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Grazing induced changes in plant diversity is a critical factor controlling grassland productivity in the Desert Steppe, Northern China

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ABSTRACT

The desert steppe is a large component of the semi-arid grassland ecosystem in northern China, and provides significant resources for livestock production. However, overgrazing is regarded as one of main causes of its degradation and desertification over recent decades. Quantifying the direct and indirect effects of grazing disturbance on plant community productivity in the desert steppe ecosystem can provide insights into appropriate measures for the restoration of degraded grassland and biodiversity conservation. Here, we examine the effects of four grazing intensity treatments: no grazing (control), light grazing (LG), moderate grazing (MG) and heavy grazing (HG) on the plant community and soil nutrients with sheep grazing over 12 years in a desert steppe in Inner Mongolia, northern China. The results showed that increasing grazing intensity resulted in decreased species richness, Shannon-Wiener and Pielou's index, as well as above- and belowground biomass. Soil moisture, nitrogen, available potassium and soil organic carbon were not affected ($P > 0.05$) by grazing disturbance. In addition, grazing disturbance had a greater indirect effect on aboveground biomass via plant diversity. Consequently, plant diversity is a key indirect factor that determines community productivity in response to grazing disturbance. Reducing grazing pressure can contribute to maintaining relatively high species diversity and productivity in the desert steppe of northern China.

1. Introduction

Grasslands are one of the largest terrestrial ecosystems in the world. The multi-functionality of grasslands has brought many economic and ecological benefits to livestock keepers and society, and increasing attention is now paid to sustainable management of grassland systems (Isselstein et al., 2007). China has the third largest grassland area in the world (FAO 2001), covering 3.9×10^8 ha, or 41% of China's total terrestrial area (Nan, 2005). These grasslands include meadow steppe, typical steppe, alpine steppe and desert steppe (Kang et al., 2007).

Grassland-based animal husbandry in northern China provides 33% of goat and sheep meat, 70% of wool, 14% of beef and 10% of milk produced in China (Li et al., 2008b). Within the region, it also supports the livelihoods of over 40 million people, and livestock production accounts for 80% of the total value of agricultural output (Kemp et al., 2011). Historically, herders have adopted nomadic practices, which helped maintain healthy grassland by implementing grazing rotation while avoiding overgrazing. During the implementation of the household system of land management from the 1950s to the 1980s, grassland regions experienced a sharp increase in stocking rate (Li et al., 2000). This led to severe ecological problems as evidenced by a decline in forage productivity and a loss of biodiversity, resulting in grassland degradation and desertification (Akiyama and Kawamura, 2007).

Herbivore grazing is the primary disturbance affecting grassland ecosystems, including grassland productivity and ecosystem functions (An and Li, 2014; Liu et al., 2015b). In the soil-plant-herbivore system, herbivore grazing affects species composition and diversity in plant community (Belsky, 1992), and impacts soil physical and chemical properties (Zhou et al., 2010). For instance, long-term grazing disturbance can cause a shift in the plant community from dominated perennial C_3 grasses to C_4 grass species (Augustine et al., 2017), and can affect soil nitrogen and phosphorus distribution and dynamics (Chaneton et al., 1996). According to the intermediate disturbance hypothesis, light and moderate grazing intensity contributes to increasing community productivity and higher diversity due to plant compensatory effects (McNaughton, 1983). However, heavy grazing

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intensity negatively affects litter accumulation and soil coverage (Schönbach et al., 2011), causes decreases in soil quality and fertility, and weakens aboveground and belowground plant productivity (Liang et al., 2009). However, some previous studies have pointed out that the effect of grazing on diversity and productivity have been overestimated in comparison with the effects of environmental variability (Christensen et al., 2004), and that grazing intensity has a weak effect on species composition and diversity after the relatively short-term grazing (Ren et al., 2012).

Some studies have revealed the direct and indirect effects of grazing disturbance on grassland productivity. Tilman et al. (2001) found that productivity increased with species richness of the grassland community. Plant diversity and species composition have been considered to be key factors affecting plant community productivity due to the strong direct effect of grazing on the richness of subordinate forb species (Shi et al., 2016). Gao et al. (2008) reported that the effect of grazing on belowground net primary productivity depends on species composition and diversity in the plant community, because species diversity can contribute to belowground productivity by increasing the vertical niche differentiation of root systems and the proportion of deep-rooted biomass (Mueller et al., 2013).

The desert steppe covers 39% of the total grassland area in northern China, and is the most arid grassland ecosystem in the Eurasian steppe (Li et al., 2000). It is an important component of the semi-arid grassland region in northern China, with a long history of supporting livestock grazing (Li et al., 2008a; Wang et al., 2017). In addition, the response of the plant community in the desert steppe to grazing disturbance will be distinctive from the responses of other grassland types, because aridity dictates relatively low plant species richness and primary productivity (Li et al., 2008a). Therefore, species loss due to grazing would have more serious consequences in the desert steppe than in other species-rich plant communities (McNeely, 2003). However, there has been little previous research on biodiversity conservation and sustainable management in the desert steppe ecosystem (Liu et al., 2015a). Therefore, this study examined the effect of sheep grazing on grassland vegetation and soil properties in a desert steppe, and quantified the direct and indirect effects of grazing disturbance on grassland productivity. The objectives of this study were: (1) to determine whether plant diversity, grassland productivity, and soil moisture and nutrients decreased with increasing grazing intensity; (2) to clarify whether species diversity is a key indirect factor in the response of grassland productivity to grazing disturbance; and (3) to provide insight into appropriate measures to conserve the ecological environment and support sustainable agricultural development in the desert steppe region.

