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EFFECTS OF ARTIFICIAL IRRIGATION ON GRASSLANDS PRODUCTION IN DIFFERENT TYPES OF INNER-MONGOLIA STEPPE

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Abstract

Soil water is a major limiting factor to determine the grassland productivity in temperate grassland of China. Artificial irrigation is a useful way to increase the grassland productivity to improve the grassland service. However, the irrigation effects might be different among different grassland types including desert, typical, and meadow steppes across the Chines North Temperate grassland due to the variation in water limitation among them. To test it, three controlled water addition experiments were conducted in three steppe types including a desert, a typical, and meadow grassland, respectively. In each steppe, 18 plots with 1 m^2 were setup, and six treatments (i.e. added none, 20, 40, 60, 80, and 100 percent of annual mean annual precipitation) were supplied during growth season. We assessed the biomass production of each plot at the end of growth season. We found artificial irrigation had strong positive effects on grassland productivities of the three steppes. However, as expected, the effects of irrigation differed among the three different grassland types. The effect was stronger for typical steppe than for other two steppe types. In the meadow steppe, the grassland productivity did not increase anymore after the irrigation more than 40% of the local annual mean precipitation, possibly because the source limitation from water to nutrient. Further studies are still needed to test to improve the grassland management and service.

Key words: Biomass, Grassland service, Grassland yield, Nutrient limitation, Precipitation, Water limitation.

Introduction

Grassland, covering about 25% of the global land surface, is one of the most widespread vegetation types globally (Shantz, 1995). Grassland ecosystems play a critical role in the ecosystem services and functions (Sala *et al.*, 1996; Weisser *et al.*, 2017), from forage production and development of the livestock industry (Reynolds *et al.*, 2005) to the preservation of biodiversity (Weisser *et al.*, 2017). Across the Eurasian continent, temperate grasslands are widely distributed around the world (Bredenkamp *et al.*, 2002; Kim *et al.*, 2015; Gao *et al.*, 2016). In these regions, grassland productivity is primarily limited by precipitation (Bai *et al.*, 2004; Li *et al.*, 2017). Moreover, with global climate change, it is predicted that the changes of the precipitation regimes are still uncertain; the extremely dry events will increase in future (IPCC, 2013). As a consequence, the ecosystem services provided by grasslands in the arid and semiarid ecosystems are also easily challenged by extremes drought events induced by global climate change. Therefore, artificial irrigation in this region might be an effective way to increase the grassland productivity in normal year, and to prevent large grassland productivity loss in extremely dry year.

The temperate grassland in China covers most area in Northern China (Werger & Van, 2012). There are three type grasslands including meadow, typical, and desert steppes due to reduction of precipitation from east to west along the Northern grassland of China (Werger & Van, 2012). Because of the large variance in precipitation among different steppes, water limitation for grassland productivity might also be different, in which the limitation by water availability would be higher for desert steppe than meadow steppe. Many studies documented that irrigation might elevate the amount and stability of biomass production of grasslands (Dantas *et al.*, 2016; Sanches *et al.*, 2017; Tian *et al.*, 2017). However, few studies tested whether the effects of artificial irrigation on grassland productivity differ among different types of steppe. Therefore, understanding it of response pattern of grassland productivity to artificial irrigation in different grassland type is important for the model projection (Dukes *et al.*, 2014) and grassland management to achieve higher productivity with more efficient and more sustainable irrigation way in the water-limited areas.

To test whether the effects of artificial irrigation on grassland productivity differ among different steppes in China, three controlled water addition experiments were conducted in a site of desert, typical, and meadow steppe, respectively. In each site, 18 plots with 1m^2 were setup, and six irrigation (0, 20, 40, 60, 80, and 100% additional mean annual precipitation) levels were conducted during the growth season. We assessed the biomass production of each plot to test: 1) Does artificial irrigation increase the biomass production of all steppes? 2) Does the effects of artificial irrigation on grassland productivity differ among the three steppes? If so, in which steppe the effect is strongest?

