Annual Variability of Biomass and Species Composition, and Gross Primary Productivities of Two Dominant Species in Dry Year in Inner Mongolian Grassland

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Xiaoxing HU

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Xiaoxing HU

CONTENTS

Abbreviations

NEP	net ecosystem production
GPP	gross primary production
NPP	net primary productivity
PUE	precipitation use efficiency
ER	ecosystem respiration
TR	transpiration rate
WUE	water use efficiency
EV	estimated volume
EB	estimated biomass
AGB	aboveground biomass
BGB	belowground biomass
PAR	photosynthetically active radiation
SWC	soil water content
PVC	transparent polyvinyl chloride

Chapter 1 General introduction

1-1 Background

Grassland is the main biome on the earth and occupies a fifth of the land surface area. Grasslands are play a fundamental role in nature conservation and currently estimated to contribute to the livelihoods of over 800 million people (Reynolds et al. 2005) and provide a series of ecosystem goods and services such as fodder provision, soil stability and fertility including C sequestration, as well as water and climate regulation (de Bello et al. 2010). It is both an important geographical barrier and a natural defense that prevents the spread of the desert and acts as an ecological barrier. In addition, it is also a natural base for the development of animal husbandry. From Hungary to northeastern China, a vast Eurasian grassland of about 250 million hectares spreads in a belt-like manner on the Eurasian Continent (Archibold 1995). The average annual rainfall is about 150 to 600 mm. Also, there are significant differences in grassland vegetation distribution and community species composition (Sochava 1979; Hilbig 1995). Eurasian grasslands have been used sustainably for agriculture and as pasture by pastoralists, but recently the regeneration of grassland and desertification by overuse has progressed and the sustainability is being lost (Gibson 2009).

Grassland in China is about 400 million hectares, accounting for 41% of the country's land area, and the main type is temperate steppe (Chen 2008; Squires et al. 2010; Suttie et al. 2005). Studies on the distribution of grassland vegetation and species composition of communities are central contents in grassland ecology (Chen et al. 2010). Grassland degeneration is one of the most serious environmental problems in China and globally. The long-term inappropriate use of grassland and interaction of climate change, amongst other factors, have resulted in grassland degeneration (Cui et al. 2012). Grassland degeneration is a transition, destabilizing the ecosystem by grazing pressure, land clearance, and grass cutting, etc. (Li 1990). As of 2010, the grazing pressure in China has possibly exceeded by about 20% to 30% of the grassland's environmental capacity (Liu 2010). Factors of desertification and degeneration are not uniform in grasslands, which include reduced rainfall owing to climate change, artificial factors owing to different grazing methods, and social factors owing to excessive economic activity (Xuri et al. 2008).

In the Inner Mongolia Autonomous Region of China, more than 70% of the total area is occupied by grasslands and pastoralism is the main industry (Bao et al. 2005; Ito et al. 2006). The grassland in Hulunbuir, Inner Mongolia is the main body of northern China and should play a protective role against desertification with the Greater Khingan Mountains. Xin Barag Right Banner in Hulunbuir is a livestock industry area of Inner Mongolia and is connected with Russia and Mongolia. However, recently, with the combined effects of drought induced by climate change, overgrazing, and human disturbance, the degeneration of the inner Mongolian grassland has become a serious problem and desertification is increasing (Kawada et al. 2011). Even at the Xin Barag Right Banner, owing to the rapid growth in meat demand within China, the numbers of livestock have inevitably increased, and vegetation regression owing to overgrazing has occurred. In the Inner Mongolian grassland, which occupies 25% of the total grassland area in China, the challenge is to improve productivity and prevent degeneration of grassland (Ito et al. 2006). Abundant evidence has demonstrated that grazing changes species composition, community structure, and ecosystem functioning, especially in arid and semiarid grassland. Cheng et al. (2013) showed that grazing pressure and cultivation activity changed grassland species composition from plant sociological classification, possibly resulting in a decrease in the number of species in the area. However, according to McIntyre and Lavorel (2001), Liu F et al. (2012), Konagaya et al. (2005), Li (1995), grazing activities, including trampling with livestock feeding, changes species composition, abundance, and community characteristics. Both livestock stepping on grasslands, and sheep eating grass near the earth are resulting in overgrazing (Konagaya et al. 2005; Li 1995). Continuous severe grazing activities cause the degradation of vegetation coverage, height, biomass, etc. (Zhao and Zhao 2005). Therefore, going forward, to protect the grassland for its sustainable use, it is necessary to clarify the influence of overgrazing on vegetation.

Changes in species composition can occur as a result of (Nakamura et al. 1998, 2000; Wuyunna et al. 1999, 2011; Li et al. 2008; Cheng et al. 2011). According to Nakamura et al. (2000), the abundance of *Leymus chinensis* and *Stipa krylovii* are decreasing owing to an increase in grazing pressure, and *Carex korshinsky* and *Allium polyrhizum* are increasing. In addition, as the grazing intensified, the vegetation biomass decreased, but the species composition remained unchanged. However, grazing pressure changed the order of the constituent species of the community (Wuyunna et al. 1999). Also, it has been shown that vegetation biomass and species composition changed, and vegetation regressed as grazing pressure increased (Nakamura et al. 1998; Jiang and Zhou 2002; Sun et al. 2007; Yan and Tang 2007). However, studies on the relationship between the annual variation of grassland species composition and grazing pressure in Hulunbuir grassland are limited.

However, it has been shown that climatic conditions also have a great influence on changes in species composition in arid areas, with respect to the annual variation of grassland vegetation (Cheng et al. 2011; Sasaki et al. 2009). However, precipitation regimes have been predicted to change in the future. Báez et al. (2013) showed that as climate patterns have predicted decreases in rainfall frequency in the future, drought frequency could also increase. Therefore, it is necessary to understand how grassland respond to future climate models on the Mongolian grassland where the climate is predicted to be drier and hotter in the coming decades.

