Responses of Grassland Net Primary Productivity to Environmental Variables in Northern China

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Abstract: Various environmental factors affect net primary productivity (NPP) of grassland ecosystem. Extensive reports on the effects of environmental variables on NPP can be found in literature. However, the agreement on the relative importance of various factors in shaping the spatial pattern of grassland NPP has not yet been reached. Here a grassland in situ NPP database comprising 602 samples in northern China for 1980–1999 was developed based on a literature review of published biomass and forage yield field measurements. Correlation analyses and dominance analysis were used to quantify the separate and combined effects of environmental variables (climate, topography and soil) on spatial variation in NPP separately. Grassland NPP ranged from 4.76 g C m⁻²a⁻¹ to 975.94 g C m⁻²a⁻¹, showing significant variations in space. NPP increased with annual precipitation and declined with annual mean temperature significantly. Specifically, precipitation had the greatest impact on deserts, followed by steppes and meadows. Grassland NPP decreased with increasing altitude because of water limitation, and positively correlated with slope, but weakly correlated with aspect. Soil quality showed positive effects on NPP. Annual precipitation was the dominant factor affecting the spatial variability of net primary productivity, followed by elevation.

Key words: Grassland net primary productivity; Field measurements; Environmental variables; Dominant factor; Northern China

1 Introduction

Grassland net primary productivity (NPP) is an important component of the global carbon cycle (Parton et al. 1995; Scurlock and Hall 1998; Ma et al. 2010). Spatial and temporal variability of grassland NPP depends on complicated interaction between climate, topography, soil and vegetation (Schimel et al. 2001). Thus studying the impact of environmental variables on NPP, single or in combination, is therefore very important to understand the mechanism between them and to allow the spatial prediction of NPP.

The effect of climate change on NPP has been a scientific focus during the past decades (Nemani et al. 2003; Huxman et al. 2004; Bai et al. 2008; Hsu 2011; Guo et al. 2012). However, the relationship between them remains unclear (Guo et al. 2012), especially to their combined effects (Wu et al. 2011). More efforts on this topic are required to verify the current conclusions. While recent studies on this topic have mostly focused on the impact of interannual variability of climate on NPP (Yang et al. 2008), the effect of the spatial pattern of climate variables (Wang et al. 2008) has received less attention. We therefore study the spatial responses of grassland net primary production to climatic...
variables with a large number of NPP observations. Along with climate variables, many other factors influence the productivity of an ecosystem, including soil properties, topography, and biodiversity (Luck 2007; Vanderbi 2010). Topography is an important variable that impacts NPP by influencing the water redistribution over the landscape (Chen et al. 2013; Gao et al. 2013). Soil quality is simply defined as the capacity of soil to provide nutrition to plants, and to absorb and drain water, which largely determines grass growth.

A broad range of models for estimating NPP has gained broad acceptance for making spatially detailed estimates for large regions (Cramer and Field 1999). Furthermore, estimated NPP is widely used to explore the response of NPP to environmental conditions (Wang et al. 2008; Gerten et al. 2008). Based on the recent comparison of such models, the spatial pattern of NPP and its response to major climatic variables are similar in most areas (Cramer et al. 1999). However, the models differing in the spatial and seasonal distribution of simulated NPP and the sensitivities of NPP to climate are also illustrated (Cramer et al. 1999; Ruimy et al. 1999; Bondeau et al. 1999). Schloss (1999) has implied the largest difference in sensitivities occurred in regions with NPP limited by both temperature and precipitation. So field data on the relation of NPP to environmental factors are needed to resolve these uncertainties.

While impacts of environmental conditions on grassland net primary productivity has been considered in previous studies, the agreement on the relative influence of these variables has not yet been reached. Furthermore, large amount of field observations are important for exploring the relation between grassland NPP and environmental conditions to reduce the uncertainty of models. We therefore developed a grassland NPP database for northern China spanning 1980–1999 consisting of 602 samples based on field measurements of biomass and forage yield collated from literature published until 2012. We examined the spatial patterns and correlation of NPP with environmental variables, including climate, topography and soil quality. Dominance analysis was used to compare the relative contribution of each environmental variable. The specific objectives were: (1) based on large amount of in situ measurements, to examine the relationship of environmental variables and grassland net primary productivity separately at site scale in Northern China? (2) to perform dominance analysis on environmental variables on grassland NPP, and investigate the relative importance among the variables.

