Impacts of future climate change on Net Primary Productivity of grassland in Inner Mongolia, China

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Abstract. Net Primary Productivity (NPP) of grassland is a key variable of terrestrial ecosystems and is an important parameter for characterizing carbon cycles in grassland ecosystems. In this research, the Inner Mongolia grassland NPP was calculated using the Miami Model and the impact of climate change on grassland NPP was subsequently analyzed under the Special Report on Emissions Scenarios (SRES) A2, B2, and A1B scenarios, which are inferred from Providing Regional Climates for Impacts Studies (PRECIS) climate model system. The results showed that: (1) the NPP associated with these three scenarios had a similar distribution in Inner Mongolia: the grassland NPP increased gradually from the western region, with less than 200 g/m^2/yr, to the southeast region, with more than 800 g/m^2/yr. Precipitation was the main factor determining the grassland NPP; (2) compared with the baseline (1961-1990), there would be an overall increase in grassland NPP during three time periods (2020s: 2011-2040, 2050s: 2041-2070, and 2080s: 2071-2100) under the A2 and B2 scenarios; (3) under the A1B scenario, there will be a decreasing trend at middle-west region during the 2020s and 2050s; while there will be a very significant decrease from the 2050s to 2080s for middle Inner Mongolia; and (4) grassland NPP under the A1B scenario would present the most significant increase among the three scenarios, and would have the least significant increase under the B2 scenario.

Keywords: Net Primary Productivity, grassland, PRECIS, Inner Mongolia.

Introduction

Grassland ecosystems are one of the most important and widespread ecosystems, accounting for approximately 20% of the earth's land surface (Scurlock and Hall 1998), and play a significant role in the global carbon cycle and climate regulation (Hall *et al.* 1995; Scurlock and Hall 1998; Fan 2008). The 392 million hectares of grasslands in China provide approximately 16.3% of the world's total grassland. The grassland in Inner Mongolia covers about 79.2 million hectares, accounting for 20% of the grasslands in all of China, making it one of the largest grassland regions in the world, and the largest grazing area in China (Ni 2004; Kawamura *et al.* 2005; Ma *et al.* 2008; Zhang *et al.* 2011). As a key region of the Europe-Asia steppe, the Inner Mongolia grassland is an important natural resource for husbandry, and serves as an ecological barrier in northern China. It is an extremely valuable resource to the agricultural industry, providing a significant percentage of forage for 9.2 million heads of livestock (Zhao *et al.* 2005).

Net Primary Productivity (NPP) is the rate at which carbohydrates are accumulated in the plant's tissue in an ecosystem, and usually, units of energy or biomass (per unit of area and per unit of time) are used as measures of net primary productivity. Net primary productivity provides a link between the biosphere and the climate system through the global cycling of carbon, water and nutrients and is a critical indicator of carbon sink and ecological regulatory behaviour for the secondary production of an ecosystem (Roy and Saugier 2001; Gao 2009). Grassland NPP in Inner Mongolia is extremely sensitive to inter-annual variation in climate, land-use change grazing, and anthropogenic activities (Xiao *et al.* 1995). Recent climate change has exerted significant influences on terrestrial ecosystems and impacts are projected to be even greater in the future (Yu *et al.* 2012). Zhang *et al.* (2011) pointed out that ecosystem productivity in Inner Mongolia from 1956 to 2006 decreased due to severe water deficiency, which resulted from the decreased precipitation and the subsequent increase in temperature and potential evapotranspiration. Zhao (2007) also reported that the drier and warmer climate caused the average forage productivity to decrease from 1951 to 2005 in the typical steppe area. However, the research into the future climate change impact on the grassland NPP in Inner Mongolia is relatively limited (Niu 2001; Buhe *et al.* 2003); this is an important topic for future studies.

