Caragana microphylla Lam	SS	10.21

Plant function group(PFG): perennial bunchgrass (PB); perennial rhizome (PR); annuals and biennials (AB); shrubs and semi-shrubs (SS); perennial forbs (PF).

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

Table 2. Warning distance determined by the use rate of rangeland

Steppe type	Sample	LL(m)	WD(m)	WD:LL
mean steppe	1	1420	730	51.41:100
	2	1260	140	11.11:100
	3	1080	342	31.67:100
	Mean			31.40:100
typical steppe	1	4780	380	7.95:100
	2	1460	130	8.90:100
	3	1600	140	8.75:100
	Mean			8.53:100
desert steppe	1	900	328	36.44:100
	2	1260	522	41.43:100
	3	1700	829	48.76:100
	Mean			42.21:100

Note: LL represents line length and WD represents warning distance

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

Table 1(on next page)

Table 1. Species composition of the thresholds of the three types of steppe

Plant function group(PFG): perennial bunchgrass (PB); perennial rhizome (PR); annuals and biennials (AB); shrubs and semi-shrubs (SS); perennial forbs (PF)

Table 1. Species composition of the thresholds of the three types of steppe

Steppe type	Species	PFG	Relative biomass (%)
Meadow steppe	*Leymus secalinus*	PR	42.33
	Cleistogenes squarrosa	PB	22.21
	Potentilla tanacetifolia	PF	17.39
	Leymus chinensis	PR	17.21
	Plantago asiatica	PF	14.91
	Potentilla bifurca	PF	11.32
	Iris dichotoma	PF	10.84
	Festuca ovina	PB	10.30
Typical steppe	*Cleistogenes squarrosa*	PB	55.93
	Potentilla acaulis	PF	39.46
	Convolvulus ammanii	AB	25.24
	Artemisia frigida Willd	SS	18.39
	Leymus chinensis	PR	16.52
	Stipa grandis	PB	15.88
	Oxytropis hirta	PF	11.86
	Ixeris denticulata	AB	10.17
Desert steppe	*Stipa breviflora* Griseb.	PB	37.91
	Convolvulus ammanii	AB	27.75
	Artemisia frigida Willd	SS	25.03
	Salsola collina	AB	21.64
	Cymbaria dahurica	PF	14.88
	Leymus chinensis	PR	11.24
	Caragana microphylla Lam	SS	10.21

Plant function group(PFG): perennial bunchgrass (PB); perennial rhizome (PR); annuals and biennials (AB); shrubs and semi-shrubs (SS); perennial forbs (PF).

Table 2(on next page)

Table 2. W arning distance determined by the use rate of rangeland

Note: LL represents line length and WD represents warning distance

Table 2. Warning distance determined by the use rate of rangeland

Steppe type	Sample	LL(m)	WD(m)	WD:LL
mean steppe	1	1420	730	51.41:100
	2	1260	140	11.11:100
	3	1080	342	31.67:100
	Mean			31.40:100
typical steppe	1	4780	380	7.95:100
	2	1460	130	8.90:100
	3	1600	140	8.75:100
	Mean			8.53:100
desert steppe	1	900	328	36.44:100
	2	1260	522	41.43:100
	3	1700	829	48.76:100
	Mean			42.21:100

Note: LL represents line length and WD represents warning distance

Figure 1(on next page)

Figure 1. Schematic diagram of the grazing system (in the typical steppe).