2 Materials and methods

2.1 Study area

Northern China refers to the arid to semi-arid region covering Xinjiang, Inner Mongolia, Ningxia and most of Gansu (73.50° to 126.08°E and 34.34° to 53.33°N, Fig. 1). The elevation varies greatly from -188 m to 7670 m. With a total area of 3.08×10^6 km^2, 67.21% of this region is grassland mainly consisting of three types: steppes, meadows and deserts. The three dominant soil types are sandy, chestnut, and brown desert soil, accounting for 37.88% of the area. With a typical arid and semi-arid continental climate, the annual precipitation in this area ranges from 14.81 to 555.8 mm and the annual mean temperature ranges from −4.66 to 14.75°C.

2.2 NPP observations

NPP is estimated from biomass and forage yield data, which were measured or estimated in field studies during 1980 to 1999 obtained from journals and reports. In total, 602 samples were selected based on the following criteria: (1) no obvious human influence, such as grazing, firing or harvesting; (2) within a normal detection range; (3) the vegetation type was consistent with the grassland type map; (4) with records of either biomass or yield data. Samples that did not meet all criteria were not considered for further analysis.
cases where multiple samples were available for a site in 1 year, the sample with the maximum value was used for the analysis. In addition to the biomass and forage yield data, all available information including the location, environment, sampling, biotic factors and data source was recorded (Table 1).

### 2.3 Environmental datasets

#### 2.3.1 Climate data

Precipitation and temperature are the main climate factors controlling vegetation growth and distribution (Gomez-Mendoza et al. 2008). It is also demonstrated that elevation has a marked impact on precipitation (Goovaerts 2000) and temperature (Hong et al. 2005). Annual gridded datasets of precipitation and temperature were constructed from interpolating precipitation and temperature station datasets (125) provided by the China Meteorological Data Sharing Service System (http://cdc.nmic.cn/) using the cokriging method based on elevation (Fig. 2a and 2b). The climate factors at the sampling sites were then extracted by overlaying maps of climate prediction and sample location to analyze the site-specific relationships of NPP and the climate variables.

#### 2.3.2 Topography data

By affecting spatial variations of climatic variables, soil water movement and soil temperature, topography has a considerable effect on vegetation productivity (Chen et al. 2007). A 90-m resolution digital elevation model (DEM) provided by Geospatial Data Cloud (http://www.giscloud.cn/) was incorporated into the spatial prediction of the climate variables. Additionally, topographic variables (Fig. 2c, 2d

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**Table 1  Data collection of grassland field measurements**

<table>
<thead>
<tr>
<th>Category</th>
<th>Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>site name; latitude; longitude; altitude</td>
</tr>
<tr>
<td>Environmental factors</td>
<td>mean annual temperature; mean annual precipitation; soil type; topography</td>
</tr>
<tr>
<td>Sampling</td>
<td>sampling time; sample size; method</td>
</tr>
<tr>
<td>Biotic factors</td>
<td>grassland type; dominant species; biomass data; forage yield; root-shoot ratio</td>
</tr>
<tr>
<td>Data source</td>
<td>title; journal; publication year</td>
</tr>
</tbody>
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Fig.2  Spatial distribution maps of the environmental variables (1980-1999): a. annual mean temperature; b. annual precipitation; c. elevation; d. slope; e. aspect; f. soil quality
and 2e), such as elevation, slope and aspect derived from DEM, were analyzed to investigate the dependence of NPP on topography. Altitude was grouped into five levels: <500 m, 500-1000 m, 1000-1500 m, 1500-2000 m, and >2000 m. Slope was divided into four groups: <3°, 3-8°, 8-15°, and >15°. Aspect was reclassified into eight classes: north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W) and northwest (NW).

2.3.3 Soil quality
Soil quality data, extracted from the Land Resources map of China at a scale of 1:10,000,000 (Shi 1989), were classified into four levels representing the quality of the grassland (Fig. 2f). Level one represented the best quality land for grass growth, level two represented the moderate quality soil, and level three indicated the poorest quality soil. Level four represented the unsuitable land for grass growth. In the dominance analysis, soil quality was considered as a categorical variable.