In 1996, the Intergovernmental Panel on Climate Change (IPCC) began to develop a new set of emissions scenarios, to update and replace the IS92 scenarios (the emission scenarios developed for the 1992 Supplementary Report to the IPCC Assessment). The approved new set of scenarios is described in the IPCC Special Report on Emission Scenarios (SRES). Four different narrative storylines (A1, B1, A2, and B2) were developed to describe the relationships between the forces driving emissions and their evolution, and to add context for the scenario quantification. The A2 scenario refers to a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other scenarios. The B2 scenario illustrates a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (but lower than the A2 scenario). The intermediate economic A1B scenario is one of the three A1 groups, which describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The A1B scenario is a balance across all sources (Nakićenović 2000).

Therefore, it is essential to assess the climate change impact on grassland NPP in the context of global environmental change studies and adaptation to climate change, and important to assess forage quality in grassland management. The objectives of our study are: first, to estimate the distributions of grassland NPP in all of Inner Mongolia under different climate scenarios; second, to analyze the trends of NPP change under different scenarios; finally, to discuss some effective strategies to enhance the sustainable utilization of grassland resources.

Materials and Methods

Study area

The study was conducted in the Inner Mongolian region, located in northern China, extending from about 40 to 50°N and 107 to 125°E (Fig. 1). From northeast to southwest, the mean annual temperature (MAT) increases from -5°C to 9°C and the annual precipitation (MAP) decreases from 600 mm to less than 100 mm. The area experiences more than 2700 h of sunshine, and the frost-free period is 80 to 150 days per year. It is mainly controlled by temperate continental climate, with cold, dry winters and warm, rainy summers. Most of the rainfall occurs from May to September, coinciding with high temperatures. The occurrence of both high moisture and temperature contributes to higher rain-use efficiency than most other areas in the semi-arid and arid region (Yu *et al.* 2004; Ma *et al.* 2008; Zhang *et al.* 2011). From east to west, the grasslands can be classified as meadow steppe, typical steppe, and desert steppe.

Data collection

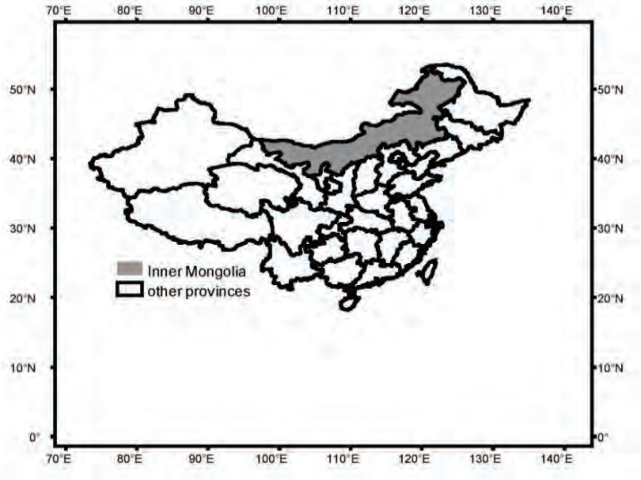

Figure 1 Study region, Inner Mongolia, China.

The climatic data of the three IPCC SRES A2, B2, and A1B scenarios used in this study was derived by PRECIS (Providing Regional Climates for Impacts Studies) and the nested global circulation model HadCM3. The PRECIS model is a regional climate model system (GCMs) developed by the UK Met Office Hadley Centre for Climate Prediction and Research and introduced to China in 2003 to develop high-resolution (50 × 50 km) SRES climate change scenarios (A2, B2, A1B) of China (Zhang *et al.* 2006). There are 145 grids in longitude and 112 grids in latitude, and the horizontal resolution is 0.44 × 0.44° in rotation coordinates. The baseline data (1961-1990) was employed to evaluate the model’s capacity for simulating the present climate compared with the observations (Xu *et al.* 2006).