Gao and Reynolds (2003) and Li et al. (2005) showed that grasslands in arid and semi-arid areas are ecologically vulnerable and sensitive to climate variation and human disturbances, especially to changes in rainfall events (Sala et al. 1988; Knapp and Smith 2001; Ma et al. 2007; Guo et al. 2012). Photosynthetic activity is the foundation for growth, biomass production, and carbon accumulation of plants. Robertson et al. (2009) showed that the response of a community is an integrated product of the responses of individual species; therefore, examining the responses of species is essential to understand the response of the community. Thus, to demonstrate the response of grassland species communities to changeable precipitation, I measured the net ecosystem production (NEP) and gross primary production (GPP) of the dominant species of the grassland in the summer for three years. Li et al. (2014) determined the productivity response of *L. chinensis*, a dominant perennial grass in semi-arid grasslands in Inner Mongolia, to different precipitation regimes. Additionally, Sun and Du (2017) explored the effect of climate on net primary productivity (NPP) and precipitation use efficiency (the ratio of aboveground productivity to precipitation, PUE) and reported that NPP increased with precipitation, whereas PUE decreased. Although most of the previous studies were based on annual productivity, which reflects all the precipitation events over the entire year (Hooper and Johnson 1999; Harpole et al. 2007), the patterns of precipitation events may change greatly in a year. Guo et al. (2016) reported that N enrichment significantly increased the total GPP in response to a temporal rainfall event in an Inner Mongolian grassland. Their study shows that the productivity also responds to temporal rainfall events (Guo et al. 2016). Thus, to more accurately predict the influence of rainfall on productivity, an understanding of how productivity responds to temporal rainfall events is necessary. Additionally, an understanding of the influence of rainfall regimes on different types of species is also necessary.

Several studies examined the responses of different species to changes in rainfall or drought. Liu Y S et al. (2012) demonstrated that two species (*L. chinensis* and *Stipa grandis*) in an Inner Mongolian grassland had different responses in biomass to changes in rainfall. As shown in the study of Chen et al. (2013), the responses of growth to drought stress were significantly different between *S. grandis* and *S. krylovii* in an Inner Mongolian grassland. Similar studies have also been conducted for different species in other regions. In alpine grassland on the Qinghai-Tibetan Plateau, Zhang et al. (2009) demonstrated differences in NEP among three species and discussed the underlying mechanisms that the aboveground biomass and soil water content might contribute to the differences among the three species. In the same region, Hirota et al. (2006) compared four wetland species and found that water depth was the major environmental driver of NEP seasonal variation. Robertson et al. (2009) reported that three dominant species with different functional traits differed in response to the variation in the annual amount and patterns of precipitation in a grassland of North America. *Dasylirion leiophyllum*, a C_3 shrub species, responded to frequent, large precipitation events, whereas *Bouteloua curtipendula*, a C_4 grass species, was correlated with frequent, small summer rainfall events with short interval periods, and *Opuntia phaeacantha*, a crassulacean acid metabolism (CAM) succulent species, was responsive to small winter and fall rainfall events with short interval periods.

Many ecological studies have been conducted with *S. krylovii* and *A. polyrhizum*, which are two widely distributed dominant perennial C_3 species in Inner Mongolian grasslands (Cheng et al. 2013). *S. krylovii* community is a major grassland community type in the moderate temperate zone of central Asia and is distributed over a large area, forming important pasture in Inner Mongolia. According to Zhao et al. (2006), *S. krylovii* is a perennial tussock grass that is rich in nutrients and palatable for livestock. Chen et al. (2013) reported that *S. krylovii* utilizes a tolerance strategy for drought stress. Although *A. polyrhizum* is also a perennial tussock grass, the *A. polyrhizum* community is considered to be a degraded grassland type, and the expectation is that *A. polyrhizum* will increase as grassland deteriorates (Cheng et al. 2013). Regarding physiological features, Ivanov et al. (2004) characterized *A. polyrhizum* by the high photosynthetic rate under conditions of sufficient water supply. Therefore, the two species are of considerable ecological importance and apparently have comparable physiological features relating to drought and the rainfall regime. Clarifying the ecophysiological features of these two species will provide a comprehensive understanding of the response of the ecosystem in an Inner Mongolian grassland.

Abundant evidence has demonstrated that climate change, overgrazing, and land use change are the key causes for decreasing grassland coverage, loss of biological diversity, and degradation of grassland ecosystem functions (Li 2012; Liu et al. 2013). Understanding the effects of these factors is critical to grassland management.

1-2 General objectives

My studies were carried out in a typical grassland in Inner Mongolian, including light (L), medium (M), heavy (H), and forbidden (F) grazing areas. To accurately evaluate the influence of grazing on vegetation, the influence of climate changes, especially precipitation variation, on biomass, species composition, and productivity of grassland vegetation, it is necessary to include annual and temporary variation. However, although Xin Barag Right Banner is an important grazing area in Inner Mongolian, there are several studies on grazing pressure and species composition of vegetation (Cheng et al. 2013) and GPP variation of species, but limited studies about annual fluctuations and temporary precipitation. Therefore, my knowledge about how species from the same community differ in their responses to changes in rainfall amount and pattern remains poorly understood. Therefore, the general objectives of this study were the to:

(1) analyze and evaluate the effects of overgrazing and rainfall patterns change on the vegetation composition and productivity in the grassland of the Xin Barag Right Banner;

(2) demonstrate the relationships between GPP and environmental conditions (temperature and light intensity) for *S. krylovii* and *A. polyrhizum*;

(3) determine the effect of a temporal rainfall event on the GPP of the two species in a dry year;

(4) compare and determine the effect of a rainfall event on the GPP of the two species between a wet year and dry years; and

(5) ascertain which species is more sensitive to temporal and long-term rainfall.