2.4 Methods

2.4.1 Biomass estimation method
Biomass is defined as above-ground (the sum of live matter, standing dead matter and litterfall) and below-ground (the sum of dead and live roots) biomass. Total biomass was calculated by summing the above-ground and below-ground values. Two methods were applied to fill any data gaps for components in the total biomass calculation. The first method estimated the missing data for a specific component by comparing the ratio of components in samples with a complete biomass measurement. The second method applied the ratio of below- to above-ground biomass of grassland (Piao et al. 2004) to estimate the above- or below-ground biomass.

For the forage yield data, biomass was calculated by subtracting forage yield from the water content in air-dry grass (Fang et al. 1996).

2.4.2 NPP estimation method
A series of grassland NPP estimation algorithms from biomass measurements are described by Scurlock et al. (2002), where the assumptions may only apply in certain sub-biomes (Scurlock et al. 2002). In this study, grassland NPP was estimated from biomass measurements using the following equation (Chen et al. 2008; Wang et al. 2010):

$$ NPP = B_g \times S_{bg} \times (1 + S_{bg}) $$

(1)

Where NPP refers to the total grassland NPP (g C m⁻² a⁻¹); $B_g$ is the dry matter yield of above-ground (g m⁻²); $S_{bg}$ is the conversion factor from dry matter yield to NPP (g C g⁻¹) estimated at 0.45 (Fang et al. 1996); and $S_{bg}$ is the ratio of below- to above-ground biomass.

2.4.3 Relationship analysis between grassland NPP and environmental variables
Analysis of variance (ANOVA) was used to examine the relationship between grassland NPP and grassland type and soil quality. Pearson correlation was applied to evaluate the relationship between grassland NPP and climate variables. Student-Newman-Keuls (S-N-K) test at 5% level of probability was used to test the significance of differences.

2.4.4 Methods for dominance analysis
Dominance analysis was conducted to determine the relative importance of environmental variables. Previous studies have proposed ways to measure the relative importance of predictors using multiple regression (Budescu 1993). However, considering the shortcoming of the standardized coefficient as a measure of importance (Roger and Alberto 2009), Pratt’s measure (Pratt 1987) — a combination of coefficients and correlations — was used in this study. This measure equals to the product of the regression coefficients and the zero-order correlation for the predictor (Coolen 2008).

A categorical regression with optimal scaling was used to determine the relationship between environmental variables and total NPP. This method was preferred to linear regression analysis because the technique makes nominal and ordinal variables suitable for regression analysis (Coolen 2008).

All statistical analyses were performed with Predictive Analytics Software (PASW Statistics 18.0).

3 Results

3.1 NPP estimate
Within the 602 samples, NPP estimate ranged from 4.76 g C m⁻² a⁻¹ to 975.94 g C m⁻² a⁻¹, with an average value of 268.20 g C m⁻² a⁻¹. However, 65.78% of the samples were distributed from 100 g C m⁻² a⁻¹ to 500 g C m⁻² a⁻¹.

Large variations in NPP exist across all samples (Fig.3). NPP in the eastern part of the study region was higher than that in the middle and the western part. The similar pattern was found in Inner Mongolia. Relative high NPP was observed in eastern part of Inner Mongolia. The NPP samples in the western study region (Xinjiang) were mainly distributed in the Ili Valley, with an average biomass of 298.94 g C m⁻² a⁻¹. According to the central study area, samples with relatively low NPP were mainly distributed in the Hexi Corridor and Alxa League, desert of West Alxa and Mazong Mountain-Nuomin Gobi, with an average biomass of119.62 g C m⁻² a⁻¹, 117.48 g C m⁻² a⁻¹ and 73.40 g C m⁻² a⁻¹, respectively.

Remarkable differences in NPP were also found in different grassland types (Fig. 4). The average NPP for meadows (324.97 g C m⁻² a⁻¹) was the highest, followed by steppes (289.58 g C m⁻² a⁻¹). The lowest of NPP occurred in deserts, with an average NPP value of 153.06 g C m⁻² a⁻¹.

3.2 Environmental variables controls on NPP

3.2.1 NPP and climate
Site-specific Pearson correlation between NPP and climate variables is listed in Table 2. Statistically significant negative correlation was found between NPP and annual mean temperature, whilst statistically significant positive correlation
occurred between NPP and annual precipitation. Furthermore, the correlation coefficients between NPP and annual precipitation were higher than those between NPP and annual mean temperature, indicating that the impact of precipitation on vegetation is greater than that of temperature in the study area.