Generally speaking, PRECIS can simulate the climate of China, and it also can simulate the mean annual surface air temperature and mean annual precipitation in China (Xu and Richard 2004; Xu *et al.* 2006). The mean air temperature distribution of Inner Mongolia over 30 years (from 1961 to 1990) was expressed well by the PRECIS model, especially the trend of increasing temperature from the northeast to the southwest parts of this region (You *et al.* 2009). In this study, the baseline was considered as the present climate, and the mean annual temperature and the mean annual precipitation in Inner Mongolia were the main climate factors used to simulate the future climate change compared with the baseline.

Miami Model

A variety of climate-based models, including the Miami model, the Thornthwaite memorial model (Lieth 1977), Chikugo model (Uchijima and Seino 1985), and the Synthetic model (Zhou and Zhang 1995) have been used to evaluate the distribution of NPP in China and its responses to global climate change (He 1986; Chen 1987; Hou and You 1990; Zhang and Yang 1990; Xu *et al.* 1994). Of the various methods for calculating the NPP, the Miami Model is one of the most popular and mature methods. This model was produced by H. Lieth, given at the Second Congress of American Institute of Biological Sciences, Miami, 1971 (Lieth H 1973; Yang

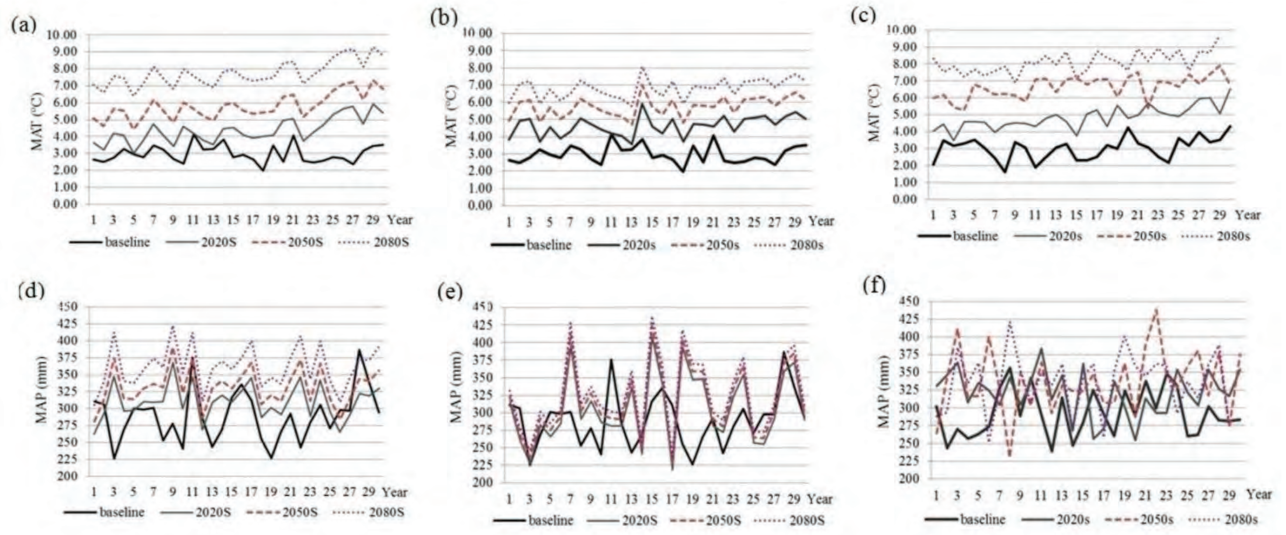

Figure 2. Temporal evolutions for the future climate change (2020s, 2050s, and 2080s) of the Inner Mongolia region under the A2, B2, and A1B scenarios, (a)-(c) are for the mean annual temperature (MAT) of the A2, B2, and A1B scenarios, respectively, and (d)-(f) are for the mean annual precipitation (MAP) of the A2, B2, and A1B scenarios, respectively.

