Journal of Environmental Management 274 (2020) 111144

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Research article

Net Primary Productivity Loss under different drought levels in different grassland ecosystems

Tianjie Lei [a,b], Jie Feng [a,b], Juan Lv [a,b], Jiabao Wang [a,b,*], Hongquan Song [c,**], Wenlong Song [a,b], Xiaofeng Gao [d]

[a] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, Beijing, 100038, China
[b] China Institute of Water Resources and Hydropower Research (IWHR), Beijing, 100038, China
[c] Key Laboratory of Geospatial Technology for the Middle and Lower Yellow River Regions, Ministry of Education, Henan University, Kaifeng, Henan, 475004, China
[d] School of Civil Engineering, Qingdao University of Technology, Qingdao, 266033, China

ARTICLE INFO

Keywords:
Drought
SPI
Biome-BGC
Grassland productivity
NPP loss

ABSTRACT

Drought is one of the most prominent natural threats to grassland productivity, although the magnitude of this threat is uncertain due to the different drought-levels. However, drought-productivity dynamics has not yet received much attention. It is necessary to establish the method to evaluate quantitatively the effect of different drought-levels on grassland productivity. To better understand the impact of different drought-levels on productivity dynamics, an assessment method to assess the quantitative effects of different drought-levels on grassland productivity was proposed based-on long-term observation data, standardized precipitation index (SPI) and Biome-BGC process model. Based-on assessment indicator of net primary productivity (NPP), NPP loss caused by moderate, severe and extreme drought was dramatically different in grasslands with a significant exponential change with gradient of different drought-levels. Furthermore, NPP loss variation in different grassland types under the same drought level was significantly different. Besides, the effect of drought on NPP gradually decreased by an exponential relationship in desert, typical and meadow steppe. However, the percentage of NPP loss in desert, typical and meadow steppe reduced by 20.5%, 13.1% and 17.5% with U-shaped, respectively. Meanwhile, our results can offer scientific basis to improve assessment impact of extreme climate events used by ecosystem model and data, and cope with carbon cycling management and climate change.

1. Introduction

Grassland composes approximately 40.5% of the Earth's continents and sequestrates approximately 34% of total carbon of terrestrial ecosystem (Kemp et al., 2013; Acharya et al., 2012). However, drought posed a serious threat to carbon sequestration of ecosystem that accumulated over a number of years (Ciais et al., 2005; Zhao and Running, 2010). Compared with other ecosystems, grassland is more susceptible to droughts (Raich and Tufekciogul, 2000). Some studies have showed that drought was the main triggers of inter-annual variations in grassland productivity (Ciais et al., 2005; Pereira et al., 2007). Thereby, it is of great significance to research the response of grassland's productivity to drought within the context of climate change (Fang et al., 2018; Lei et al., 2016).

However, the impacts of droughts on grassland productivity seem to be matter of debate. Whereas some studies found reduced productivity in natural and simulated droughts (Smith, 2011), other studies found that productivity remained surprisingly stable in the face of local 100-year drought events (Kreyling et al., 2008). Conversely, productivity was found to increase in a steppe in Ireland, mixed prairies of North America and Brazilian and African savanna (Scott et al., 2010). The degree of lag effects of a drought is determined by the intensity of the drought and its duration (van der Molen et al., 2011). Generally, different intensities of drought have diverse effects on productivity. Surprisingly, in the face of severe droughts for grassland communities in central Europe, productivity remained stable across all years of drought manipulation (Jentsch et al., 2011). However, most studies only focus on the response of to a certain level or intensity of drought. We do not know how ecosystem responds when it is in the face of different levels or intensities of drought and how the evolution of different drought grades affects the productivity. Indeed, different grassland ecosystems have

* Corresponding author. China Institute of Water Resources and Hydropower Research (IWHR), Beijing, 100038, China.
** Corresponding author.
E-mail addresses: jiabao_wang@126.com (J. Wang), hqsong@henu.edu.cn (H. Song).

https://doi.org/10.1016/j.jenvman.2020.111144
Received 8 April 2020; Received in revised form 6 July 2020; Accepted 26 July 2020

Notation

SPI	standardized precipitation index
Biome-BGC	ecological process model
NPP	net primary productivity($gC/m^2/yr$)
GPP	gross primary production($gC/m^2/yr$)
R_{plant}	autotrophic respiration of plant($gC/m^2/yr$)
LRM	linear regression method

productivity, and the relationship between NPP and drought was analyzed by using long-time series data. Therefore, NPP was used to characterize the effect of different drought levels on grassland productivity in this study.

