Divergent responses of vegetation aboveground net primary productivity to rainfall pulses in the Inner Mongolian Plateau, China

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Abstract

The differential responses of vegetation types to rainfall pulses are still not fully understood in the Inner Mongolian Plateau. This study firstly investigated the hierarchical responses of vegetation aboveground net primary productivity (ANPP) to rainfall pulses in the Inner Mongolian Plateau using Normalized Difference Vegetation Index (NDVI) as a proxy. Forty-eight independent rainfall events were selected between 2000 and 2013 for three study sites within a precipitation gradient transect. Results of the threshold-delay model revealed that vegetation in the Gobi desert and Typical steppe responded much faster with 3.6 ± 2.0 day and 6.4 ± 4.6 day, respectively, contrast with a durable response in Desert steppe (10.2 ± 6.5 day). Desert steppe had the highest upper threshold of rainfall (80.2 mm), which was about two-fold of Gobi desert (36.1 mm) and Typical steppe (41.2 mm). Pulse size, timing, soil texture and plant functional type (PFT) were the main drivers that influenced the rate and magnitude of vegetation responses. The results highlight the differential responses of vegetation types to rainfall pulses in the Inner Mongolian Plateau and may contribute to a better understanding of the impact of changing rainfall patterns on vegetation dynamics in arid and semiarid regions.

Keywords: ANPP; NDVI; threshold-delay model; rainfall pulses

1 Introduction

Precipitation is a primary factor that influences vegetation growth in arid and semiarid regions, since vegetation in such regions is sensitive to the quantity, timing and frequency of rainfall events (Fravolini et al. 2005; Gamon et al. 2013; Li et al. 2013; Liu et al. 2012). However, current limitations of the knowledge about consequences of global and regional rainfall regimes on plant metabolic activity and physiological processes constrain the developments of mitigation strategies in the context of further intensification of rainfall variability in the near future (Heisler-White et al. 2008; Hsu 2011; Miranda et al. 2009; Stocker et al. 2013), especially in arid and semiarid regions. In particular, vegetation activity is significantly dependent on episodic precipitation events or “pulses” due to scarce groundwater and low soil moisture content in arid and semiarid ecosystems (Gamon et al. 2013; Liu et al. 2012). Therefore, it is critical to evaluate the vegetation responses to rainfall pulses in arid and semiarid regions.

The Inner Mongolian Plateau with a large area of $3.4 \times 10^5 \text{ km}^2$ is located in arid and semiarid regions and has a distinct east-west precipitation gradient. It also supports a population of 25 million, and provides crucial ecosystem service for northern China (Ye et al. 2000). Previous studies usually focus on a single ecosystem (Burgess 2006; Li et al. 2013; Ogle and Reynolds 2004; Ross et al. 2014; Ryel et al. 2008; Zhao and Liu 2010), and a comprehensive understanding of the responses of vegetation activity along the precipitation gradient is still lacking. Therefore, it is urgent to investigate the divergent responses of vegetation aboveground net primary productivity (ANPP) to rainfall pulses here along its precipitation gradient.

Several models, such as two-layer hypothesis (Walter 1971), the pulse-reserve (Noy-Meir 1973) and threshold-delay models (Ogle and Reynolds 2004) have been proposed to predict

plant response variation in rainfall event regimes. Among them, the threshold-delay model proposed by Ogle overcomes limitations, such as plasticity in the rooting habits of woody plants, potential delayed response of plants to rainfall, explicit precipitation thresholds, and vagaries in plant phenology (Ogle and Reynolds 2004), and it has been demonstrated to be a good tool for assessing the response of vegetation changes to precipitation regimes and has been widely used in the USA (Ogle and Reynolds 2004; Ryel et al. 2008), Australia (Burgess 2006; Ross et al. 2014) and China (Li et al. 2013; Zhao and Liu 2010).

In this study, we combine the threshold-delay model, retrieved daily Normalized Difference Vegetation Index (NDVI) and meteorological observations to investigate the possibly divergent responses of aboveground vegetation activity to different rainfall regimes along a precipitation gradient in the Inner Mongolian Plateau. Specifically, we aim to answer the following two questions: 1) Is there a divergent response of ecosystems to different rainfall regimes along with the precipitation gradient? and 2) What factors dominate the ANPP changes in response to rainfall pulses?