and Yang 2000). The formulas are as follows:

$$Y_T = 3000 / (1 + e^{(1.315 - 0.119\,T)}) \quad (1)$$

$$Y_R = 3000\,(1 - e^{(-0.000664\,R)}) \quad (2)$$

Where Y_T, Y_R refers to the grassland potential productivity according to mean annual temperature and mean annual precipitation, respectively, in unit g/m^2/yr. Finally, according to Liebig's restrictive factor law, the local productivity is controlled by the smaller of either Y_T or Y_R (Chen 1987), so we chose the smaller result as the grassland NPP at Inner Mongolia. Chen used the Miami Model to calculate the primary production of the ecosystem in China. The Miami Model was also applied to analyse the net primary productivity of the natural grassland from 2000 to 2009 in Qinghai Province (Cang 2011). In this study, we chose the Miami Model to calculate the NPP of grassland in Inner Mongolia.

NPP increasing rate

In this study, the increasing rate of grassland NPP was introduced to illustrate the vulnerability of different areas influenced by climate change. The formula for the rate of NPP increase is:

$$(NPP_P - NPP_{BS}) / NPP_{BS} \quad (3)$$

Where NPP_p refers to the NPP of three periods (2020s, 2050s, and 2080s) under the A2, B2, and A1B scenarios, respectively, NPP_{BS} refers to the NPP of baseline (1961-1990) under the A2, B2, and A1B scenario, respectively. The NPP would increase when the increasing rate is more than zero, while it would decrease when the increasing rate is less than zero.

Data analysis

Mean annual temperature (MAT) and mean annual precipitation (MAP) were the main climatic factors controlling NPP in the Miami Model. In this research, we calculated MAT and MAP based on the daily temperature and precipitation data from year 1961 to year 2100, and subsequently used these calculated results to simulate NPP for each year. Inverse Distance Weighing (IDW), which is an interpolation technique that estimates cell values in a raster from a set of sample points that have been weighted, was applied to map the spatial distributions of grassland NPP and the NPP increasing rate in Inner Mongolia, respectively.

Results

Climate changes in the entirety of Inner Mongolia

The MAT and MAP for Inner Mongolia were analyzed in this study. Figure 2 demonstrated to us that there would be an overall increasing trend for MAT and MAP. Under the A2 and B2 scenarios, the MAT has a similar trend during each period, while under the A1B scenario, the MAT doesn't show the same trend compared with the former scenarios. Under the A2 scenario, there are three significant increasing periods after year 2032, 2062, and 2092, during 2020s, 2050s, and 2080s, respectively. Under the B2 scenario, there are three decreasing periods, from year 2018 to 2023, from year 2048 to 2053, and from year 2078 to 2083, during 2020s, 2050s, and 2080s, respectively; and from year 2023, 2053, and 2083, there are three sharp increases. Then after year 2023, 2053, and 2083, there are three very slight increases during 2020s, 2050s, and 2080s, respectively. The MAP shows the same variation trend during each period, under the A2 and B2 scenarios, while under all three scenarios, the MAT depicts a more extremes fluctuation indicating that the occurrence of drought events or extreme precipitation events are projected to be more frequent, especially under the B2 and A1B scenarios.

Compared with the baseline MAT, it can be seen that the 30-year average value of MAT under the A2 scenario during 2020s (2011-2040), 2050s (2041-2070), and 2080s (2071-2100) would increase by 1.4°C, 2.8°C, and 4.8°C, respectively, and under the B2 scenario this value would increase by 1.7°C, 2.8°C, and 3.8°C,

Table 1. The increase of MAT and MAP under the three scenarios relative to the baseline

	Mean Annual Temperature (°C)			Mean Annual Precipitation (mm)		
	2020s	2050s	2080s	2020s	2050s	2080s
A2	1.4	2.8	4.8	7.5%	15.0%	25.0%
B2	1.7	2.8	3.8	5.8%	9.6%	13.2%
A1B	1.8	3.6	5.1	9.6%	15.1%	15.0%