Materials and Methods

Field site: To test the responses of productivities of different grasslands to irrigation, three sites were selected along 44° N in Inner Mongolia, China. All these three sites are located in the Northeast China grassland, in which the mean annual temperature ranges from 0 to 6ºC, the mean annual precipitation (MAT) varies from 130 to 900 mm. The community height, density, and coverage decreased from east to west in this region, with poplar trees (*Populus alba*) only occurred in the wet region (Ni, & Zhang, 2000; Ni, & Wang, 2004). We chose a desert, a typical and a meadow steppe as our study sites (Fig. 1). The first Site (Site I) located in a desert steppe (43°43'N, 113°32'E) in Abag Banner (Fig. 1), in which the mean annual precipitation (MAP) is 215 mm. In this site, the dominant native species were *Leymus chinensis*, *Stipa krylovii* and *Convolvulus ammannii*. The second site (Site II) located in a typical steppe (43°59'N, 115°04'E, Fig. 1) in Xilinhot city, in which the mean annual precipitation is 262 mm. In this site, the dominant native species were *Artemisia pectinata*, *S. krylovii*, and *L. chinensis*. The third site (Site Ⅲ, 44°12'N, 123°56'E) represented the meadow steppe (Fig. 1) in Changling County, in which the mean annual precipitation is 470 mm. In this site, the dominant native species were *L. chinensis* and *S. grandis*. The distance between site I and site II is about 100 km, but Site Ⅲ is more than 900 km away from other two sites.

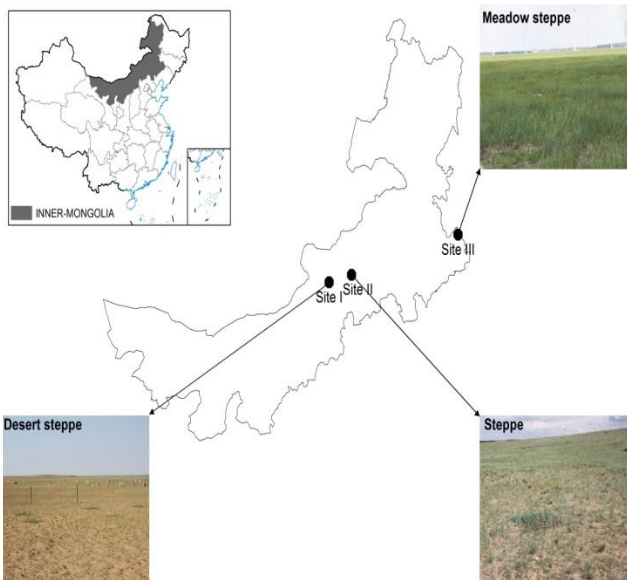

Fig. 1. Overview and locations of the irrigation experiment sites (I, II and III) in 2011.

Experiment details: The study was conducted with manipulative experiment and local observation (Miao *et al.*, 2018). To compare the effects of irrigation on grassland productivities among three sites, similar water addition experiments were conducted at all the sites in 2011. At each site, 18 plots (1m × 1m) were set up in June, with six irrigation levels including 0%, 20%, 40%, 60%, 80%, and 100% of the local mean annual precipitation, and three replicates for each irrigation levels in the experiment site. From June 18 to August 7, the irrigation treatments were supplied five times. Each time, a 1 m^2 mild steel was put to mark the plot boundary on each plot, and groundwater equaling 1/5 amount of the local MAP was supplied to the plot using a watering can. To avoid the water leakage from plots, some soil around the metal frame was piled every time. After the irrigation treatments for one growth season, the aboveground part of all plants in each plot was harvested, oven-dried (500 W, 2 min) immediately, and air-dried for 2 h until the samples had been taken to the lab. After that, all biomass was oven-dried at 65°C (Liu *et al.*, 2018, Sagar *et al.*, 2019) for 48 h, and weighted in the laboratory. The biomass of the dominant species was collected separately, but biomass of other species was collected together in each plot.

Data analysis: All statistical analyses in this study were performed using R 3.3.2 (Team, 2016). To test the effects of irrigation treatments and grassland types on grass productivity, two-way ANOVA were performed for the response variable aboveground biomass production and production of *L. chinensis* of each plot. To test the correlations between biomass production and irrigations, linear regressions were carried out using the lm function in R. Besides, the linear regression analysis for each steppe, loess smoothed fit curves were plotted using ggplot2 (Wickham, 2016) in R.