2 Materials and methods

2.1 Study area

This study was conducted at a transect in the Inner Mongolia Plateau of northern China, which has a clear west-east precipitation gradient (50-450 mm) and consists of three different land cover classes (Zhang 2007) in Fig.1, including desert, desert steppe and typical steppe. Three sites are selected to represent these three vegetation types along a precipitation gradient, considering the combination of shrub-grass ecosystem, soil texture and belowground water conditions (Fig. 1). Despite the spatial heterogeneity, areas within same land cover class have many similarities in precipitation, temperature and vegetation. The meteorological condition and vegetation composition of each site is within the scope of the corresponding land cover

class (Table S1), so these three study sites can represent each vegetation type. Study site #1 in the desert is referred to as Gobi desert, study site #2 in the desert steppe is referred to as Desert steppe, and study site #3 in the typical steppe is referred to as Typical steppe in this paper. Our study region is a part of the Inner Mongolia grassland, which is representative of the Eurasian steppe region. The grassland is significantly different from the North American prairies and the African savannas in terms of climate, soils, and dominant plant functional types (Bai et al. 2008). Our study region is dominated by a continental temperate climate. The mean annual precipitation (MAP) amounts of the study sites are 58.8 (Gobi desert), 136.2 (Desert steppe), and 353.3 mm (Typical steppe), respectively, with 60% occurring from June to August (Table 1). The mean annual temperature (MAT) ranges from 3.0 to 9.1°C (during 2000-2013). The linear regressions of MAT of corresponding weather stations over the past 60 years shows an increase of 0.03-0.06°C/year. The typical soil types are Hapli-Orthic Aridosols, Sali-Orthic Aridosols, and Hapli-Ustic Cambosols according to the USDA Soil Taxonomy (Staff 1994), and the corresponding soil textures are sand, loamy sand, and sandy loam from the Gobi desert to the Typical steppe. Gobi desert, Desert steppe and Typical steppe are mainly composed of shrubs and grasses (Fig. 1), with the dominant shrub species being *Reaumuria songarica*, *Caragana tibetica*, and *Caragana microphylla*, respectively. The compositions of grass species are listed in Table 1. Based on our field investigation during August of 2011, the biomasses of the grass layer in Gobi desert, Desert steppe and Typical steppe were 0, 15.22, and 142.67 g/m², while those of shrub were 247.58, 280.95 and 295.17 g/m², respectively.

Fig. 1 (I) Location of the study area in China; (II) land cover classes, study sites and corresponding weather station; (a) - (c) are photos of landscapes in the study sites.

Table 1. Characteristics of meteorology, vegetation and soil in the study sites

Characteristics	Gobi desert	Desert steppe	Typical steppe
MAP (mm)	58.8	136.2	352.3
June to August precipitation(mm)	35.2	83.2	224.8
MAT(°C)	9.1	8.9	3.0
Altitude(m)	1160	1186	1423
Main shrub	<i>Reaumuria songarica</i>	<i>Caragana tibetica</i>	<i>Caragana microphylla</i>
Main grass	Few	<i>Stipa capillata</i> ; <i>Ajania pallasiana</i> ; <i>Cleistogenes squarrosa</i>	<i>Cleistogenes squarrosa</i> ; <i>Stipa capillata</i> ; <i>Artemisia frigida</i>
Grass biomass(g/m ²)	0	15.22	142.67
Shrub biomass(g/m ²)	247.58	280.95	295.17
Grass coverage(%)	0	20.7	43.0
Shrub coverage(%)	2.6	4.3	13.4
Soil types	Hali-Orthic Aridosols	Sali-Orthic Aridosols	Hapli-Ustic Cambosols
Soil texture	sand	loamy sand	sandy loam

Weather station	Dingxin	Linhe	Duolun
Distance(km)	22.1	70.1	81.0

Note: MAP and MAT represents the annual means from 2000 to 2013; Distance represents the length between study sites to corresponding weather stations.