Different grassland types showed similar responses to the climatic conditions (Table 2). Three types of grassland showed negative correlation with annual mean temperature, and significant positive response to annual precipitation ($p<0.05$). Annual mean temperature had a significant limiting impact on meadows and steppes ($p<0.05$), whereas for deserts no significance was observed. The correlation coefficients indicated that precipitation exhibited a greater influence than temperature. Furthermore, annual precipitation had the strongest impact on deserts, followed by steppes and meadows in sequence. A reverse trend was found for annual mean temperature.

### 3.2.2 NPP and topography
Average NPP decreased with elevation (Fig. 5a), reaching the highest value when elevation was less than 500 m (453.10 g C m$^{-2}$a$^{-1}$). Comparing the average NPP of different slope degrees (Fig. 5b), average NPP increased with slope, reaching the maximum value of $390.61$ g C m$^{-2}$a$^{-1}$ when the slope was steeper than $15^\circ$ and the minimum value of $258.78$ g C m$^{-2}$a$^{-1}$ at a slope degree less than $3^\circ$. Aspect had a weak impact on NPP (Fig. 5c), with a maximum value of $337.80$ for the northwestern slope and a minimum value of $210.11$ for the western slope.

### 3.2.3 NPP and soil quality
Using analysis of variance with the S-N-K test on soil quality of different grades, significant difference in NPP was found between the first and the remaining two grades. The difference between the second and the third grade was also significant (Fig. 5d). Average NPP increased with the improvement of soil quality, reaching the highest value of $317.23$ g C m$^{-2}$a$^{-1}$ at first grade quality and the lowest value of $206.08$ g C m$^{-2}$a$^{-1}$ at third grade.

### 3.2.4 Dominance analysis among environmental variables
We conducted a categorical regression to determine the relationship between environmental variables and NPP (Table 3, $p<0.001$). Pratt’s measure of relative importance (Pratt 1987) allowed the interpretation of the predictor contributions to the regression. The standardized coefficients indicated the change in the response variable with a change in the variable under consideration keeping the other variables constant.
Results showed that the effects of annual precipitation and elevation were significant at the 5-percent level. Pratt’s values revealed that the annual precipitation, the most important explanatory variables in the order of importance, was the dominant factor for plant growth in northern China with a Pratt’s measure of 0.70. The standardized coefficient indicated, one standard deviation increase of the variable yielded 0.33 standard deviation increases in the overall group functioning. DEM was the second most important variable with a Pratt’s measure of 0.17, negatively correlated with NPP. Although soil quality presented positive impact without significance, it is the third largest contributor to explaining the spatial variation in grassland NPP.

Different results were observed in the correlation between annual mean temperature and NPP in the Pearson correlation and dominance analysis. Negative correlation was observed in both methods, but significance differed. The reason for the difference was the interaction among various environmental factors affecting the impact of single variable on NPP.

4 Discussion
In the present study, 602 samples were collated in northern China for 1980-1999 through a comprehensive search of published biomass data greatly enriching the existing NPP field measurement database. Moreover, we analyzed the
relationship between NPP and environmental variables including climate, soil characteristics, and topography. Dominance analysis helped to measure the relative importance of variables and identified the dominant one.

The spatial variability of NPP was dependent on grassland type in two ways: physiological characteristics of vegetation directly controlling NPP, and responses of different vegetation to limiting factors, such as climate, water, soil and light. Meadows had the highest mean NPP due to a high density of plant communities. Deserts had the lowest mean NPP because of low precipitation and sparsely distributed plant communities.

Precipitation played a dominant role in influencing the spatial variability of grassland NPP in this region. This was also demonstrated by Wu et al. (2013) who carried out a similar study in Inner Mongolia-Ningxia on an arid grassland region calculating the NPP product from NOAA/AVHRR remote sensing data. Furthermore, a strong positive relationship between precipitation and NPP was observed, which supported the idea that NPP generally increases with increasing precipitation (Knapp and Smith 2001; Liu and Gao 2009). Studying the same place as this study, Ni (2004) concluded that the total NPP of grassland vegetation was not significantly controlled by rainfall. Different results may be attributed to different estimation methods and data sources. It was worth noting that the correlation between annual mean temperature and grassland NPP was significant in Pearson correlation but not significant in the dominance analysis. The reason for the opposite conclusions was the interaction among various environmental factors would affect the impact of single variable on NPP, leading to a more reliable result.