In recent years, field data, remote sensing data and ecological modelling were used to assess the impact of drought in one or two types of grassland on a short time scale. Firstly, some scholars only had used stations data observed by short time scale to analysis the mechanism and effect of drought (Wu et al., 2018). Secondly, remote sensing data was used to evaluate the impact of drought in a semi-arid region (Vicente-Serrano, 2007). Thirdly, ecological models were also used to assess

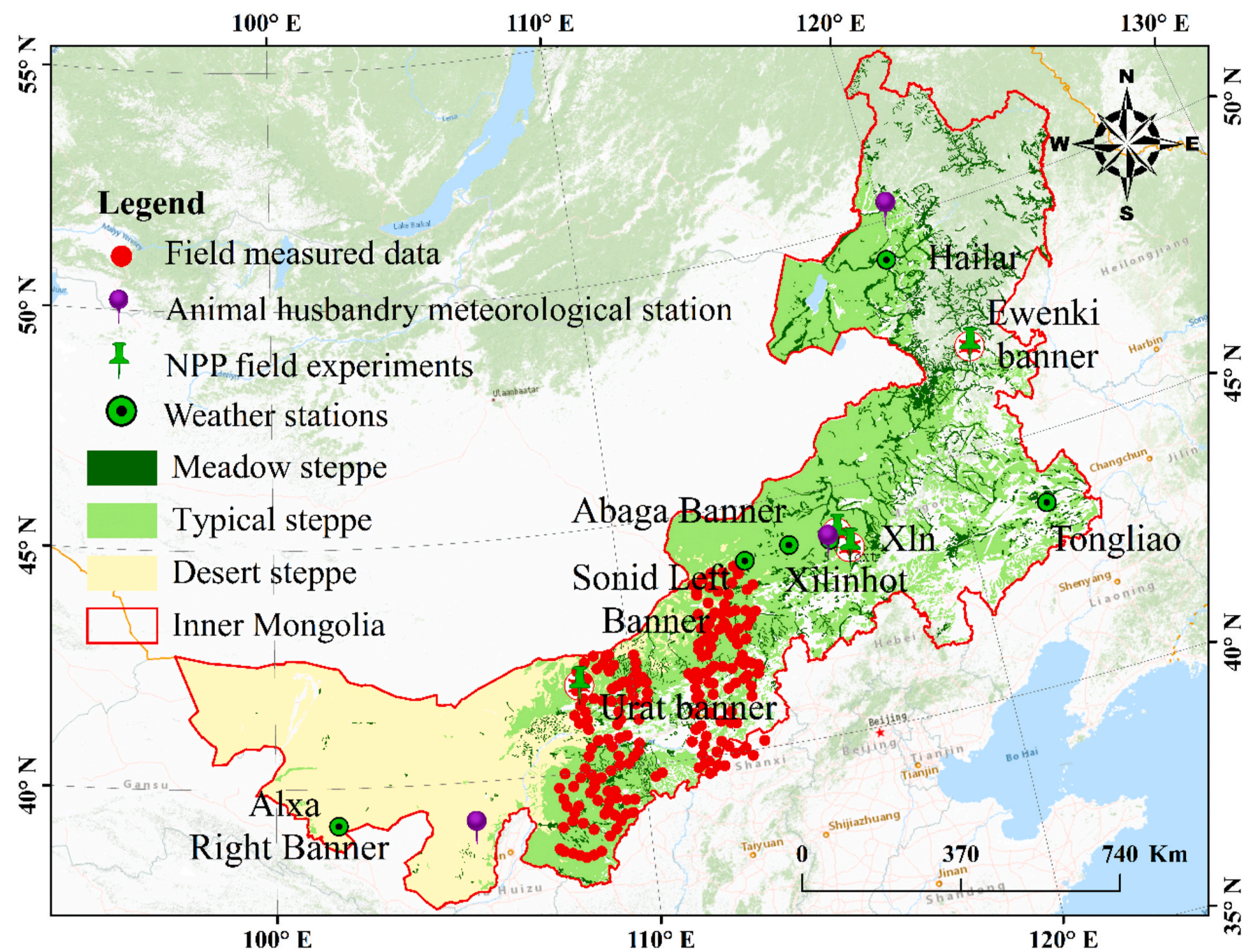

Fig. 1. Location of the study area, distribution of grassland types, weather stations and field experiments (Meadow steppe: Hailar and Tongliao; Typical steppe: Xilinhot and Abaga; and Desert steppe: Alxa Right and Sonid Left).

different responses to droughts. The magnitude of drought effects depends on the maturity of the grass and the drought sensitivity of each species (Ryan and Law, 2005). For example, C3 species may be more drought-sensitive than native C4 perennials due to difference in water-use efficiency between C3 and C4 species (Chimner and Welker, 2005). Virtually, high plant species diversity promoted stable above-ground vegetation C storage during droughts (Bloor and Bardgett, 2012). Moreover, all minor components of the climax were more susceptible to drought damage than the dominant species (Herbel et al., 1972). Furthermore, as a proxy for total value of ecosystem services, NPP was usually used to assess the amount of plant growth and carbon sequestration (Costanza et al., 2006). Precipitation deficit affected NPP significantly in grasslands (Knapp and K, 2002). NPP could be an appropriate index to estimate the effect of drought on grassland the impact of drought on grassland productivity in many regions (Bloor and Bardgett, 2012; Shi et al., 2014). At present, a lot of work had studied the process and correlation of drought index on grassland productivity based on flux observation experiment, precipitation control experiment, remote sensing monitoring and model simulation. However, these approaches have been not able to consider continuous information on a long-term spatiotemporal scale (Abudu et al., 2018). Moreover, differences in the effects of various drought levels between different vegetation types cannot be easily analyzed with these procedures. Also, many works focused on the impact of a single drought event, rather than the average impact of different drought levels in history. Although there was certain difference in the effect of each drought event, it was difficult to quantify the impact of a certain level of drought. It is of great significance to use as a reference scale for assessment the impact of the same level drought events in the future.