Chapter 2 Overview of the study area

2-1 Geographical position

Inner Mongolia (37°24′–53°23′N, 97°12′–126°04′E) is located in the eastern steppe regions of Eurasia. It is classified as a provincial-level division in China. It stretches 2,400 km from West to East and 1,700 km from North to South. Inner Mongolia is the main body of northern China and should play a protective role against desertification with the Greater Khingan Mountains. There are eight provinces and regions in its South, East and West, and Mongolia and Russia in its North.

My study site (lat. 48°32′N, long. 117°00′E, 500–650 m above sea level) is located in Xin Barag Right Banner, Hulunbuir, Inner Mongolia, China (Figure 2.1). Xin Barag Right Banner is located at lat. 43°05′N, long. 141°20′E of the Kherlen River basin in the eastern Mongolian grassland. It is a livestock industry area of Inner Mongolia and is connected with Russia and Mongolia.

In the present study, owing to grazing intensity, we set up four survey areas including light, medium, heavy, and forbidden grazing areas based on grazing strength in the grassland of Xin Barag Right Banner (Figure 2.1, 2.2). I will give a detailed introduction to the four survey areas in Chapter 3, 3-2-1.

2-2 Climate

The climate of Inner Mongolia is a temperate monsoon type. It is characterized by low and variable precipitation, and tremendous changes of temperature. Winter lasts for a very long time with freezing cold temperatures. The annual precipitation is about 50–450mm from West to East. January is the coldest month from -10 to -32°C. Summer is warm and short for just one or two months. The hottest month usually comes in July with the highest temperatures of 36 to 45°C.

The annual average temperature and precipitation in Hulunbuir is -5 to 2°C and about 400 mm and that in Xin Barag Right Banner, Hulunbuir for 1958–2014 were 1.7°C and 242 mm. The annual average integrated temperature was 2,600–2,700°C (raw period) (Wuyunna et al. 2012). I only utilized the precipitation data of the vegetation growing season, according to climatic conditions in my study area, and my survey was conducted in late July for 2012–2016; thus, only rainfall data for March to July were utilized.

2-3 Vegetation

The grassland area in Hulunbuir is about 8.7×10^4 km^2 and with available grassland area of 7.4×10^4 km^2. The distribution from East to West is meadow steppe semi-arid, and arid.

The grassland in Xin Barag Right Banner is classified as a typical temperate grassland and dominated by *S. krylovii* and *Cleistogenes squarrosa* (Wuyunna et al. 2009, Cheng et al. 2013). Other common species as follow:

annual grass: *Chenopodium acuminatum*, *Salsola collina*, *Bassia dasyphylla*.

biennial grass: *Chamaerhodos erecta*.

perennial grass: *Allium polyrhizum*, *Allium ramosum*, *Artemisia adamsii*, *Leymus chinensis*, *Carex korshinskyi*, *Potentilla bifurca*, *Agropyron cristatum*.

small semi shrub: *Artemisia frigida*, *Ptilotrichum canescens*.

dwarf shrub: *Caragana stenophylla*.

2-4 Soil

The main soil type in Hulunbuir grassland in Inner Mongolia is Kastanozems (Lin et al. 2013), which is the type mainly distributed in typical grassland. The pH (H_2O) of the surface soil was 6.5–8.0, which was neutral to weakly basic, however, as the depth of the soil deepened, the value of pH (H_2O) increased. The amount of organic carbon and total nitrogen was 9.17–30.05 ($g \cdot kg^{-1}$) and 1.05–2.92 ($g \cdot kg^{-1}$), respectively (Kanda 2015). The soil hardness, organic matter content and total nitrogen in the 0-10 cm soil layer were 14.10 ± 0.46 mm, 2.7 ± 0.1% and 3.90 ± 0.28 $g \cdot kg^{-1}$, respectively (Lin et al. 2013). The total nitrogen and bacteria amount of soil in the light, medium, heavy grazing areas were significantly different, and with the grazing intensities increased, the total nitrogen and bacteria amount decreased (Lin et al. 2013).

2-5 Social environment

In ancient times, the people in Inner Mongolia lived a nomadic life; therefore, there was no overgrazing. However, as cultivation developed, the traditional life style changed, from stockbreeding to farming and from nomadism to fixed pasture (Shinchilelt 2014). It has been an unresolved problem in livestock husbandry as to how herdsmen redispose seasonal grassland with the mode of production from changing nomadism to fixed pasture utilization in the warm season and house feeding in the cold season. Recently, even in Xin Barag Right Banner, with tourism development, and the rapid growth in meat demand within China, the numbers of livestock raised has increased accordingly, and degeneration and desertification of grassland has occurred (Ito et al. 2006).