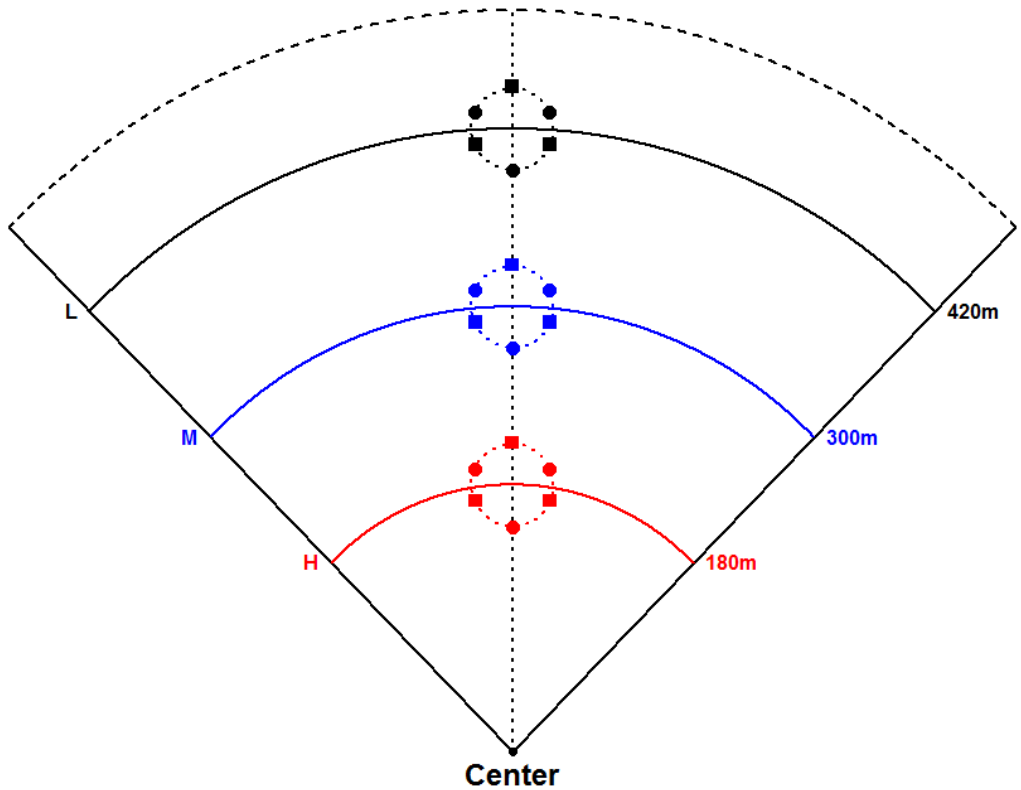
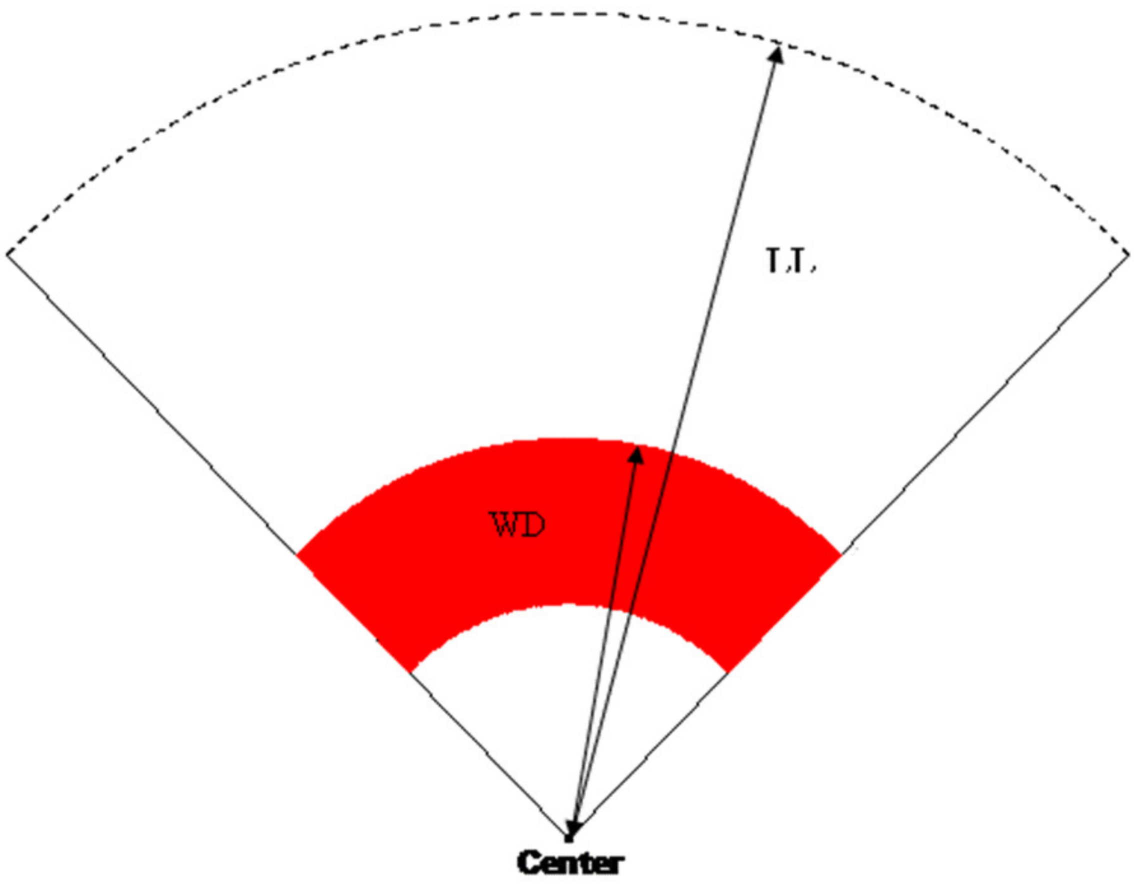