In this paper, we used monthly standardized precipitation index (SPI) and Biome-BGC process model to estimate quantitative effects of different drought-levels on grassland productivity based-on combination long-term data with ecosystem model. Therefore, basic framework and main objectives of this study were:1) Detailed description of scientific issues, research areas, data and methods, 2) to estimate how much NPP loss on average under different drought levels in history, 3) to estimate how much NPP loss of drought-induced on average in different grasslands, and 4) to describe and discuss the scientific value and rationality of research results. As a result, our results may offer scientific basis to improve assessment impact of extreme climate events used by model-data fusion, and cope with the effect of same drought level on ecosystem.

2. Materials and methods

2.1. Study area and data

Inner Mongolia grasslands that located in the north of China (97°12′~126°04′E, 37°24′~53°23′N) are mainly composed by three major types of ecosystem: meadow, typical and desert steppe, as shown in Fig. 1. We chose representative grassland ecosystem to assess the quantitative impact of drought in grassland productivity loss in meadow, typical and desert steppe. Furthermore, we used soil, meteorological, vegetation types and NPP of field observation data to drive and calibrate the Biome-BGC model. The China meteorological data sharing network provided nearly 50 (1961–2009) years of meteorological data of six stations that located in the study area (http://cdc.cma.gov.cn). Also, the grid daily and monthly data from 1961 to 2012 were used to drive the Biome-BGC model and SPI drought monitoring index, respectively. These data included daily maximum temperature, daily minimum temperature, average daily temperature, total daily rainfall and length of daytime. Using MTCLI model simulated average vapor pressure and average short-wave radiation flux density. Monthly precipitation was used for the calculation of SPI at each month. In the study area, vegetation types were obtained from the editorial board of Chinese vegetation type map at the scale of 1:1,000,000, which can be expressed vegetation distribution pretty well (http://www.geodata.cn). We collected soil texture that included sand, silt and clay content and depth data from the International Soil Reference and Information Center (ISRIC, http://www.isric.org). Nitrogen-deposition data and CO_2 data were obtained from the UK Air Pollution Information System (APIS: http://www.apis.ac.uk) and Pro Oxygen from the Mauna Loa Observatory/NASA, Hawaii (http://www.co2now.org), respectively.