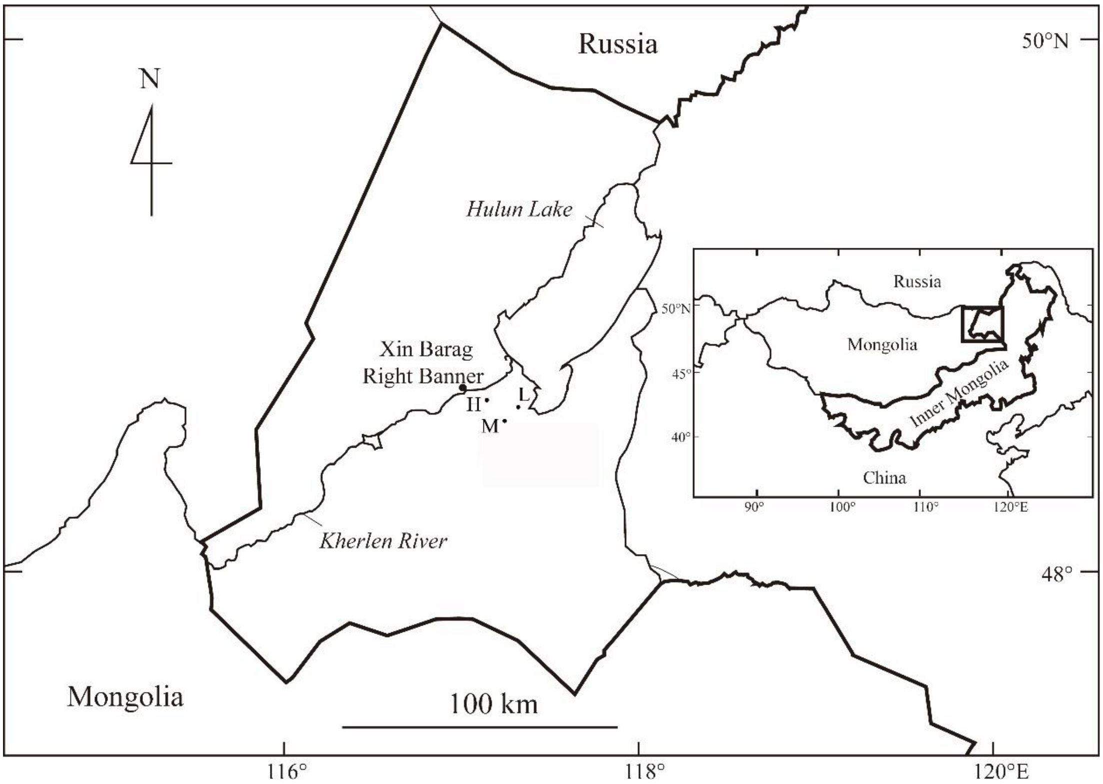

Figure 2.1 Location of the study site in Xin Barag Right Banner, Hulunbeir, Inner Mongolia, China.

L: light grazing area; M(F): medium grazing area (F: grazing forbidden area); H: heavy grazing area.

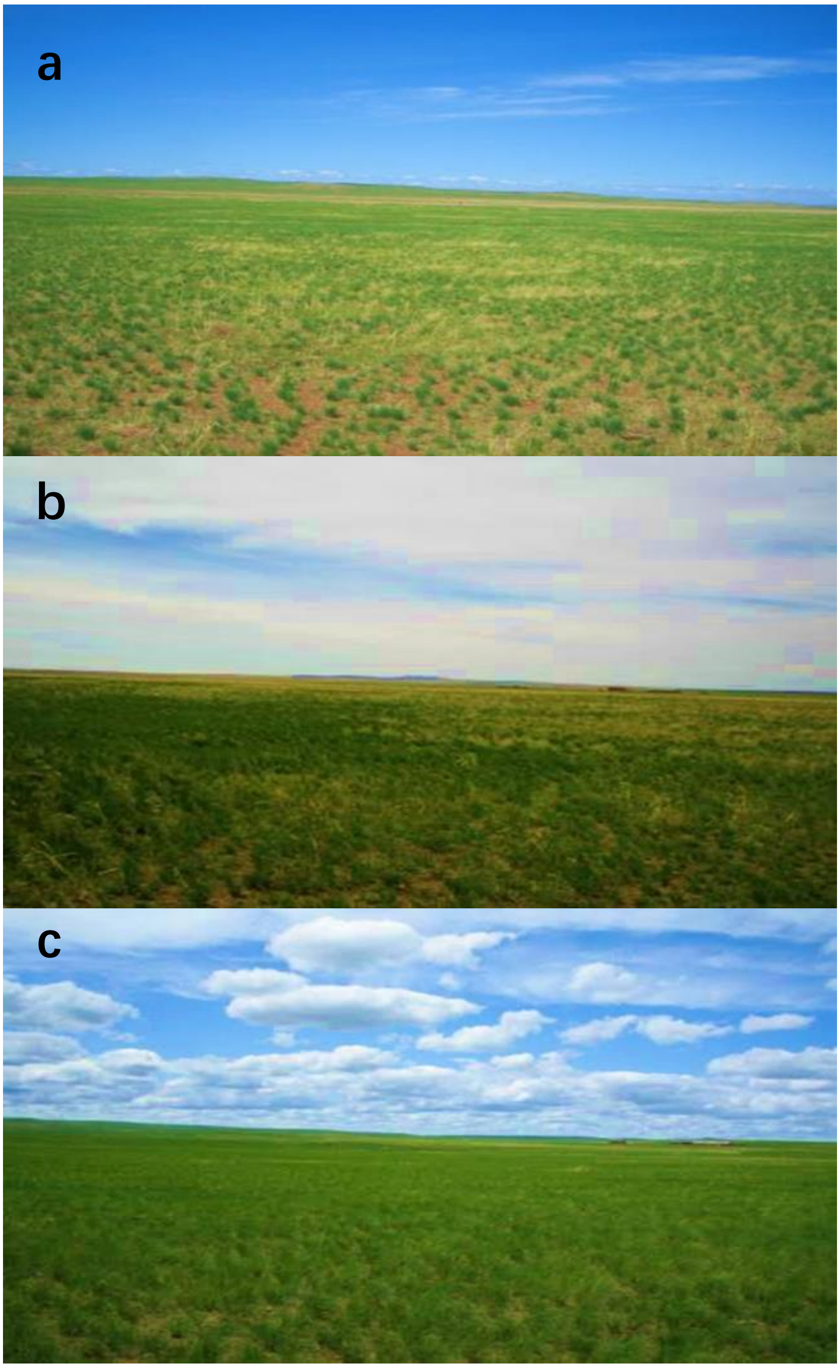

Figure 2.2 Photographs of the three intensities areas in Xin Barag Right Banner.

a: Heavy grazing area; b: Medium grazing area; c: Light grazing area.