2.2 Data collection and processing

ANPP represents aboveground net primary productivity, which is primarily constrained by water in water limited regions (Heisler-White et al. 2008). ANPP increases after plants absorb the water provided by pulses, which influence the structure and function of ecosystems. Therefore, analysis of ANPP responses to rainfall pulses is critical to understanding the response mechanisms (Li et al. 2013). While NDVI is a kind of vegetation indices of remote sensing, which provides information on plant productivity, biomass and coverage on the ground (Wang et al. 2003). Previous study showed a positive and statistically significant relationship between NDVI and ANPP (Paruelo and Burke 2008). Therefore, NDVI derived from satellite can be used as a proxy for ANPP of plants on the ground (Li et al. 2013).

NDVI data were calculated based on the spectral images of MODIS datasets (MOD09GQ, <http://ladsweb.nascom.nasa.gov>) with a 250 m spatial resolution and a 1-day temporal resolution during 2000-2013. Previous studies on the time-lag effect of climate on NDVI were almost based on NDVI with time resolutions of 8 days (Li et al. 2013), 14 days (Wang et al. 2003), or even longer (Nezlin et al. 2005), for which it is easy to exaggerate or reduce the lag effect and shield the detailed information. In this study, NDVI with a 1-day temporal resolution possibly enables accurate temporal investigation of ANPP along the growing season and provides detailed understanding of regional phenomena. The location and range of the study sites were determined by both field investigation and image recognition. After selecting an open area with a GPS locator in the field, this area was positioned and distinguished in MODIS images in order to exclude village, building and other non-vegetation

cover areas and to determine the domain of the study sites. MOD09GQ images were directly extracted in the active growing season (June, July, and August) (Fan et al. 2009) during 2000-2013. After image mosaic and re-projection in the ModisTool software, NDVI was calculated in ENVI 5.0 by the original spectral bands of red and near-infrared that MOD09GQ included. The mean NDVI were extracted for this area using NDVI images that were clipped by the border of a study area in ENVI.

The observed daily precipitation and temperature data during 2000-2013 for the meteorological stations near the study sites were obtained from the China Meteorological Data Sharing Service System (<http://cdc.nmic.cn>). In this study, a rainfall event was defined as a continuous rainy period recorded in the observation data. Rainfall events of 0-5mm have certain impact on arid ecosystem (e.g., sustain bursts and wet surface soil) (Cui and Caldwell 1997). However, the NDVI responses to rainfall events (<5 mm) were generally so small that it was hard for satellite sensors to accurately catch (Li et al. 2013). Therefore, 0-5mm rainfall events were excluded in our analyses for explicitly exploring plant responses to rainfall events. 16 rainfall events at each study site were selected based on the following criteria (Table2): (1) no other major rainfall (> 5 mm) at least 5 d before and after the rainfall event; (2) the event occurred toward the middle of the growing season, when temperature was relatively high (June to August)(Li et al. 2013; Wang et al. 2003); (3) the rainfall event was distributed evenly at a particular rainfall class. Consequently, every rainfall event selected can be called a pulse, which is characterized by a discrete and variable episode that can significantly influence the structure and function of an ecosystem. Additionally, there is a sufficient period after the events selected to observe the response of ANPP to a rainfall event.

Vegetation and soil data were used to explain the divergent responses of different vegetation types. The data come from field investigation carried out by our research group from August 9 to 26 of 2011. Three randomized 25 m × 25 m plots as three replicates were separately

established at Gobi desert, Desert steppe and Typical steppe. In each plot, three 5 m × 5 m quadrats for shrub patched and 1 m × 1 m quadrats for interspace grass patches were used to analyze grass biomass. Aboveground biomass was sampled by clipping live vegetation rooted within the quadrat to the ground surface. Belowground biomass was dug within estimated shrub roots at depths ranging from 0 to 100 cm at 10 cm intervals. The roots were washed and oven-dried at 65°C to constant weight for determination of biomass. The areas of shrub patches were recorded on paper in the field in each 25 m × 25 m plot and then digitized using ArcGIS 9.3 to estimate shrub coverage. Soil samples were collected at depths of 0-100 cm at 10 cm intervals. The soil samples were air-dried and then sieved to pass through a 2 mm screen. For grain size distribution, the sand fraction (2000 to 50 µm) was measured by sieving, and the silt (50-2 µm) and clay (<2 µm) fractions were determined using the pipette method. Soil texture was determined according to the proportion of sand, silt and clay.