NPP data were obtained from the global NPP database at the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC; available at http://www.daac.ornl.gov/NPP/npp_home.html) and experimental stations, including the Evenki Banner (meadow steppe: 1989–2005), Xilinhot and Xilingol (typical steppe: 1980–2006) and Urat banner sites (desert steppe: 1982–2006). NPP data also derived from biomass data of various animal husbandry meteorological stations (Ma, 2007). In addition, measured data mainly included field observation data and animal husbandry meteorological station data. In 2007, a total of 200 groups of field measurement data were collected in Inner Mongolia grassland. The observation interval was daily, and the main observation factors were precipitation, temperature, soil water content, and vegetation biomass. Also, animal husbandry meteorological stations were Hulunbeir League, Xilingol and Alxa League, respectively. These animal husbandry meteorological experimental stations were typical representatives of meadow, typical and desert steppe, respectively. The observation time was from 1981 to 1993, and the observation interval was 10 days. The observation factors mainly included precipitation, soil water content, vegetation biomass and other meteorological and ecological indicators.

2.2. Drought levels identifying

SPI has been used to estimate drought levels SPI has been used to represent short-term, middle-term and long-term drought conditions. It also has been proved that is useful in monitoring drought conditions, at timescales of 1-, 2-, 3-, 4-, 5-, 6-, 9-, 12- and 24-months (Mishra and Singh, 2010; Wilhite, 2005). In this study, the SPI index was used to monitor and identify drought disasters (Abdulrazzaq et al., 2019). The calculation steps were as follows:

1) Assuming that the precipitation in a certain period is a random variable x, the probability density function of its distribution was Γ:

$$f(x) = \frac{1}{\beta^{\gamma}\Gamma(r)} x^{\gamma-1} e^{-x/\beta}, x > 0. \tag{1}$$

$$\Gamma(\gamma) = \int_0^{\infty} x^{\gamma-1} e^{-x} dx \tag{2}$$

where $\beta > 0$, $\gamma > 0$ were scale and shape parameters in equation (1) (2), β and γ can be obtained by maximum likelihood estimation method:

$$\hat{r} = \frac{1 + \sqrt{1 + 4A/3}}{4A} \tag{3}$$

$$\hat{\beta} = \bar{x}/\hat{\gamma} \tag{4}$$

$$A = \lg\bar{x} - \frac{1}{n}\sum_{i=1}^{n} \lg x_i \tag{5}$$

In equation (5), x_i was the precipitation data sample, and $\bar{x}$ was the multi-year average value of precipitation.

After the parameters in the probability density function were determined, for precipitation x_0 in a certain year, the probability that the random variable x was less than the event x_0 can be calculated as follows:

$$P(x < x_0) = \int_0^{\infty} f(x) dx \tag{6}$$

Using numerical integration, we can calculate the approximate estimate of event probability after substituting equation (1) into equation (6).

2) The event probability of 0 precipitation was estimated by the following equation:

$$P(x = 0) = m/n \tag{7}$$

In equation (7), m was the number of samples with precipitation of 0, and n was the total number of samples.