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References

Adams J M, Faire H, Faire-Richard L, et al. 1990. Increases in terrestrial carbon storage from the last glacial maximum to the present. Nature, 348:711-714.

Archibold O W. 1995. Ecology of World Vegetation. Chapman & Hall, London.

Báez S, Collins S L, PockmanW T, et al. 2013. Effects of experimental rainfall manipulations on Chihuahuan Desert grassland and shrubland plant communities. Oecologia, 172:1117-1127.

Bai Y F, Wang W J, Zhang Z R. 1992. Study on fluctuations of *Stipa grandis* steppe community in southeastern Inner Mongolia. Grassland of China, 12(4）: 1-5.

Bai Y F, Xu Z X, Li D X. 1994. Study on seasonal fluctuations of biomass for *Leymus chinense* grassland. Grassland of China, 14(3）: 1-5.

Bai Y F, Xu Z X. 1997. A model of aboveground biomass of *Leymus chinense* community in response to seasonal precipitation. Acta Prataculturae Sinica, 6(2）: 1-6.

Bai Y F. 1999. Influence of seasonal distribution of precipitation on primary productivity of *Stipa krylovii* community. Acta Phytoecologica Sinica, 23(2）: 155-160.

Bao Y, Yin S, Alatengtuya, et al. 2005. Study on the dynamics of land desertification in the middle part of Inner Mongolia. Quarterly Journal of Geography, 58:114-115.

Braun-Blanquet J. 1964. Pflanzensoziologie. Springer-Verlag, New York.

Briggs J M, Knapp A K. 1995. Interannual variability in primary production in tall-grass prairie: climate, soil moisture, topographic position, and fire as determinants of aboveground biomass. American Journal of Botany, 82:1024-1030.

Berry J A, Björkman O. 1980. Photosynthetic response and adaptation to temperature in higher plants. Annual Review of Plant Physiology, 31:491-543.

Chen B R, Li H S, Zhu Y X, et al. 2010. The spatial pattern and environmental interpretation of the plant community of Hulunber grassland. Acta Ecologica Sinica, 30(5):1265-1271. (in Chinese)

Chen S H, Zhang H, Wang L Q, et al. 2001. Grassland Plant Roots in Northern China. Jilin, China: Jilin University Press, 81-83&470-471. (in Chinese)

Chen S P, Lin G H, Huang J H, et al. 2009. Dependence of carbon sequestration on the differential responses of ecosystem photosynthesis and respiration to rain pulses in a semiarid steppe. Global Change Biology, 15: 2450-2461.

Chen L P, Zhao N X, Zhang L H, et al. 2013. Responses of two dominant plant species to drought stress and defoliation in the Inner Mongolia Steppe of China. Plant Ecology, 214:221-229.

Chen Z Z. 2008. Into the Grasslands. China Forestry Publishing House, Beijing, 5-13. (in Chinese)

Cheng Y, Tsubo M, Ito T, et al. 2011. Impact of rainfall variability and grazing pressure on plant diversity. Journal of Arid Environments, 75: 471-476.

Cheng Y X, Kamijo T, Tsubo M, et al. 2013. Phytosociology of Hulunbeier grassland vegetation in Inner Mongolia, China. Phytocoenologia, 43(1-2):41-51.

Ciais P, Reichstein M, Viovy N, et al. 2005. Europewide reduction in primary productivity caused by the heat and drought in 2003. Nature, 437:529-533.

Cui X, Guo K, Hao Y, et al. 2012. Eurasian steppes. Ecological problems a livelihoods in a changing world, degradation and management of steppes in China. Plant and Vegetation, 6:475-490.

Dai A G. 2011. Drought under global warming: a review. Wires Climate Change, 2(1) : 45–65.

de Bello F, Lavorel S, Díaz S, et al. 2010. Towards an assessment of multiple ecosystem processes and services via functional traits. Biodiversity and Conservation, 19:2873–2893.

Falge E, Baldocchi D, Olson R J. 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agricultural and Forest Meteorology, 107:43-69.

Gamalei Y V, Shiirevdamba T. 1988. Structural types of Desert Plants, in Pustyni Zaaltaiskoi Gobi: kharakteristika rastenii-dominantov (Deserts of the Transaltai Gobi: Characteristic of the Dominant Plants). Leningrad: Nauka, 45-66.

Gao Q, Reynolds J F. 2003. Historical shrub-grass transitions in the northern Chihuahuan Desert: modeling the effects of shifting rainfall seasonality and event size over a landscape gradient. Global Change Biology, 9:1475-1493.

Gao Y Z, Giese M, Brueck H, et al. 2013. The relation of biomass production with leaf traits varied under different land-use and precipitation conditions in an Inner Mongolia steppe. Ecology research, 28:1029-1043.

Gibbens R P, Lenz J M. 2001. Root systems of some Chihuahuan desert plants. Journal of Arid Environments, 49: 221-263.

Gibson D J. 2009. Grasses and Grassland Ecology. Oxford University Press, New York.

Granier A, Reichstein M, Breda N, et al. 2007. Evidence for soil water control on carbon and water dynamics in European forests during the extremely dry year:2003. Agricultural and Forest Meteorology, 143:123-145.

Gunin P D, Bazha S N, Danzhalova E V, et al. 2015. Regional features of desertification processes of ecosystems on the border of the Baikal basin and Central Asian internal drainage basin. Arid Ecosystems, 5(3):117-133.