Table 2. Selected rainfall events and the corresponding response duration

	Gobi desert				Desert steppe				Typical steppe			
	ST	ET	P (mm)	RD (d)	ST	ET	P (mm)	RD (d)	ST	ET	P (mm)	RD (d)
1	00-6-5	00-6-6	5.6	2	00-6-2	00-6-3	18.8	12	01-7-25	01-7-26	24.7	6
2	01-7-23	01-7-23	6.1	2	00-7-3	00-7-3	15	11	02-6-22	02-6-26	48.1	12
3	02-6-7	02-6-9	12.7	3	01-8-13	01-8-13	26.7	12	02-8-25	02-8-26	6	2
4	02-7-7	02-7-7	7.8	5	03-6-25	03-6-25	6.8	3	03-6-10	03-6-14	23.1	2
5	03-6-9	03-6-9	10.4	2	04-6-3	04-6-5	24.7	16	03-6-22	03-6-23	25.6	12
6	03-6-25	03-6-25	11	1	04-6-29	04-6-29	10.8	3	05-8-11	05-8-12	19.9	7
7	04-7-24	04-7-25	30.6	3	06-6-6	06-6-6	9.7	2	06-8-16	06-8-16	9.5	6
8	05-7-12	05-7-12	5.6	3	06-7-29	06-7-29	14.5	16	09-6-6	09-6-8	56.5	17
9	06-7-6	06-7-8	6.5	4	06-8-18	06-8-20	52.2	12	09-7-4	09-7-6	25.1	4
10	08-7-12	08-7-13	7.7	6	07-8-25	07-8-25	5.1	6	09-8-16	09-8-17	15	11
11	09-7-7	09-7-7	5.9	4	09-8-18	09-8-18	13.1	8	11-8-14	11-8-15	19.4	3
12	11-8-12	11-8-15	36.1	9	10-8-20	10-8-20	5.7	2	12-7-31	12-7-31	17.8	2
13	12-6-5	12-6-6	9	5	11-6-29	11-6-29	5.9	6	12-8-26	12-8-27	7.6	2
14	12-7-29	12-7-29	5.1	5	12-6-26	12-6-28	80.2	26	13-6-7	13-6-9	9.5	2
15	13-7-4	13-7-4	5.0	2	12-8-10	12-8-11	15.9	12	13-6-15	13-6-16	32.3	5
16	13-7-24	12-7-25	17.8	2	13-7-21	13-7-21	15.7	16	13-7-15	13-7-15	41.2	9

Note: ST- start time; ET- end time; RD- response duration, which was estimated from the time

intervals between the date of the rainfall pulse and the following date of maximum NDVI ($NDVI_{max}$); P- precipitation.

2.3 Statistical Analysis

The threshold-delay model (Ogle and Reynolds 2004) was applied in the study to identify the vegetation responses to rainfall pulses, including the magnitude, duration and the thresholds of responses. In addition, the variation in vegetation responses at different precipitation conditions was investigated. The plant responses to a rainfall pulse can be modelled as follows(Ogle and Reynolds 2004):

$$y_t = k \times y_{t-1} + \delta_t \quad (1)$$

$$\delta_t = \text{Min} \left[y_{max} \times (1 - k), \delta_t^* \times \left(1 - \frac{y_{t-1}}{y_{max}} \right) \right] \quad (2)$$

$$\delta_t^* = \begin{cases} \frac{\delta_{max}}{R^U - R^L} (R_{t-\tau} - R^L) & R^L < R_{t-\tau} < R^U \\ 0 & R_{t-\tau} \leq R^L \\ \delta_{max} & R_{t-\tau} \geq R^U \end{cases} \quad (3)$$