L
420m
M
300m
H
180m
Center

Figure 2

Figure 2. Schematic diagram of the spatial threshold.

Spatial threshold=WD/LL, where WD represents the warning distance, which is the distance from a center point to one point, with the point presenting the same utilization threshold according to the long line transect data of 2009; and LL represents the line length, which is the distance from the center point to fences



PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2915v1 | CC BY 4.0 Open Access | rec: 6 Apr 2017, publ: 6 Apr 2017

Figure 3

Figure 3. Model of the functional groups with the utilization percentage in the meadow steppe

perennial bunchgrass (PB); perennial rhizome (PR); annuals and biennials (AB); shrubs and semi-shrubs (SS); perennial forbs (PF)

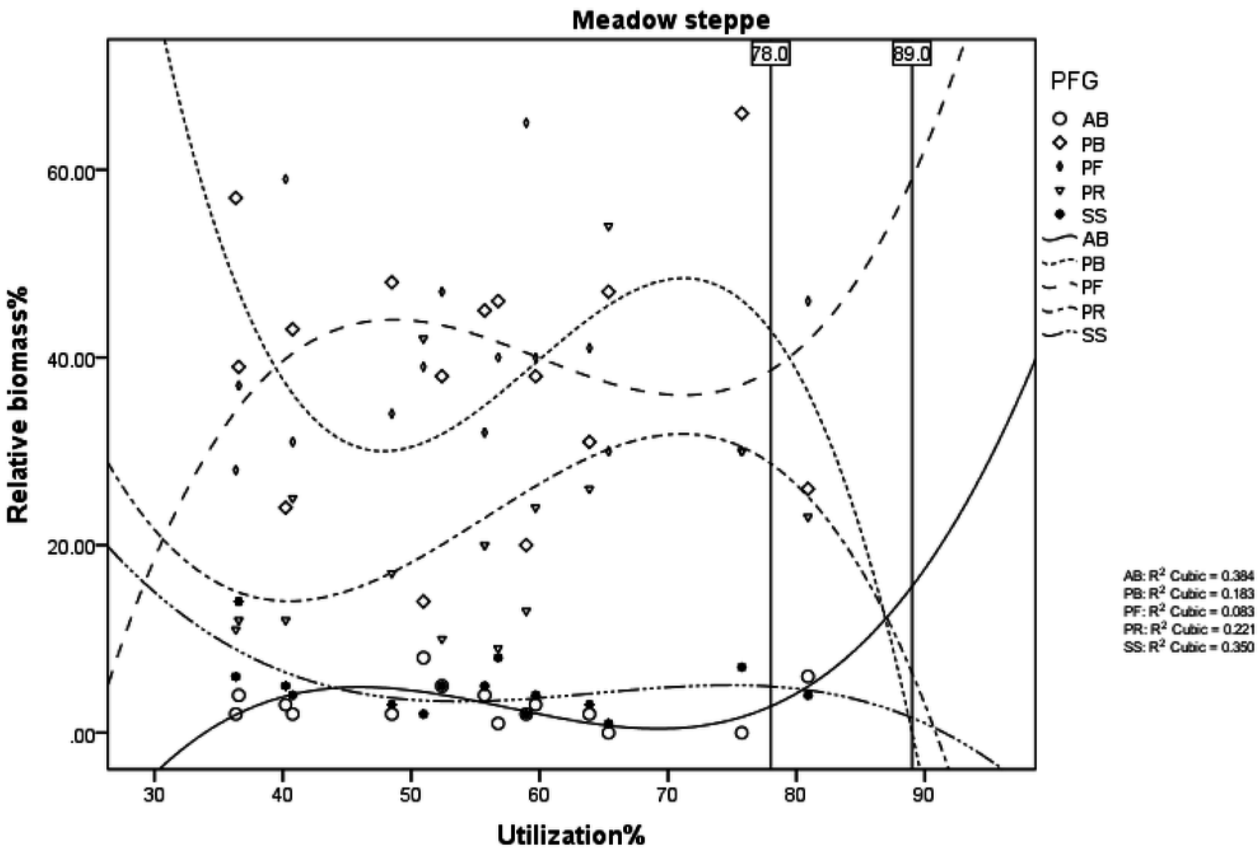


Figure 4

Figure 4. Model of the functional groups with the utilization percentage in the typical steppe.

perennial bunchgrass (PB); perennial rhizome (PR); annuals and biennials (AB); shrubs and semi-shrubs (SS); perennial forbs (PF).

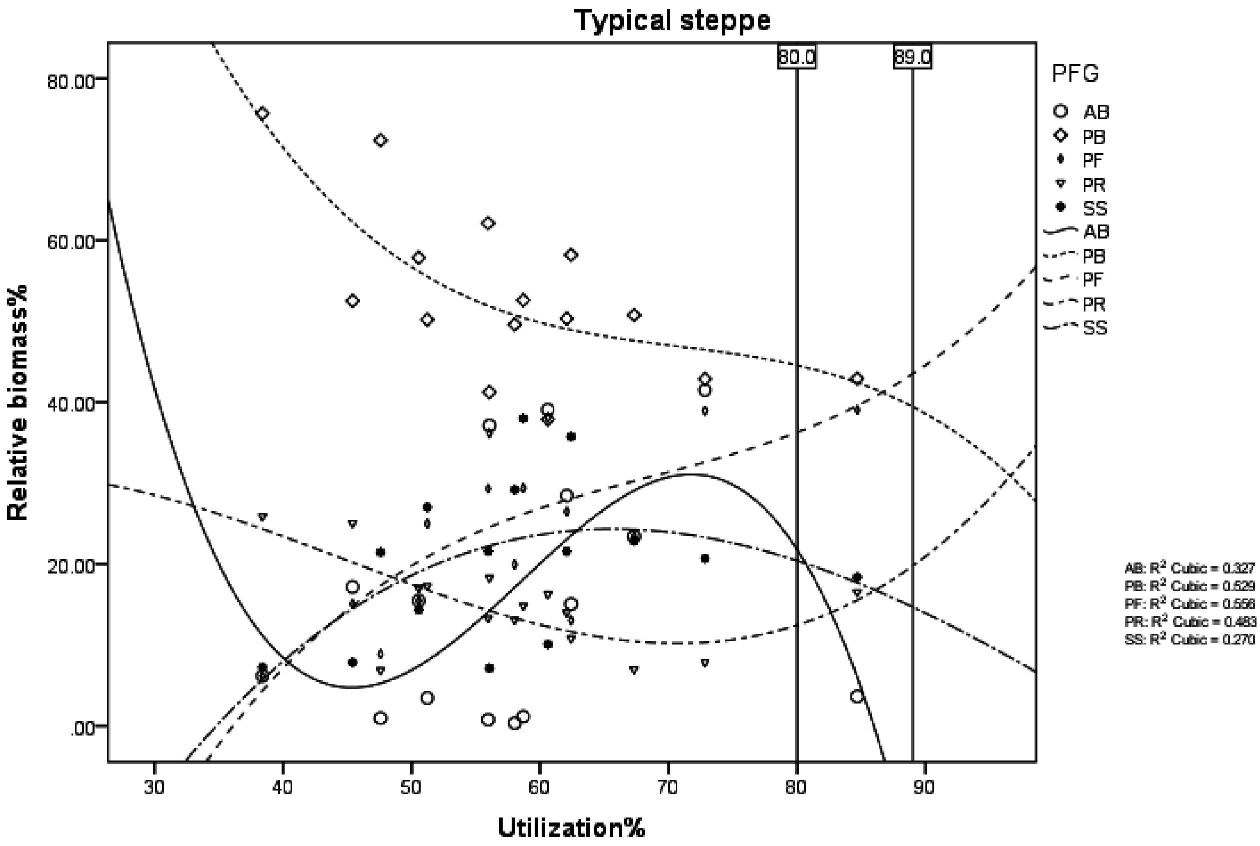


Figure 5

Figure 5. Model of the functional groups with the utilization percentage in the desert steppe

perennial bunchgrass (PB); perennial rhizome (PR); annuals and biennials (AB); shrubs and semi-shrubs (SS); perennial forbs (PF).