Guo Q, Hu Z, Li S, et al. 2012. Spatial variations in aboveground net primary productivity along a climate gradient in Eurasian temperate grassland: effects of mean annual precipitation and its seasonal distribution. Global Change Biology, 18:3624-3631.

Guo Q, Hu Z M, Li S G, et al. 2016. Exogenous N addition enhances the responses of gross primary productivity to individual precipitation events in a temperate grassland. Scientific Reports, 6:26901.

Han D M, Wang G Q, Xue B L, et al. 2018. Evaluation of semiarid grassland degradation in North China from multiple perspectives. Ecological Engineering, 112:41-50.

Hao L, Sun G, Liu Y Q, et al. 2014. Effects of precipitation on grassland ecosystem restoration under grazing exclusion in Inner Mongolia, China. Landscape Ecology, 29(10):1657–73.

Hao Y B, Wang Y F, Mei X R. 2010. The response of ecosystem CO_2 exchange to small precipitation pulses over a temperate steppe. Plant Ecology, 209:335-347.

Harpole W S, Pott D L, Suding K N. 2007. Ecosystem responses to water and nitrogen amendment in a California grassland. Global Change Biology, 13:2341-2348.

Hirota M, Tang Y H, Hu Q W, et al. 2006. Carbon dioxide dynamics and controls in a deep-water wetland on the Qinghai-Tibetan plateau. Ecosystems, 9: 673-688.

Hirota M, Zhang P C, Gu S, et al. 2009. Altitudinal variation of ecosystem CO_2 fluxes in an alpine grassland from 3600 to 4200 m. Journal of Plant Ecology, 2(4):197-205.

Hirota M, Zhang P C, Gu S, et al. 2010. Small-scale variation in ecosystem CO_2 fluxes in an alpine meadow depends on plant biomass and species richness. Journal of Plant Research, 123: 531-541.

Hodson M J, Bryant J A. 2012. Functional Biology of Plants. Chichester: John Wiley & Sons, Ltd, 166-188.

Hooper D U, Johnson L. 1999. Nitrogen limitation in dryland ecosystems: Responses to geographical and temporal variation in precipitation. Biogeochemistry, 46: 247-293.

Huang D H, Chen Z Z, Zhang H F. 1985. Comparisons of belowground biomass in *Stipa baicalensis*, *S. krylovii* and *Filifolium sibiricum* steppes. Research of Grassland Ecosystem, 5: 46-52.

Hunt J E, Kelliher F M, Mcseveny T M, et al. 2004. Long-term carbon exchange in a sparse, seasonally dry tussock grassland. Global Change Biology, 10:1785-1800.

Huxman T E, Snyder K A, Tissue D, et al. 2004. Precipitation pulses and carbon fluxes in semiarid and arid ecosystems. Oecologia, 141: 254-268.

IPCC. 2007. IPCC WGI Fourth Assessment Report. Climatic Change 2007: The Physical Science Basis. Intergovernmental Panel on Climate Change, Geneva.

Ito M, Ao M, Ito K. 2006. Inner Mongolian Grasslands: Situation and Concern. Journal of weed science and technology, 51:256-262. (in Japanese)

Ivanov L A, Ivanova L A, Ronzhina D A, et al. 2004. Structural and functional grounds for *Ephedra sinica* expansion in Mongolian steppe ecosystems. Russian Journal of Plant Physiology, 51(4) :469-475.

Jiang S C, Zhou D W. 2002. The effect of three types of overgrazing, deep harrowing, close nursery on the degraded *Leymus chinense* grassland. Grassland of China, 24(5):5-9.

Kanda T. 2015. Effects of climate and land use on the form and dynamics of soil organic carbon in Eurasian steppe. University of Tsukuba, Ph.D. Thesis. (in Japanese)

Kawada K, Wuyunna, Nakamura T. 2011. Land degradation of abandoned croplands in the Xilingol steppe region, Inner Mongolia, China. Japanese Society of Grassland Science, 57:58-64.

Konagaya Y, Shinjilt, Nakawo M. 2005. Environment policy ecology immigrants in China. Showado, pp, 13-15.

Knapp A K, Smith M D. 2001. Variation among biomes in temporal dynamics of aboveground primary production. Science, 291: 481-484.

Laobusheng D, Sun C Z, Chen Z Z, et al. 1990. The dynamic of biomass and relationship between biomass and precipitation of desert steppe in Inner Mongolia. Arid Land Geography, 13(1): 10-17.

Lehouerou H N, Bingham R L, Skerbek W. 1988. Relationship between the variability of primary production and the variability of annual precipitation in world arid lands. Journal of Arid Environments, 15:1-18.

Li A, Wu J G, Huang J H .2012. Distinguishing between human induced and climate-driven vegetation changes: a critical application of RESTREND in inner Mongolia. Landscape Ecology, 27:969-982.

Li B. 1990. China's grasslands. Science Press, Beijing, 12-16. (in Chinese)

Li B. 1995. Grassland biodiversity conservation in China. Inner Mongolia University Press, Hohhot, pp.1-12. (in Chinese)

Li C, Hao X, Zhao M, et al. 2008. Influence of historic sheep grazing on vegetation and soil properties of a Desert Steppe in Inner Mongolia. Agriculture, Ecosystems and Environment, 128: 109-116.

Li F, Zhao W Z, Liu H. 2013. The response of aboveground net primary productivity of desert vegetation to rainfall pulse in the temperate desert region of northwest China. PLoS One, 8(9): e73003.

Li S G, Asanuma J, Eugster W, et al. 2005. Net ecosystem carbon dioxide exchange over grazed steppe in central Mongolia. Global Change Biology, 11: 1941-1955.

Li Z L, Zhang Y T, Yu D F, et al. 2014. The influence of precipitation regimes and elevated CO_2 on photosynthesis and biomass accumulation and partitioning in seedlings of the rhizomatous perennial grass *Leymus chinensis*. PloS One, 9(8): e103633.