2. Materials and methods

2.1. Site description

The study site is a desert steppe located at Siziwang Banner in Inner Mongolia, China (41°46′43.6″N, 111°53′41.7″E, 1450 m) (Fig. 1). Siziwang Banner covers an area of 25,500 km^2 with a population of about 210,000, and is typical of the desert steppe region in northern China. Animal husbandry using extensive production methods plays an important role in the economy and food security for herders, and sheep account for about 70% of the local livestock population (Han et al., 2011). Over the past 50 years, livestock grazing intensity has continuously increased, reaching about 1–1.5 sheep equivalents/ha in recent years. At present, 90% of grasslands in Siziwang Banner have been classified as degraded, and household incomes are limited by unproductive and degrading grasslands (Kemp et al., 2011).

This region has a semi-arid climate with a dry and windy spring followed by a rainy and hot summer. Meteorological records over 57 years show that annual mean precipitation is 289.8 mm and the annual mean temperature is 3.6 °C (Supplementary Fig. 1). The enclosures in the study site were established on grassland that had previously been moderately grazed over a long period. The soil is a Kastanozem (FAO soil classification) with a sandy loam texture. The dominant plant species are *Stipa breviflora* Griseb., *Cleistogenes songorica* (Roshev.) Ohwi (C_4 grass) and *Artemisia frigida* Willd. *S. breviflora* is highly palatable forage in early spring and late fall periods, but has low palatability in the flowering and mature periods. *C. songorica* and *A. frigida* are highly palatable and are preferred forage for sheep. Additionally, 25 subordinate plant species were found in this site (Table 1). Preferred forage with a relatively high intake ratio in the sheep diet mainly consists of annual and biennial forbs, as well as some perennial forbs (Liu et al., 2016b).

2.2. Experimental design

A grazing experiment with a complete randomized block design with 4 treatments and 3 replicates, making a total of 12 plots (4.4 ha per plot), was established in June 2004. The treatments were 4 levels of grazing: no grazing as a control with 0 sheep ha^{-1} $month^{-1}$ (control check, CK), light grazing at 0.15 sheep ha^{-1} $month^{-1}$ (i.e. 4 sheep in the plot) (LG), moderate grazing at 0.30 sheep ha^{-1} $month^{-1}$ (i.e. 8 sheep in the plot) (MG), and heavy grazing at 0.45 sheep ha^{-1} $month^{-1}$ (i.e. 12 sheep in the plot) (HG). Grazing occurred from June to November every year and from 6 am to 6 pm on each day during the grazing period, with sheep penned in an enclosure at night. Two year old wethers were selected for this study and were replaced every 3 years with new 2 year old wethers.

2.3. Sampling and measurements

In this study, all experimental data was measured from 2012 to 2015. Ten moving cages (1.5 m × 1.5 m) were set randomly before grazing in each plot. At the end of August, herbaceous plants were clipped to ground level after removing litter and measuring plant individual density within a 1-m^2 quadrate in each cage. Belowground biomass was sampled at two depths: 0–10 cm (shallow roots) and 10–40 cm (deep roots) using 3 soil samples per plot (each soil sample was mixed by 2 soil cores with 7.5 cm diameter). The roots were removed from soil by rinsing in water, and were then oven-dried at 65 °C for 48 h with other living plant materials and weighed as aboveground and belowground biomass, respectively. The frequency of plant species and functional groups was calculated by percentage frequency (Number of sampling units in which the species occurs/Total number of sampling units × 100). Species richness was estimated by the number of species in the quadrate scale. Margalef's richness index was calculated as

$$D = (S - 1)/\ln n \tag{1}$$

where S is the number of species, and n is the number of individuals. Shannon-Wiener index was calculated as

$$H' = -\Sigma Pi \ln Pi \tag{2}$$

where Pi is the proportion of individual species i representing the relative density of plant species (species density/total density for all species × 100). Pielou's index was calculated as

$$E = H'/\ln S \tag{3}$$

Soils were systematically sampled in 2004 when the experiment was established. Thirty soil samples (0–10 cm and 10–20 cm) were collected in each plot, and analyzed for organic carbon (1.46% in 0–10 cm and 1.22% in 10–20 cm), total nitrogen (1.82 g kg^{-1} in 0–10 cm and 1.58 g kg^{-1} in 10–20 cm), available phosphorus (4.86 mg kg^{-1} in 0–10 cm and 3.11 mg kg^{-1} in 10–20 cm), available potassium (247.16 mg kg^{-1} in 0–10 cm and 107.20 mg kg^{-1} in 10–20 cm) (Jiao, 2006). Soils were systematically re-sampled in each year from 2012 to 2015 with 6 soil cores (3.5 cm dia. × 30 cm deep) in each plot in mid-August. The samples were divided into 3 depth segments, air-dried, and