where y_t is the response variable (NDVI) at time t , k is the y_t change rate over time, y_{t-1} is the antecedent value of this variable, δ_t is the magnitude of the response increase due to a rainfall pulse, y_{max} is the maximum potential value for the response variable, δ_t^* is the potential maximum response at time t , δ_{max} is the maximum potential response increase, R^L is the lower threshold of rainfall, R^U is the upper threshold of rainfall, τ is the time lag, t is the response time, and $R_{t-\tau}$ is the effective rainfall event. R^L is the lower threshold below which no response to rainfall event is observed. R^U is the upper threshold such that no further response can be observed. The values of y_{max} , δ_{max} , and τ are the average values of the 16 rainfall pulses at each site. k was determined by linear regression with Eqs.1. Other parameters of the threshold-delay model were calculated by multiple linear regression based on Eqs.1, 2, and 3. All parameters of the model combined can be used to illustrate the diverse vegetation

responses to different precipitation gradients.

Fig. 2 Conceptual diagram of the threshold-delay model based on Eqs. 1, 2 and 3 (Ogle and Reynolds 2004). (A) is the relationship between y_{t-l} and δ_t , where δ^* is the maximum potential increase; (B) is the relationship between δ^* and rainfall event size at lag τ (days); and (C) provides a hypothetical response curve. Reproduced with permission from Springer.

Rainfall classes were divided into five grades: 5-10 mm, 10-15 mm, 15-20 mm, 20-30 mm, and >30 mm, according to the number and distribution of 48 rainfall events. Timing ranging from 1- 92 represented the date when the rainfall event occurred from June to August. One-way ANOVA was used to analyze whether there was a significant difference in NDVI responses to rainfall pulses between the three study sites. Subsequently, linear regressions were performed for investigating the relationships between NDVI increments, NDVI growth rate, RD, and rainfall events at different sites. NDVI growth rate is calculated as the ratio of NDVI increments to NDVI values before the rainfall pulse ($\text{NDVI}_{\text{before}}$). Rainfall use efficiency (RUE), which is the ratio of the NDVI increment to the rainfall event, was calculated to understand ANPP responses to variations in precipitation across the study sites. A Least Significant Difference (LSD test) was used to perform comparisons between group means with SPSS 20.0. Spearman correlation between NDVI increment, NDVI growth rate

and the influential drivers were analyzed with SPSS20.0. Because previous study (Wang et al. 2003) found only a weak negative correlation between temperature and NDVI in the middle growing season (including our study period), temperature was not considered as an influential factor in this study. Consequently, the rainfall event was considered to have the primary influence on NDVI.

3 Results

3.1 Rainfall pulse characteristics and the dynamics of NDVI and climatic factors

The MAP amounts of the study sites at the Gobi desert, Desert steppe, and Typical steppe ecosystems during 2000-2013 were 58.8, 136.2, and 353.3 mm, respectively. The distributions of rainfall event frequency with varying size significantly differed among the three sites along with the precipitation gradient (Fig. 3). Approximately 60% of the total rainfall occurred during June to August for the past decade (Table 1). Rainfall events with 0-5 mm and >30mm contributed a majority of the total annual precipitation for sites in Gobi desert and Typical steppe, respectively. Small rainfall events are becoming more prevalent along with a decreasing MAP (Fig. 3). The frequency of rainfall events of 0-5 mm increased from 40.9% to 78.7% from Typical steppe to Gobi desert, whereas the frequency of > 30 mm decreased from 13.8% to 2.4%. In general, there is an increasing trend in the rainfall event frequency with decreasing rainfall size.

Change of precipitation, temperature and NDVI during the growing season was shown in Fig. 4. The temperature of Gobi desert was similar to that of Desert steppe, but that of Typical steppe was appreciably lower. The NDVI increased with MAP. All of these three elements fluctuated over time.

Fig. 3 Mean rainfall amount and frequency of rainfall events in different rainfall classes from June to August between 2000 and 2013 in the study sites. (The columns represent rainfall amount, while the line chart represents rainfall frequency)

Fig. 4 Change of precipitation, temperature and NDVI during June-August from 2000-2013 for the three study sites.