Lin L, Wuyunna, Tamura K, et al. 2013. Variation of soil physicochemical and microbial properties in degraded steppes in Hulunbeir of China. Chinese Journal of Applied Ecology, 24(12):3407-3414. (in Chinese)

Liu F, Li H, Dong Z, et al. 2012. Advances in research on enclosure effects on vegetation restoration and soil physicochemical property of degraded grassland. Science of Soil and Water Conservation, 10(5):116-122.

Liu J. 2010. Continuously developing grassland animal husbandry of China. Pratacultural Science, 27 (4) :1-3.

Liu J M . 2001. Impacts prediction of climatic change on distribution and production of grassland in Inner Mongolia. Acta Agrestia Sinica, 9(4),276-281. (in Chinese)

Liu X Q, Wang R Z. 2006. Photosynthetic and morphological functional types in the vegetation from North-Beijing agro-pastoral ecotone, China. PHOTOSYNTHET-ICA, 44:365-386.

Liu Y S, Pan Q M, Zhang S X, et al. 2012. Intra-seasonal precipitation amount and pattern differentially affect primary production of two dominant species of Inner Mongolia grassland. Acta Oecologica, 44:2-10.

Liu Y Y, Evans J P, McCabe M F, et al. 2013. Changing climate and overgrazing are decimating Mongolian Steppes. PLoS One, 8(2):e57599.

Ma S Q. 1987. Aboveground stand crop biomass of *Stipa grandis* and *S. krylovii* grasslands in inner Mongolia. Journal of Arid Land Resources and Environment, 1(2) : 95-105.

Ma S, Baldocchi D D, Xu L K, et al. 2007. Inter-annual variability in carbon dioxide exchange of an oak/grass savanna and open grassland in California. Agricultural and Forest Meteorology, 147: 157-171.

Ma Y, Fu H, Chen S et al. 1989. *Flora Intramongolica* (Volume 3), 2nd edn. Typis Intramongolicae Popularis, Huhhot, China. 1-716. (in Chinese)

Ma Y, Fu H, Chen S et al. 1990. *Flora Intramongolica* (Volume 2), 2nd edn. Typis Intramongolicae Popularis, Huhhot, China.1-759. (in Chinese)

Ma Y, Fu H, Chen S et al. 1993. *Flora Intramongolica* (Volume 4), 2nd edn. Typis Intramongolicae Popularis, Huhhot, China.1-907. (in Chinese)

Ma Y, Fu H, Chen S et al. 1994. *Flora Intramongolica* (Volume 5), 2nd edn. Typis Intramongolicae Popularis, Huhhot, China.1-634. (in Chinese)

Ma Y, Fu H, Chen S et al. 1998. *Flora Intramongolica* (Volume 1), 2nd edn. Typis Intramongolicae Popularis, Huhhot, China.1-408. (in Chinese)

McIntyre S, Lavorel S. 2001. Livestock grazing in subtropical pastures: steps in the analysis of attribute response and plant functional types. Journal of Ecology, 89:209-226.

Michael A. 2004. A Dictionary of Ecology. Oxford University.

Miehe S, Kluge J, von Wehrden H, et al. 2010. Long-term degradation of Sahelian rangeland detected by 27 years of field study in Senegal. Journal of Applied Ecology, 47:692-700.

Nakamura T, Go T, Li Y, et al. 1998. Experimental study on the effects of grazing pressure on the floristic composition of a grassland of Baiyinxile, Xilingol. Inner Mongolia Vegetation Science, 15:139-145.

Nakamura T, Go T, Wuyunna, et al. 2000. Effects of gazing on the floristic Composition of grasslands in Baiyinxile, xilingol, Inner Mongolia. Grassland Science, 45(4): 342-350.

Nakano T, Nemoto M, Shinoda M. 2008. Environmental controls on photosynthetic production and ecosystem respiration in semi-arid grasslands of Mongolia. Agricultural and Forest Meteorology, 148:1456-1466.

Novick K A, Stoy P C, Katul G G, et al. 2004. Carbon dioxide and water vapor exchange in a warm temperate grassland. Oecologia, 138:259-274.

Obermeier W A, Lehnert L W, Ivanov M A, et al. 2018. Reduced Summer Aboveground Productivity in Temperate C3 Grasslands Under Future Climate Regimes. Earth's Future, 6(5):716-29.

Pereira J S, Chaves M M, Caldeira M C, et al. 2006. Water availability and productivity. In: Morrison J I L, Morecroft M D, Plant growth and climate change. London, UK: Blackwell Publishers, 118-145.

R Core Team. 2018. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Ren H Y, Schönbach P, Wan H W, et al. 2012. Effects of grazing intensity and environmental factors on species composition and diversity in typical steppe of Inner Mongolia, China. Plos one, 7(12): e52180.

Reynolds S, Batello C, Baas S, et al. 2005. Grassland and forage to improve livelihoods and reduce poverty. In: McGilloway D A, Grassland: A Global Resource. Wageningen, The Netherlands: Wageningen Academic Publishers, 323-338.

Robertson T R, Bell C W, Zak J C, et al. 2009. Precipitation timing and magnitude differentially affect aboveground annual net primary productivity in three perennial species in a Chihuahuan Desert grassland. New Phytologist, 181:230-242.

Sochava V B. 1979. Climate and soils of grassland distribution area in the USSR. In: Ecology of grasslands and bamboolands in the world(Ed numata M). Jena: VEB Gustav Fischer, 43-48.

Sala O E, Parton W J, Joyce L A, et al. 1988. Primary production of the central grassland region of the United States. Ecology, 69(1): 40-45.