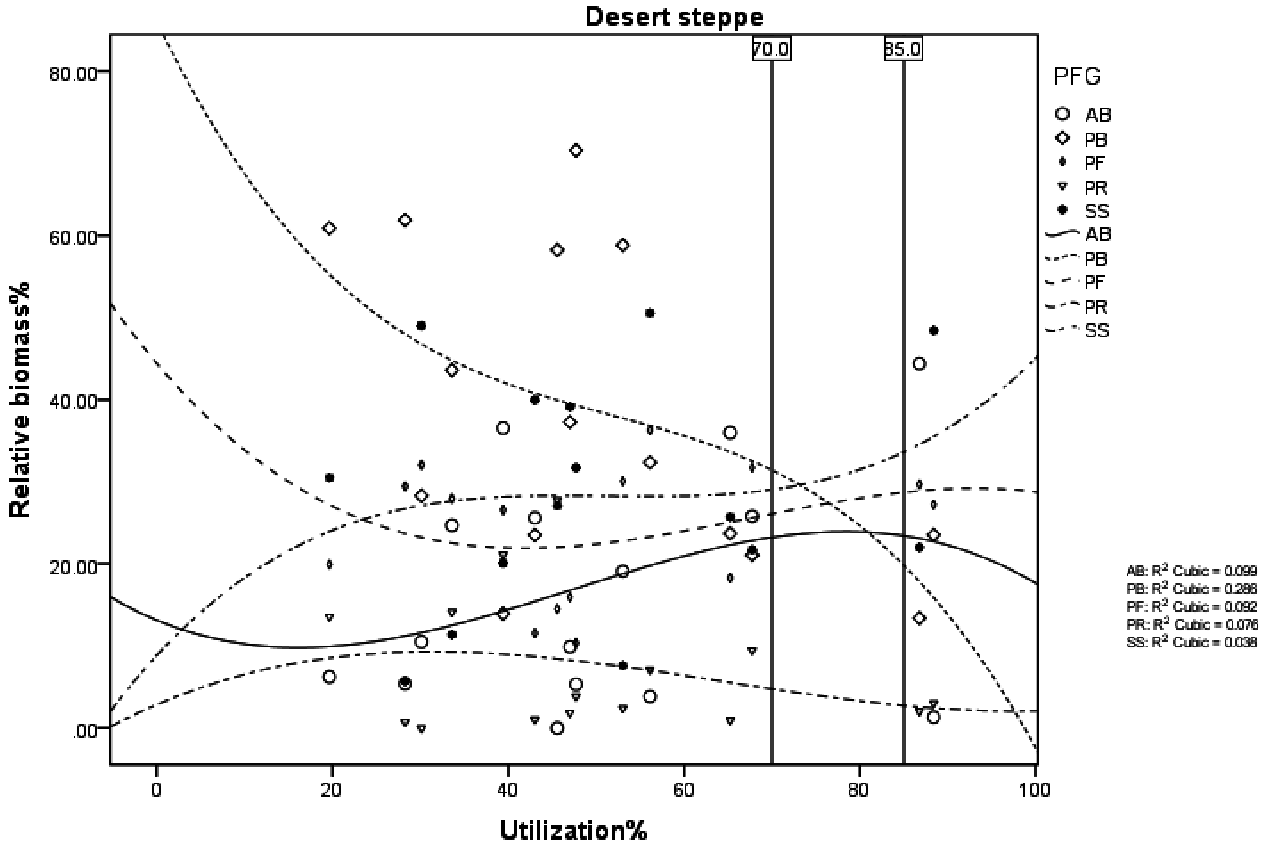
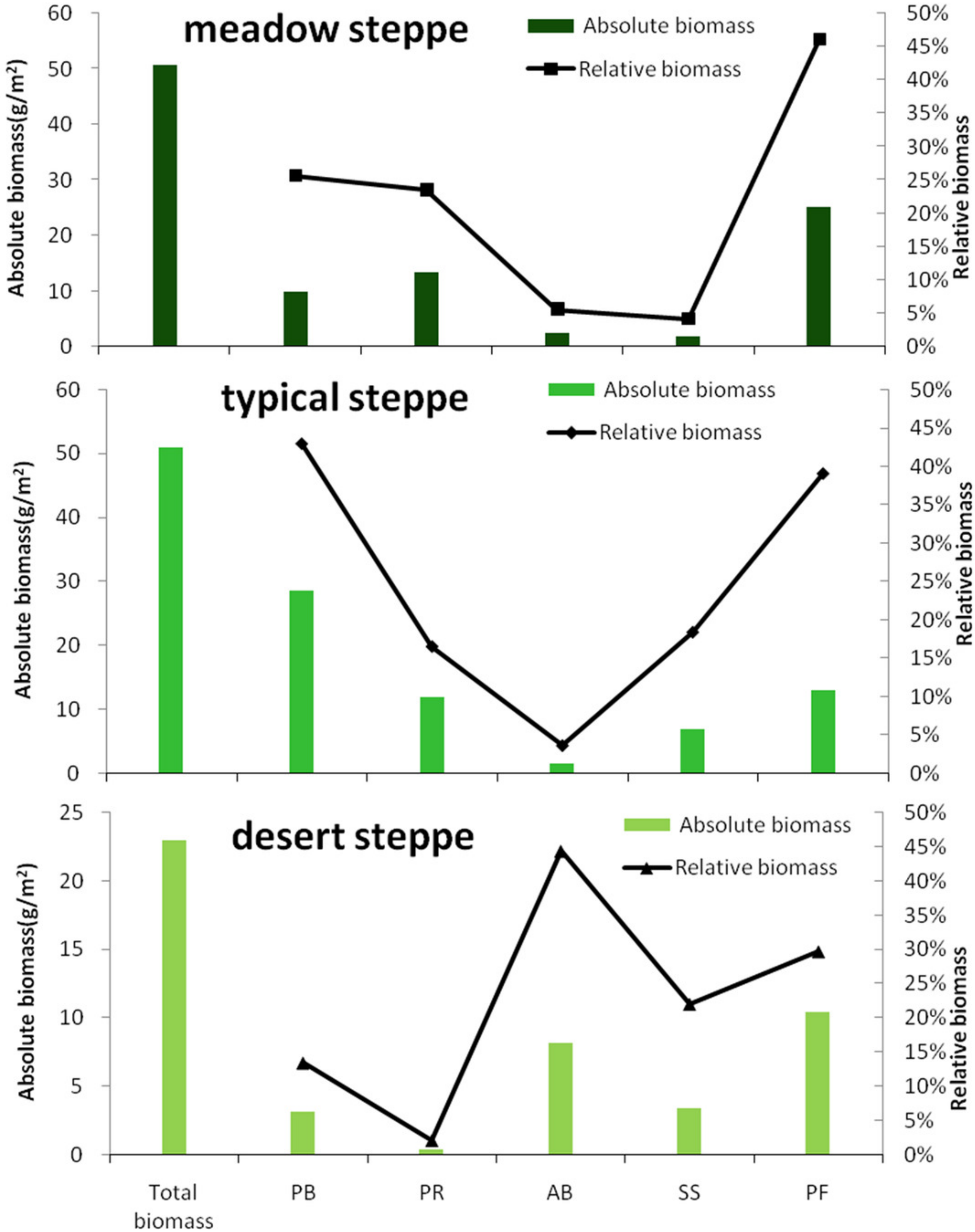


Figure 6

Figure 6. Composition of functional groups in the threshold state.

perennial bunchgrass (PB); perennial rhizome (PR); annuals and biennials (AB); shrubs and semi-shrubs (SS); perennial forbs (PF).


meadow steppe
Absolute biomass
Relative biomass
Absolute biomass(g/m²)
Relative biomass
60
50
40
30
20
10
0
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
typical steppe
Absolute biomass
Relative biomass
desert steppe
Absolute biomass
Relative biomass
25
20
15
10
5
0
Total biomass
PB
PR
AB
SS
PF