Results: On an average, irrigation treatments significantly increased the grassland productivity (F = 87.842, df = 1, p<0.001) across all the grassland types (Table 1, Fig. 2). The quantities of irrigation were positively and linearly correlated with biomass production of desert steppe (R^2 = 0.79, p<0.001) at Site I and typical steppe (R^2 = 0.53, p=0.0003) at Site II Fig. 2). The trend was similar for Site III, but the correlation between irrigation and biomass production (R^2 = 0.09, p=0.126) was non-significant (Fig. 2).

Average across the six irrigation treatments, the biomass productions also differed significantly (F = 58.580, df = 2, p < 0.0001) among the three grassland types (Table 1, Fig. 2), showing a trend that meadow steppe produced the most biomass, and desert steppe produced the least biomass (Table 1). The two-way ANOVA also showed that a significant interactive effect (F = 6.685, df = 2, p<0.0027) between irrigation treatment and different grassland type (Fig. 2). For example, 40% irrigation only elevated grassland production by 10.27 g in the desert steppe, but increased grassland production by 78.29 g and 129.73g in the typical and meadow steppe, respectively (Table 2). This means that the positive effects of irrigation on grassland productivity were different among different grassland types. Loess smoothed fit curves indicated that in the meadow steppe, the grassland productivity did not increase anymore with the irrigation after the 40% of local mean annual precipitation addition (Fig. 3). However, the grassland productivity kept increasing in the desert steppe and typical steppe (Fig. 3).

In addition, the production of *L. chinensis* did not significantly varied with treatments or sites (Table 2), possibly because the small number of replicates (only 3 for each treatment) and strong heterogeneity among the replicates. However, when the regression between the production of and irrigation quantity, the production linear increased with the irrigation quantity (R^2 = 0.711, p = 0.035) in the typical steppe (Fig. 4), but did not vary with irrigation quantity in desert (R^2 = 0.018, p = 0.799) and meadow steppe (R^2 = 0.002, p = 0.928) during the experiment (Fig. 4).

Table 1. Mean values (± SE) of grassland production under different treatments at different sites.

Treat	Desert steppe	Steppe	Meadow steppe
0%	8.19 ± 0.88Cd	68.65 ± 7.778Bb	137.73 ± 18.54Ab
20%	12.53 ± 2.11Bcd	94.60 ± 26.75ABb	194.72 ± 43.86Aab
40%	18.46 ± 2.80Cbc	146.94 ± 12.48Bab	267.45 ± 33.31Aa
60%	23.89 ± 3.69Cb	165.51 ± 22.57Bab	225.63 ± 13.45Aab
80%	35.70 ± 3.38Ba	205.24 ± 25.36Aa	208.53 ± 23.05Aab
100%	33.79 ± 3.70Ba	208.20 ± 62.23Aa	217.58 ± 16.84Aab

Note: Different lowercase letters represents significantly differences among the treatments in the same site. Different capital letters represents significantly differences among the sites in the same treatment

Table 2 Mean values (± SE) of production for *L. chinensis* under different treatments at different sites.

	Desert steppe	Steppe	Meadow steppe
0%	1.07 ± 0.46Ba	13.05 ± 8.88Ba	39.97 ± 5.61Aa
20%	1.00 ± 0.21Ba	26.15 ± 1.97ABa	95.09 ± 39.18Aa
40%	1.93 ± 0.82Ba	27.46 ± 9.49Ba	91.74 ± 16.71Aa
60%	1.79 ± 1.04Ba	30.21 ± 12.71Ba	74.11 ± 17.70Aa
80%	1.42 ± 0.42Ca	31.81 ± 7.12Ba	61.20 ± 11.43Aa
100%	1.05 ± 0.22Ca	31.24 ± 11.19Ba	58.19 ± 3.90Aa

Note: Different lowercase letters represents significantly differences among the treatments in the same site. Different capital letters represents significantly differences among the sites in the same treatment