3.2 Diverse responses of ANPP to rainfall pulses along the MAP gradient

Linear regression analysis shows an increasing NDVI increment and NDVI growth rate in response to larger rainfall events for all three ecosystems ($P < 0.05$). However, the different slopes (β) in the linear regressions imply divergent responses of both NDVI increment and NDVI growth rates to rainfall events among three study sites, along with a precipitation gradient (Fig. 5 and Fig. 6). There is a significant difference in NDVI increment between the three ecosystem types ($F = 21.718$, $Df = 2$, $P < 0.001$), but there is no significant difference in NDVI growth rate ($F = 0.691$, $Df = 2$, $P = 0.506$). The vegetation in Gobi desert with an extreme arid environment shows the smallest increase in NDVI increment of 0.0006 in response to each additional 1 mm of rainfall. Typical steppe had the largest NDVI increment, which is approximately 6 times that of Gobi desert for each additional 1 mm of precipitation (Fig. 5). However, vegetation in Gobi desert shows the highest β (1.872%, $P < 0.05$) of NDVI growth rate in response to each additional 1mm of rainfall (Fig. 6).

Fig. 5 Relationship between NDVI increments and rainfall event size along the MAP gradient, with blue, red and green markers for Gobi desert, Desert steppe and Typical steppe, respectively. The lines in this figure are fitted by linear regression for the three study sites

Fig. 6 Relationship between NDVI growth rate and rainfall events sizes along the MAP gradient, with blue, red and green markers for Gobi desert, Desert steppe and Typical steppe, respectively. The lines in this figure are fitted by linear regression for the three study sites

Linear regression illustrates that there is a generally close relationship (t-test, $P = 0.216$) between the RD of vegetation growth and rainfall events in Typical steppe ($\beta = 0.234$, $P < 0.05$) and Desert steppe ($\beta = 0.252$, $P < 0.05$), with a longer RD under larger sizes of rainfall events, except Gobi desert ($\beta = 0.089$) (Fig. 7). The six parameters of threshold-delay model were calculated and listed in Table 3. Change rate k varied among the study sites and correlated with y_{max} (0.05-0.457) and δ_{max} (0.029-0.262). The ranking of vegetation coverage level was Typical steppe > Desert steppe > Gobi desert, which was consistent with the MAP. The longest time lag (τ) and highest R^U occurred in Desert steppe, followed by Typical steppe and Gobi desert.

Fig. 7 Relationship between RD of vegetation and rainfall events sizes at different sites, with blue, red and green markers for Gobi desert, Desert steppe and Typical steppe, respectively. The lines in this figure are fitted by linear regression for the three study sites

Table 3. The parameters of the threshold-delay model.

Site	k	y_{max}	$\tau(\text{day})$	R^U	R^L	δ_{max}
Gobi desert	1.023	0.050	3.6±2.0	36.1	0	0.029
Desert steppe	0.995	0.194	10.2±6.5	80.2	0	0.114
Typical steppe	0.899	0.457	6.4±4.6	41.2	0	0.262

Further analysis for the relationships between the NDVI growth rate and the rainfall event sizes for our whole study transect reveals a marked ($P < 0.05$) increase in NDVI growth rate within rainfall events > 30 mm (Fig. 8). However, such rainfall events occurred rarely (with $< 5\%$ frequency) in desert and desert steppe (Fig. 3). The mean NDVI growth rates are 22-36% for the < 30 mm rainfall events, despite the substantial variations within each of those groups. Overall, the responses of NDVI growth rates to different rainfall classes did not show significant difference within rainfall events < 30 mm, but they did show an abrupt ($P < 0.05$) increase for under rainfall events > 30 mm (Fig. 8).

Fig. 8 NDVI growth rate in response to different rainfall size classes from the day before a rainfall event to the day of peak NDVI after the rainfall event. Different letters indicate significant differences among the mean NDVI growth rates of rainfall classes. (LSD test, $P < 0.05$), $n=16$.

The vegetation RUE showed a significant difference between the three ecosystems (Fig. 9) with the lowest RUE being observed in the Gobi desert, which had the lowest MAP and most sparse vegetation coverage. There was an increasing trend of vegetation RUE along with an increasing MAP. The RUE of Typical steppe was about 4-fold and 2-fold higher than those of Gobi desert and Desert steppe, respectively. Furthermore, the variations of RUE in each study site increased with increasing MAP.

Fig. 9 Rain-use efficiency of the three study sites. Different letters indicate significant differences among the mean RUE of the study sites (LSD test, $P < 0.05$); $n=16$.