Sasaki T, Okayasu T, Ohkuro T, et al. 2009. Rainfall variability may modify the effects of long-term exclosure on vegetation in Mandalgobi, Mongolia. Journal of Environments, 73: 949-954.

Schwinning S, Davis K, Richardson L, et al. 2002. Deuterium enriched irrigation indicates different forms of rain use in shrub/grass species of the Colorado Plateau. Oecologia, 130:345-355.

Shi Z, Thomey M L, Mowll W, et al. 2014. Differential effects of extreme drought on production and respiration: synthesis and modeling analysis. Biogeosciences, 11: 621-633.

Shinchilelt. 2014. Effects of large-Scale agriculture and livestock industry on the vegetation and soil properties in the steppe region of Kazakhstan and Inner Mongolia, China. University of Tsukuba, Ph.D. Thesis.

Squires V R, Hua L, Zhang D, et al. 2010. Towards sustainable use of rangelands in North-West China. Springer, New York.

Sun Z J, An S Z, Ma J C. 2007. Effects of fences enclosure on grassland vegetation and diversity. Arid Zone Research, 24(5):669-674. (in Chinese)

Sun J, Liu M, Li S G, et al. 2011. Survival strategy of *Stipa krylovii* and *Agropyron cristatum* in typical steppe of Inner Mongolia. Acta Ecologica Sinica, 31(8): 2148-2158. (in Chinese)

Sun J, Du W P. 2017. Effects of precipitation and temperature on net primary productivity and precipitation use efficiency across China's grasslands. GIScience & Remote Sensing, 54(6):881-897.

Suttie J M, Reyolds S G, Batello C. 2005. Grasslands of the world. FAO, Rome.

Tetens O. 1930. Uber einige meteorologische Begriffe. Z. Geophys, 6: 297-309.

Thomey M L, Collins S L, Friggens M T, et al. 2014. Effects of monsoon precipitation variability on the physiological response of two dominant C_4 grasses across a semiarid ecotone. Oecologia, 176: 751-762.

Wang Q J, Wang S M. 1993. Biomass and grazing of sheeps in sand grassland, Aohan pasture. Prataculture of Inner Mongolia, (2): 1-5.

Wang R Z. 2004a. Photosynthetic pathways and life form types for native plant species from Hulunbeier Rangelands, Inner Mongolia, North China. PHOTOSYNTHE-TICA, 42:219-227.

Wang R Z. 2004b. Photosynthetic and morphological functional types from different steppe communities in Inner Mongolia, North China. PHOTOSYNTHETICA, 42:493-503.

Wang T, Xue X, Zhou L, et al. 2015. Combating aeolian desertification in northern China. Land Degradation & Development, 26:118-132.

Wuyunna, Nakamura T, Hayashi I R. 1999. Species diversity and abundance of communities in Inner Mongolia Xilingol grassland. Grassland Science, 45(2): 140-148. (in Japanese)

Wuyunna, Zhang F J, Ran C Q. 2009. Analysis of climatic in basin of Kherlen River of Mongolia plateau for the past 50 years. Journal of Dalian Nationalities University, 11(3):193-195. (in Chinese)

Wuyunna, Zhang F J, Shiomi M. 2011. Quantitative analysis of spatial heterogeneity in species richness and composition in grassland vegetation with different grazing intensities in the northeast Inner Mongolian steppe. Arid Land Geography. 34(6): 904-911. (in Chinese)

Wuyunna, Zhang F J, Pei H, et al. 2012. The effect of temperature and precipitation during the growing season on the biomass of steppe communities in the Herlen Basin, northern China. Acta Prataculturae sinica, 21(2): 227-232. (in Chinese)

Xing Q, Liu Y Z, Han Z M. 1994. Dynamics of aboveground biomass and nutrition of typical steppe in Inner Mongolia. Prataculture of Inner Mongolia, (1-2）: 34-38.

Xiong P F, Shu J L, Zhang H, et al. 2017. Small rainfall pulses affected leaf photosynthesis rather than biomass production of dominant species in semiarid grassland community on Loess Plateau of China. Functional Plant Biology, 44(12): 1229-1242.

Xu L K, Baldocchi D D. 2004. Seasonal variation in carbon dioxide exchange over a Mediterranean annual grassland in California. Agricultural and Forest Meteorology, 1232:79-96.

Xuri, Maesako Y, Muramatsu K. 2008. Changes on life style and the availability of AVNIR-2 data onboard ALOS satellite for vegetation mapping in Inner Mongolia grassland. Osaka Sangyo University journal of human environmental studies, 7: 83-102. (in Japanese)

Yan Y C, Tang H P. 2007. Effects of exclosure on typical steppe community properties in Inner Mongolia. Acta Botanica Boreali-Occidentalia Sinica, 27(6):1225-1232. (in Chinese)

Zhang H X, Gao Y Z, Tasisa B Y, et al. 2019. Divergent responses to water and nitrogen addition of three perennial bunchgrass species from variously degraded typical steppe in Inner Mongolia. Science of the Total Environment, 647:1344-1350.

Zhang M X, Sun C Z, Laobusheng D, et al. 1992. Dynamics of aboveground biomass in *Stipa krylovii* grassland. Prataculture of Inner Mongolia, (2): 48-50.

Zhang P C, Hirota M, Shen H H, et al. 2009. Characterization of CO_2 flux in three kobresia meadows differing in dominant species. Journal of Plant Ecology, 2(4):187-196.

Zhao H, Zhao X. 2005. Desertification processes due to heavy grazing in sandy rangeland, Inner Mongolia. Journal of Arid Environments, 62(2):309-319.

Zhao N X, Gao Y B, Wang J L, et al. 2006. Genetic diversity and population differentiation of the dominant species *Stipa krylovii* in the Inner Mongolia steppe. Biochemical Genetics, 44(11-12):504-517.