The normal standardization deals with the distribution probability, and the probability values obtained from (6) and (7) were substituted into the standardized normal distribution function, namely:

$$P(x < x_0) = \frac{1}{\sqrt{2\pi}} \int_0^{\infty} e^{-z^2/2} dx \tag{8}$$

The approximate solution of formula (8) can be obtained:

$$SZ = S\frac{t - (c_2 t + c_1)t + c_0}{((d_3 t + d_2)t + d_1)t + 1.0} \tag{9}$$

$t = \sqrt{\ln\frac{1}{P^2}}$, P was the probability obtained by equation (6) or (7); when p > 0.5, s = 1; when p ≤ 0.5, s = - 1. The Z value obtained from equation (9) was the SPI.

We chose six- and twelve-month SPI characterizing growing season (4–9 month), and annual drought conditions, respectively. Based on

Table 1
Classification of the SPI values and drought levels.

SPI value	drought level
$-1.0 < \text{SPI} \leq 0$	near normal
$-1.5 < \text{SPI} \leq -1.0$	moderately drought
$-2.0 < \text{SPI} \leq -1.5$	severely drought
$\text{SPI} \leq -2.0$	extreme drought

classification of SPI defining by McKee et al. to distinguish different drought levels in the real nature world (Lloyd-Hughes and Saunders, 2002). The relationship between SPI value and drought level was showed in Table 1. The rules for drought recognition were as follows (Spinoni et al., 2014):

a) The drought started when SPI < -1.0 and ended when SPI > −1.0;
b) The duration of the drought was determined using the start and end months of the drought;
c) The lowest value of SPI was used as the judgment criterion to identify different levels of drought events.

2.3. Grassland NPP loss assessment

Based on the ecological process model (Biome-BGC) and SPI, a quantitative assessment method to assess quantitatively different drought levels on productivity in different grasslands was proposed based-on model-data fusion. The flowchart of the work, as shown in Fig. 2:

As climate, soil and vegetation types are used as input parameters, Biome-BGC can simulate daily data of ecosystem variables to annual data of NPP, and it is widely used in the global scope (White et al., 2000). The present version of Biome-BGC was used to study the impacts of climate, atmospheric chemistry, disturbance and management history and plant ecophysiological characteristics on the terrestrial components of the carbon, nitrogen and hydrologic cycles. Based on Biome-BGC model NPP was simulated, as showed in equation (10):

$$NPP = GPP - R_{plant}. \tag{10}$$

In equation (10), *NPP* represents net primary productivity of plant. *GPP* represents the gross primary productivity of plant (products of photosynthesis). R_{plant} represents the autotrophic respiration of plant.

However, there was a certain error between real value and simulation value, as shown in equation (11):

$$NPP_{tru} = NPP_{mod} + \phi. \tag{11}$$

In equation (11), NPP_{tru} represents the true value, NPP_{mod} represents the simulation value, and ϕ represents the errors of model simulation.

We estimated that grassland productivity loss induced by drought is the difference between the mean the NPP of drought years and NPP of reference years, as shown in equation (12). The meaning of reference years is near normal years ($-1.0 < \text{SPI} \leq 1.0$) that the year neither drought year nor humidity year. Simultaneously, by subtracting the NPP of drought years from long-term average NPP across all normal years, the error of model simulation was eliminated (Lei et al., 2015).