3.3 Drivers for ANPP changes after rainfall events

Spearman correlation analysis of NDVI growth rate, NDVI increment and rainfall event, drought interval, and timing were calculated separately for the three sites (Tables 4 and 5). Rainfall event size refers to the precipitation amount during a continuous rainy period. Drought interval refers to the number of no-rain days before a rainfall event, and timing is the date when the rainfall event occurred. Rainfall event size had a significantly positive correlation with NDVI increment and NDVI growth rate at all sites ($P < 0.05$). However, drought interval did not have significant influence on ANPP change for all of those ecosystems. Moreover, there is a strong negative correlation between NDVI increments and precipitation timing in Typical steppe, whereas the negative correlation tends to fade and even shifts to a positive correlation along with a decreasing MAP (Table 5). A similar pattern was also observed in the responses of NDVI growth rate (Table 4). This indicates that vegetation in Gobi desert appeared to be more sensitive in the late growing season, while the opposite was the case in Typical steppe. This result was in accordance with the occurrence time of the monsoon at the three sites, which brings large rainfall events and stimulates large ANPP change.

Table 4. Correlation between NDVI growth rate and its drivers at different study sites

Drivers	Gobi desert	Desert steppe	Typical steppe
rainfall event size	0.748**	0.591*	0.768**
drought interval	-0.219	0.128	-0.169
timing	0.431	0.200	-0.662**

* $P < 0.05$; ** $P < 0.01$

Table 5. Correlation between NDVI increment and its drivers at different study sites

Drivers	Gobi desert	Desert steppe	Typical steppe
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rainfall event size	0.753 ^{**}	0.579 [*]	0.684 ^{**}
drought interval	-0.161	-0.220	-0.208
timing	0.466	-0.184	-0.750 ^{**}

*P < 0.05; **P < 0.01

4 Discussion

The findings of this study demonstrate that there are contrasting responses of ANPP to rainfall pulses among the different vegetation types in the Inner Mongolian Plateau, and the drivers for such divergent responses were diverse and complicated. Typical steppe had the largest NDVI increment after rainfall events (Fig. 5), which might be attributed to the following two reasons: (1) Typical steppe is composed of both grass (*C. squarrosa*, *S. capillata* and *A. frigida* etc.) and shrub (*C. microphylla*), and grasses occupies the highest coverage in typical steppe (43%) as compared with that of the desert steppe (20.7%) and Gobi desert (0%), meaning that grass contribute most part of NDVI increment in typical steppe site than that in desert steppe and Gobi desert; (2) more rainfall amount (352mm) in typical steppe site would ensure better soil moisture condition for plant growth resulting in high net primary productivity; moreover, *C. microphylla* can use soil water in shallow and deep soil layer simultaneously, a recent study by Zheng et al. (2015) revealed that water uptake by *C. microphylla* was similar at the depths of 0–20 cm, 20–60 cm and 60–100 cm, accounting for 34.66% $\pm$ 7.83%, 32.44% $\pm$ 7.42%, 32.90% $\pm$ 4.14% of the total water usage, respectively. These suggest that shrub and grass in typical steppe could simultaneously utilize surface soil moisture recharged by small pulses and deep soil water recharged by large pulses for the largest NDVI increment.

In comparison, Gobi Desert shows the highest NDVI growth rate change (β) in response to each additional 1mm precipitation, followed by Typical steppe and Desert steppe (Fig. 6).

This might be closely related with water source for plant use among different vegetation types. Previous studies in the Inner Mongolian Plateau showed that *R. songarica* in Gobi desert absorbed water mainly from 50-180 cm soil (Wu et al. 2013), *C. microphylla* in typical steppe used water from 0-100 cm soil (Zheng et al. 2015), and *C. tibetica* desert steppe usually utilized water from 0-60 cm soil (Zhang et al. 2011). The roots of *C. tibetica* are mainly laterally distributed in the soil profile, and it might not be able to distinguish between large and small rainfall pulses, this may lead to the low β of Desert steppe (Fig. 6). In contrast, *R. songarica* and *C. microphylla* could use deep soil water after large pulses when shallow soil water was already depleted, resulting in different responses to small and large pulses and therefore the high β for Gobi desert and Typical steppe.