respectively, and under the A1B scenario it would increase by 1.8°C, 3.6°C, and 5.1°C, respectively. The MAP displays a more obvious volatility than MAT, with an increase in precipitation of 7.5%, 15.0%, and 25% under the A2 scenario during 2020s, 2050s, and 2080s, respectively, and a rate of 5.8%, 9.6%, and 13.2% under the B2 scenario, respectively, and a rate of 9.6%, 15.1%, and 15.0% under the A1B scenario, respectively. From Table 1, we can conclude that MAT has the most obvious increase under the A1B scenario, and has the least obvious increase under the B2 scenario, while the MAP has the most significant increase under the A2 scenario, and has the least increase under the B2 scenario. Hence, the MAP, under the B2 scenario, has the least increase with the most significant volatility. Under the A1B scenario, the MAP was observed to slightly decrease to some extent (Figure 2 and Table 1).

Grassland NPP in Inner Mongolia under three climate scenarios

Table 2 provides the mean NPP and the range of NPP over Inner Mongolia under three scenarios. From the mean NPP we can see that there would be a significant increasing trend under the A2 scenario, and the least significant increasing trend under the B2 scenario. In addition, the minimum and maximum values of NPP would increase, with the most significant increasing trend under the A2 scenario, and the least significant increase under the A1B scenario, for the minimum values of NPP, and with the significant increasing trend under the A2 scenario, and the least significant increase under B2 scenario, for the maximum values of NPP. The range of NPP could illustrate us that the NPP at different regions would have a great difference under these three scenarios.

Spatial distribution of MAP under three scenarios in Inner Mongolia

Figure 3 illustrated us the spatial distribution of in Inner Mongolia, with a similar gradient under the three scenarios, decreasing gradually from east to west and from south to north. There is the lowest annual precipitation at the southwest region, and the highest annual precipitation at the northeast region. Along the gradients, MAP increases from less than 100 mm in the west region to more than 500 mm in the northeast region. Compared with the baseline MAP, there would be an overall increasing trend as for other three periods, under A2 and B2 scenarios, while there would be a significant decrease at the southeast region from 2050s to 2080s, under A1B scenarios.

Spatial distribution of NPP under three scenarios in Inner Mongolia

In Inner Mongolia, grassland NPP under the three scenarios resulted in a similar distribution gradient, with it decreasing gradually from east to west and from south to north, with the lowest NPP in the southwest region, and the highest NPP in the southeast region (Fig. 4). Along the gradients, NPP increased from less than 200 $g/m^2/yr$ in the northwest region to more than 800 $g/m^2/yr$ in the southeast region, which revealed there was a big difference between NPP in the southwest area and the northeast area. Compared with the NPP used for our baseline, the NPP of 2020s, 2050s, and 2080s showed an overall increasing trend, respectively, under each scenario. Under the A2 scenario, NPP in the west region, northeast region and southeast region has a very obvious increase. Under the B2 and A1B scenarios, NPP in the western Inner Mongolia and the northern Inner Mongolia has a very obvious increase.

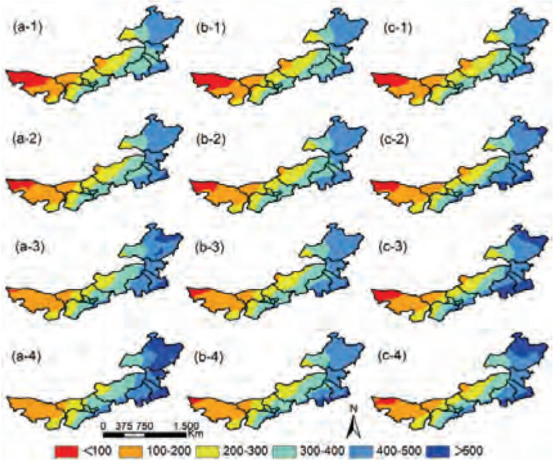

Figure 3. Spatial distribution of MAP (mm) in Inner Mongolia under the A2 scenario ((a-1), (a-2), (a-3), (a-4) of baseline, 2020s, 2050s, 2080s, respectively), B2 scenario ((b-1), (b-2), (b-3), (b-4) of baseline, 2020s, 2050s, 2080s, respectively), and A1B scenario ((c-1), (c-2), (c-3), (c-4) of baseline, 2020s, 2050s, 2080s, respectively.