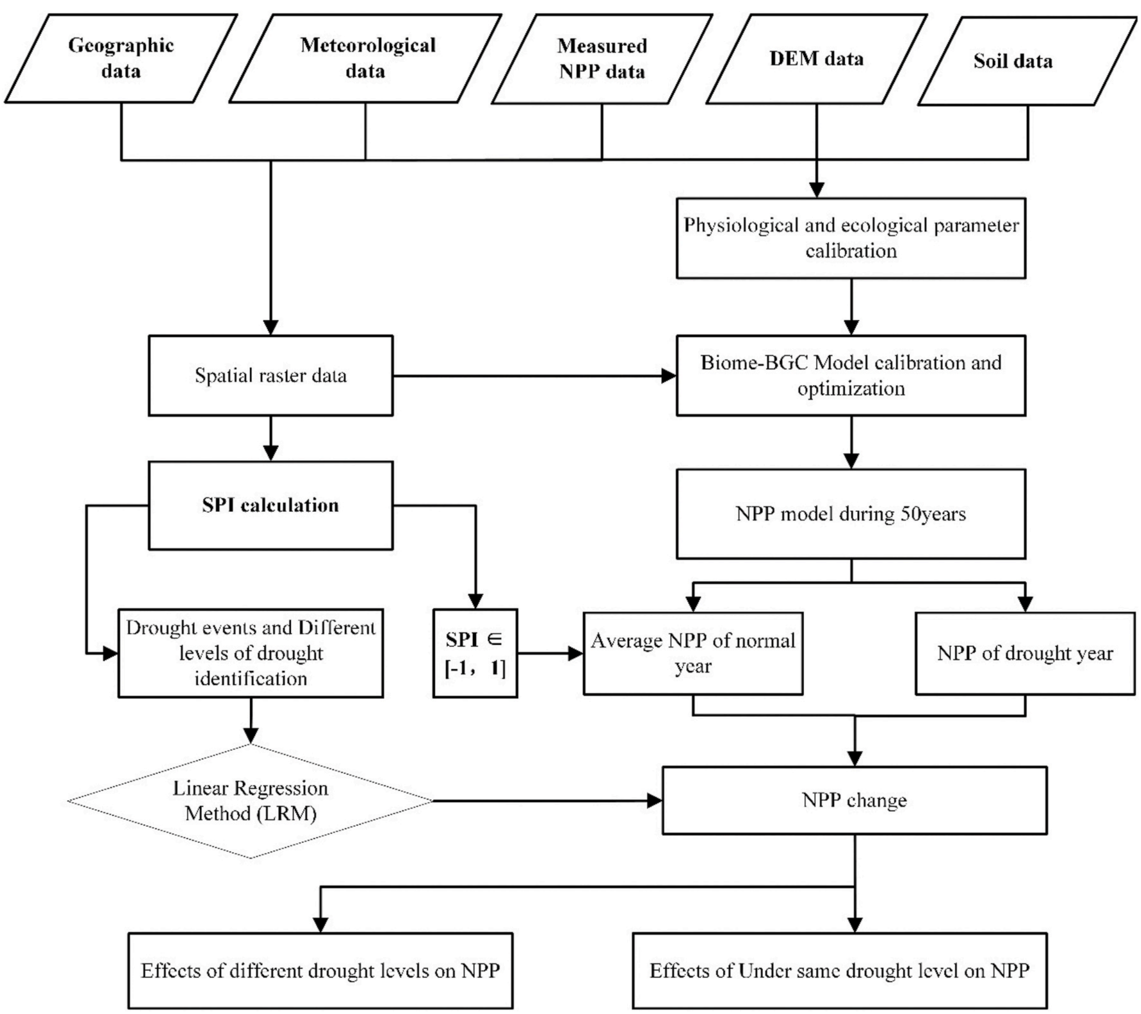

Fig. 2. The flowchart of the work.