In the case of NDVI growth rate, Gobi Desert. *R. songarica* showed a shortest (Table3, 3.6 ± 2.0 d) but intense ANPP response (Fig. 6), this because *R. songarica* can use light rain in the arid condition, a research by Xu and Li (2006) found that predawn leaf water potential of *R. songarica* increased from -4.8 ± 0.3 to -2.9 ± 0.2 MPa after rain, which would lead to a quick water absorption and highest NDVI growth rate later (Fig. 6). After rainfall absorbed by *R. songarica*, increase of ANPP brought stronger transpiration (Xu and Li 2006) which led to a quicker consume of soil water. In addition, soil moisture content is usually extremely low in Gobi Desert before rainfall pulses. Therefore the length of available soil water content might be short (Lauenroth and Bradford 2009). Vegetation possibly could not absorb more water from soil after a few days and ANPP response terminated. However, Desert steppe has the longest RD (Fig. 7) and τ (10.2 ± 6.5 d) values among all the study sites. This may also be associated with soil properties, Sali-Orthic Aridosols in Desert steppe are coarse-textured and sandy, which was proved effective in reducing evaporation and runoff (Li 2003). Zhang *et al.* (2011) found a special soil parent material with a strong ability to hold moisture under *C. tibetica* in Desert steppe. In addition, *C. tibetica* has developed many morphological

characteristics for adapting to the drought environment which help maintain moisture in plant (Zhang et al. 2011). So higher rainfall infiltration and slower evapotranspiration occurred in Desert steppe resulted in the longest availability of soil moisture to plants. Although soil texture of Typical steppe is similar to that of Desert steppe, RD is on average 4 d shorter in Typical steppe compared with Desert steppe under similar rainfall conditions (Fig. 7). A possible reason is high vegetation density in Typical steppe (Table 1). Previous study pointed out variation in vegetation density, giving rise to different rates of evapotranspiration, would affect pulse length (Schwinning and Sala 2004). Higher plant density was usually associated with higher evapotranspiration rate (Abdel-Lah et al. 1997). Therefore, higher evapotranspiration rate in Typical steppe might cause faster consumption of available soil water and further lead to a shorter RD compared with Desert steppe.

Lastly, we have to point out that the 25 x 25 m field plots used in the study are apparently smaller than MODIS grid cell for NDVI calculation, meaning that it may to a certain extent be representative for the entire grid cell, this is the real limitation of field work, and upscaling of field work to satellite scale is still a challenge faced by the researches of current earth science. Fortunately, our research sites in the study fall into the scope of one previous field surveys at 48 sites (20 x 20 m) during the growing season in 2012 and 2013 along precipitation transect in Inner Mongolia (Chen et al. 2014) , By comparison, we found that MAT, MAP, species composition in that study were consistent with our field investigation, so we analyzed vegetation types in other sites and the corresponding NDVI, and we can confirm good representativeness of the sites in the study. In addition, we also note that the field plots are a little far away from the corresponding weather stations (Table 1), this may bring about some uncertainty for NDVI variation.

5 Conclusion

In conclusion, we showed a divergent response of ANPP to rainfall pulses along a precipitation gradient. Gobi desert responded fastest of all sites (3.6 ± 2.0 day), followed by Typical steppe (6.4 ± 4.6 day) and Desert steppe (10.2 ± 6.5 day). Desert steppe with a moderate ANPP response had the highest upper threshold of rainfall (80.2 mm) which was about two-fold of Gobi desert (36.1 mm) and Typical steppe (41.2mm). Changes of ANPP in response to rainfall pulses were mediated by the timing, rainfall sizes, PFT and soil hydrological properties, which all together exerted a crucial effect on soil moisture condition in arid and semiarid regions. This paper provides a first exploration of the differential response of typical vegetation types in the Inner Mongolian Plateau to rainfall events of different sizes. By combining remotely sensed data with field research we provided new insights in the underlying dynamics of variations in vegetation greenness. The results may contribute to a better understanding of the impact of changing rainfall patterns on vegetation dynamics in the region.

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