Table 2 Grassland NPP in Inner Mongolia under three climate scenarios.

time range	Net primary productivity ($g/m^2/yr$)					
	A2		B2		A1B	
	mean	range	mean	range	mean	range
Baseline	452.4	87.7-852.7	452.4	87.7-852.7	458.1	124.5-864.1
2020s	496.4	135.9-936.6	490.7	117.2-869.9	515.6	143.6-997.8
2050s	539.3	174.4-995.4	517.3	136.1-882.8	548.7	137.3-1084.7
2080s	596.6	222.7-1073.1	541.9	154.1-898.1	559.2	164.4-1061.5

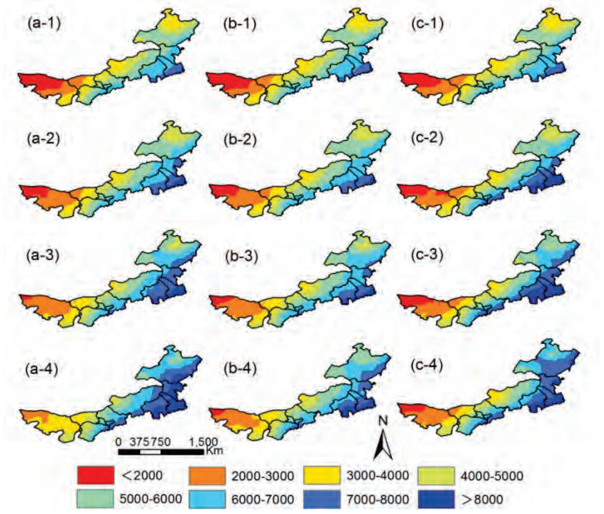

Figure 4. Spatial distribution of grassland NPP (kg/ha) in Inner Mongolia under the A2 scenario ((a-1), (a-2), (a-3), (a-4) of baseline, 2020s, 2050s, 2080s, respectively), B2 scenario ((b-1), (b-2), (b-3), (b-4) of baseline, 2020s, 2050s, 2080s, respectively), and A1B scenario ((c- 1), (c-2), (c-3), (c-4) of baseline, 2020s, 2050s, 2080s, respectively)

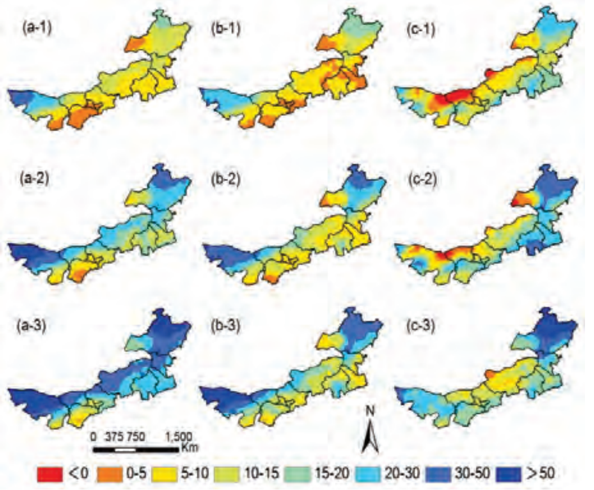

Figure 5. The spatial distribution of the rate of NPP increase (%) in Inner Mongolia under the A2 scenario ((a-1), (a-2), (a-3) of 2020s, 2050s, 2080s, respectively), B2 scenario ((b-1), (b-2), (b-3) of 2020s, 2050s, 2080s, respectively), and A1B scenario ((c-1), (c-2), (c-3) of 2020s, 2050s, 2080s, respectively)