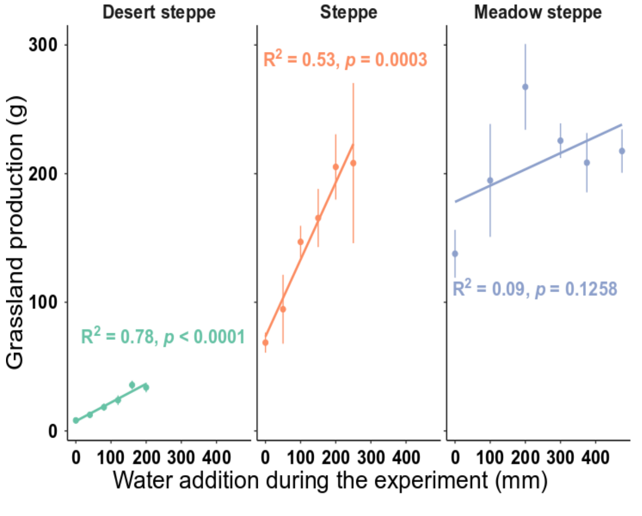

Fig. 2. Response patterns of grassland productivity to artificial irrigation at the three different grassland types. The R^2 and p values represent the statistical analysis of linear regression for each steppe.

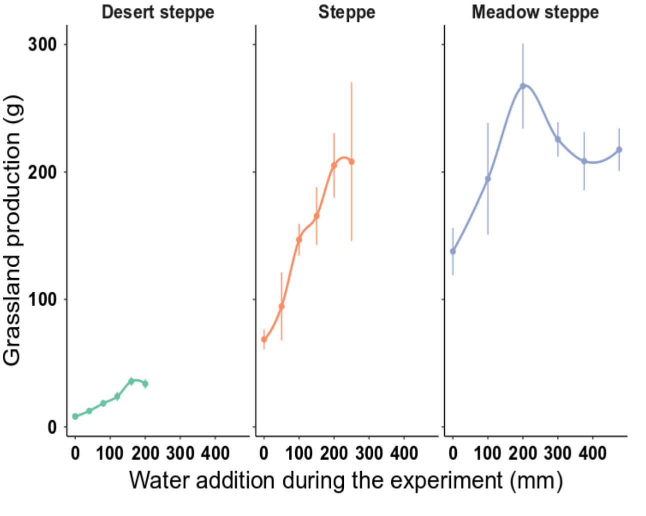

Fig. 3. Response patterns of grassland productivity to artificial irrigation at the three different grassland types. The loess smoothed fit curves were added by the package ggplot2 in R.

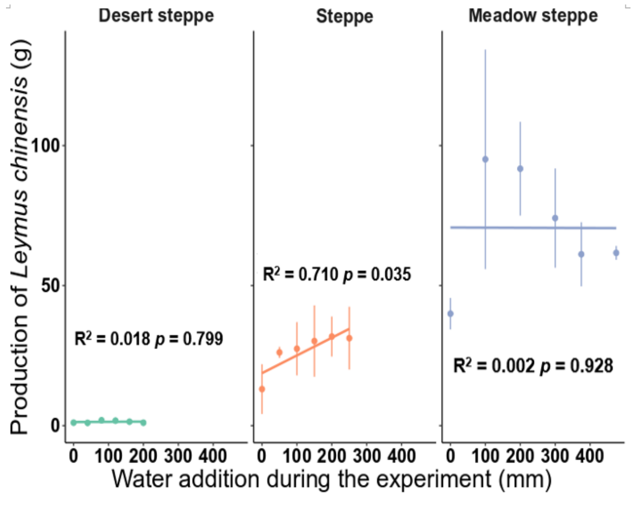

Fig. 4. Response patterns of production for *L. chinensis* to artificial irrigation at the three different grassland types. The R^2 and p values represent the statistical analysis of linear regression for each steppe.

Discussion

It is frequently suggested that precipitation limits the grassland productivity of temperate steppes (Bai *et al.*, 2004; Ren *et al.*, 2017). Our finding supported it, showing that artificial irrigation had strong positive effects on grassland productivities of the three steppes. Double precipitation increased grassland production by 312.37% and 203.29% in the desert and typical steppe (Table 1), respectively. Although double precipitation did not significantly elevate production, 40% MAP irrigation significantly elevated grassland production by 94.18% in the meadow. However, as expected, the effects of irrigation differed among desert, typical, and meadow steppe. The effect was stronger (0.60 g mm^{-1} MAP) in typical than it in desert (0.14 g mm^{-1} MAP) and meadow (0.13 g mm^{-1} MAP) steppe. We also found that the aboveground productivity in the meadow steppe was higher than that in other two steppes, and the aboveground productivity in typical steppe was higher than the desert steppe (Fig. 2).