Meanwhile, the spatial pattern of hydrothermal condition was characterized by longitudinal zonality due to land-sea distribution and atmospheric flow. Water vapor evaporating from the oceans was the main source of precipitation on land surfaces. Correspondingly, there was a clear trend from the moist and semi-moist eastern coast to the semi-arid and arid zones of the continental west along longitudinal lines (Hong and Blackmore 2015). That’s the reason why distinct longitudinal zonality was found for spatial pattern of grassland NPP in our study.

Topography affects the spatial pattern of NPP mainly through the distribution of light, water, and nutrients, which are the key regulators of grassland NPP (Kang et al. 2006; Huang et al. 2012). It was demonstrated that elevation was inversely correlated to annual precipitation ($r=-0.425$, $p<0.01$). NPP therefore decreased with elevation caused by the water limitation of NPP. Similar results were found for the Yangou watershed (Wang and Shangguan 2012). However, contrary to the results reported here, a research conducted by Chen et al. (2007) found that forest NPP increased with elevation at sites less than 1350 m, but decreased at higher altitudes. These different results were mainly caused by the different responses of NPP of various vegetation types at varying spatial scales, geographical locations.

Soil quality is a comprehensive indicator indicating soil nutrition and moisture, which has rarely been the focus of previous studies. Soil quality had a significant positive influence on spatial distribution of NPP, as the third largest contributor to the spatial pattern of grassland NPP.

Along with biomass field measurements, plot-level forage yield was also used to estimate NPP. The limitations of estimating NPP from forage yield have been discussed by Ni (2004). In this paper, the main drawback was that forage yield was the standing crop measured in the most productive period. Although the peak standing crop could be used to calculate NPP and the algorithm was suitable for temperate grassland (Scurlock et al. 2002), it may result in the under-estimation of NPP because it omitted litterfall data.

5 Conclusions

A grassland in situ NPP database was developed, including 602 field samples. Based on large amount of field data, spatial variation of grassland NPP and its responses to environmental variables were examined. Dominance analysis was performed to evaluate the relative importance of environmental variables and identify the dominant factor. Spatially, grassland NPP in the eastern part was higher than that in other parts, ranging from 4.76 g C m$^{-2}$a$^{-1}$ to 975.94 g C m$^{-2}$a$^{-1}$. Remarkable difference in NPP existed among meadows, steppes and deserts, and meadows had the highest level of NPP. Among environmental variables, precipitation was the dominant factor affecting the spatial variability of grassland NPP, followed by elevation. The impact of aspect on NPP was not significant. Specifically, NPP increased with annual precipitation and declined with annual mean temperature significantly ($p<0.05$). Grassland NPP decreased with increasing altitude because of water limitation and positively correlated with slope, but weakly correlated with aspect. Soil quality exhibited a positive effect on spatial variation of grassland NPP.

References


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摘 要：草地净初级生产力（NPP）的空间格局受到各种环境要素的影响。当前大量研究探讨了不同环境变量对草地 NPP 的影响，但各种环境变量对其空间格局影响的相对重要性尚未统一结论。而基于模型模拟的草地 NPP 会加剧这一不确定性。因此，本研究基于文献资料搜集获得我国北方草地 602 个样点的生物量和产草量数据，构建 1980-1999 年草地 NPP 实测数据库。在此基础上，采用相关分析和主导因素分析法定量探讨了环境变量对 NPP 空间变异的单独和联合影响。研究表明，北方草地 NPP 的空间分布明显异质，在 4.76 g C m⁻² a⁻¹ to 975.94 g C m⁻² a⁻¹ 间波动。草地 NPP 与年降水量显著正相关，而与年均温度显著负相关，其中降水对荒漠草地的影响最大，其次为草原和草甸。由于水资源的限制，随着海拔的增加草地 NPP 降低。草地 NPP 与坡度呈正相关，与坡度的关系微弱。土壤质量越好，草地 NPP 越大。就各种环境要素的联合影响而言，年降水量是影响草地 NPP 空间格局的最主导要素，其次是高程。

关键词：草地净初级生产力；实测数据；环境变量；主导因素；中国北方