Change trend of grassland NPP in Inner Mongolia compared with baseline

The increasing rate of grassland NPP in Inner Mongolia is calculated under the three scenarios respectively (Fig. 5), which is able to depict the different change in the level of grassland NPP more directly. From Figure 5, we can conclude that there will be a trend of increasing grassland NPP in Inner Mongolia under the A2 and B2 scenarios, and grassland NPP at the western and the northern Inner Mongolia would have the most significant increasing rate, which illustrates that grassland there is predicted to be subject to warmer and wetter conditions, while extreme precipitation events at the north region of Inner Mongolia would be more frequent because of the increasing precipitation. Under the A1B scenario, the grassland NPP in most of the region has an increasing trend, except the central region of Inner Mongolia, where grassland NPP decreased by 13%, 6%, and 2% during 2020s, 2050s, and 2080s, respectively. From 2050s to 2080s, there will be a very significant decreasing trend of NPP at the central region of Inner Mongolia. Grassland NPP has the biggest variation under the A1B scenario, which indicates that grassland would get more sensitive to the future climate change under this scenario.

Discussion and Conclusions

Using the Miami Model and the PRECIS climate dataset, we estimated the Inner Mongolia grassland net primary production and the impact upon it of future climate change under the A2, B2, and A1B scenarios. Based on the analysis, we draw the following conclusions: (1) there will be an overall trend of increase in both MAP and MAT (Figure 2, Figure 3 and Table1), which indicates that the future climate of Inner Mongolia could get warmer and wetter. This result agrees with previous studies (Ma *et al.* 2011) that concluded that MAT under SRES A1B in Inner Mongolia would increase, and that high temperature events might also rise, and heavy precipitation events may also increase. Zhang *et al.* (2006) also claimed that there would be a trend toward wetter conditions over Northern China in the future as the GHG (Green House Gas) concentration increases. Following the B2 scenario, the temperature will have an increase trend in year 2071 to 2100 (You *et al.* 2009). Under the A1B scenario, surface air temperature increases significantly for both the middle and end of the twenty-first century, and the rainfall also has a significant increase in the twenty-first century, especially for the period 2070–2099 (Chen and Jiang 2011); (2) net Primary Production is an important indicator of an ecosystem’s health and ecological balance, as well as a key element for determining carbon sink and ecological regulatory behaviour, which is a very important topic in the climate change research area. In this study, the spatial distribution and the changes of grassland NPP in Inner Mongolia under three scenarios was estimated based on the Miami Model. The grassland NPP under the three scenarios showed a similar distribution gradient, with the lowest NPP in the west region, and the highest NPP in the southeast region, which illustrated the similar gradient with the mean annual precipitation (Figures 3 and 4). Our research is consistent with the general conclusions. Compared with temperature, precipitation is the dominant factor (Zhao *et al.* 2008), and in arid and semiarid ecosystems, water is considered as the most important factor affecting the NPP. NPP was significantly related to both annual and seasonal precipitation but not to temperature (Lauenroth and Sala 1992; Zhang *et al.* 2011). It’s also widely accepted that increasing precipitation promotes the aboveground production of temperate grasslands in China (Ni 2004; Fang *et al.* 2005); and (3) there is an overall increasing trend of the grassland NPP in the entirety of Inner Mongolia under the A2 and B2 scenarios, with the most significant increase in the western Inner Mongolia and the northern Inner Mongolia. The grassland NPP of the middle-west region would decrease during the 2020s and 2050s under the A1B scenario, and other areas would have an overall increase, while from the 2050s to 2080s, grassland NPP for the middle region would decrease very significantly under the A1B scenario.

This finding provides evidence of some brief future changes of grassland NPP in Inner Mongolia, which can suggest that the government should begin taking measures and creating policy accordingly. However, due to the uncertainties of the future climate data and the low accuracy of the Miami Model, we only can illustrate an overall and brief change trend of the NPP, and could not estimate the relationship between precipitation in different seasons and the NPP. Hence, the use of models with much higher accuracy should be applied to estimate the seasonal change of grassland NPP, which should be a hot topic in the study of the impacts of future climate change on ecosystems.

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