No surprising, irrigation could significantly promote the aboveground productivity of different grassland. Grassland primary production could be affected by many factors (for example, climate warming (Lin *et al*., 2010), soil nitrogen and phosphorus condition (Wang *et al*., 2014) and water availability (Lauenroth, 1979; Wu *et al*., 2011). However, soil water availability is the primary factor which can regulate pant growth and productivity in the temperate grassland of northern China (Lauenroth, 1979; Wu *et al*., 2011; Song *et al*., 2016). Our results further corroborate many previous studies (Bai *et al*., 2008; Wu *et al*., 2011; Sala *et al*., 2012), showing that aboveground productivity of such ecosystems usually exhibits close positive correlations with precipitation increases. Furthermore, we also found that the aboveground productivities differ between the three types, with the trend that meadow steppe produced the most biomass and desert steppe produced the least biomass. This is because that the mean annual precipitation was highest for the meadow steppe, whereas lowest for the desert steppe.

We also found that the effects of irrigation on aboveground productivity differed among the three steppes, although irrigation could increase the productivity of all studied steppes. The positive effect of irrigation on productivity in the typical steppe was stronger than it in the desert or meadow steppe. Generally, the water limitation is strongest for the desert steppe than for the typical and meadow steppe (Guo *et al*., 2006; Liu *et al*., 2013; Liu *et al*., 2014). The increase effect of irrigation on grassland productivity should be stronger for desert steppe than for typical steppe or meadow steppe. Three possible reasons can explain this pattern. First, as the site description, the plant composition is different among the three sites. Different sensibility among various plant species to irrigation may lead to different response pattern of grassland production among the grassland types. Second, even though *L. chinensis* is the same dominant species in the three sites. It linearly increased in the typical steppe, but did change in other two grasslands with increasing irrigation quantity (Fig. 4). Third, the plant biodiversity of the desert steppe is generally lower than others. Species diversity was higher in the desert than it in the meadow steppe in Inner Mongolia grasslands (Zhang *et al*., 2014). A well-replicated field experiment showed that ecosystem productivity significantly enhanced with plant biodiversity in 147 grassland plots (Tilman *et al*., 1996). Therefore, both the water limitation and plant biodiversity drive the different responses of grassland productivity to irrigation we found among the three steppes.

While our results indicate that artificial irrigation significant increase the grassland productivity, it seems also a threshold for the effects on productivity increases, which can be approved by the not increased grassland productivity with the irrigation after the 40% (Table 1, Fig. 3). For the steppe in desert and semiarid (typical) area, the thresholds were not obvious, it possibly because the water limitation were stronger for them than meadow steppe, and our irrigation levels were still not enough. This is likely because that soil available nutrient usually regulates the responses of grassland productivity to water availability in the temperate steppe (Wstanley *et al*., 2007; Bai *et al*., 2008; Liu *et al*., 2018), because nutrient availability is an important factors for plant growth and other ecosystem parameters (Chen *et al*., 2011; Xia & Wan, 2013; Zhao *et al*., 2015; Kong *et al*., 2017; Zhang *et al*., 2018). With the artificial irrigation increase, the source limitation on grassland productivity would vary from the water to nutrient, and thus the productivity did not increase anymore. Although this idea seems to find general support (Bai *et al*., 2008; Wstanley *et al*., 2007; Liu *et al*., 2018), further studies are still needed to test how the water (i.e. irrigation) interacts with the soil nutrient to affect grassland productivity among different steppe, which is also useful for the grassland management and services.

Conclusions

In conclusion, artificial irrigation could increase the grassland productivity by 10.27 to 139.55 for the three types of steppe, but its increase effects were different among different steppes. For the typical steppe, artificial irrigation could increase more productivity than other steppes, possibly because the different plant community structure and different responses of production for dominant species among the three sites. Further studies are still needed to test it, and also needed to the interactions between water and nutrient on grassland productivity among these different steppes to improving the grassland management and service.

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