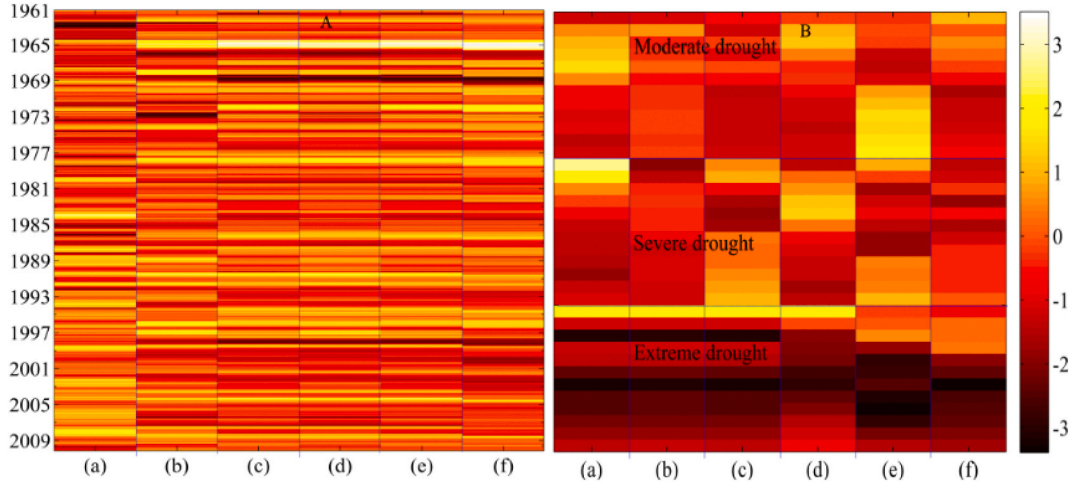

Fig. 3. Drought conditions(A) and levels of drought events(B) identified based-on 6-month SPI at representative stations in Inner Mongolia ((a) Hailar, (b) Tongliao, (c) Xilinhot, (d) Abaga, (e) Alxa Right, (f) Sonid Left). The blue short dash line was the boundary moderate ($-1.5<$ SPI $\leq$ -1.0), severe ($-2.0<$ SPI $\leq$ -1.5), and extreme drought (SPI $\leq$ -2.0), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
The impacts of different drought levels on NPP in different grasslands.

stations name	drought levels		
	moderate drought (gC/m^2/yr)	severe drought (gC/m^2/yr)	extreme drought (gC/m^2/yr)
Alxa Right Banner	21.75	32.3	40.8
Sonid Left Banner	42.89	58.85	79.38
Xilinhot	51.36	78.95	105.42
Abag Banner	26.45	47.45	55.40
Tongliao	104.37	153.9	231
Hailaer	79.95	133.53	182.91

Table 3
The impacts of at different-level drought events on NPP in different grasslands.

stations name	drought levels		
	moderate drought (gC/m^2/yr)	severe drought (gC/m^2/yr)	extreme drought (gC/m^2/yr)
desert steppe	31.02	47.75	73.45
typical steppe	44.29	68.21	127.38
meadow steppe	57.66	89.29	174.13

$$\Delta NPP = NPP_{mean} - NPP_{drought} \tag{12}$$

In equation (12), ΔNPP represents the grassland productivity loss caused by drought, NPP_{mean} represents the long-term average of simulation value of normal years across all years, $NPP_{drought}$ represents the simulation value of drought years.

The correlation between NPP loss and SPI in meadow, typical and desert steppes in Inner Mongolia was analyzed by linear regression method (LMR) (Zhao and Running, 2010). Based on the linear regression method, we analyzed the relationship between NPP loss and drought in different types of grassland in order to identify the effect of drought on NPP loss in different types of grassland.

$$y = ax + b \tag{13}$$

In equation (13), a and b represent regression coefficients, the positive and negative values of a represents the NPP or direction of drought change over time, the absolute value of a represents the NPP or drought change rate, 10a represents the NPP or climate tenancy rate indicating the rate of change per decade.

3. Results and discursions

3.1. Historical drought situation in inner Mongolia

Inner Mongolia grassland is one of the driest regions in the world and grassland ecosystem is subjected to droughts (Lei et al., 2015). We used 6-month SPI datasets to describe droughts for each month from 1961 to 2009 and identified the number of moderate, severe and extreme drought levels at each site. According to the drought recognition rules, the frequency of moderate, severe and extreme droughts occurring at each site was identified and counted based on 6-month SPI. The total number of droughts is about 21, 21, 30, 30, 29, and 27 at the Alxa Right, Sonid Left, Xilinhot, Abaga, Tongliao, Hailar site, respectively. The average number of moderate, severe, and extreme drought was about 13.7, 8.7, and 4 times at the six stations, respectively. Inner Mongolia grassland was a region with highly frequency of drought, an average of 3.16 times of drought each year. In general, the frequency of moderate, severe, and extreme drought occurred was 1.64, 0.86, and 0.48 times each year at six stations, respectively. Fig. 3 showed that drought conditions in each month from 1961 to 2009 and typical drought events of different levels were confirmed at the six stations from 1961 to 2009, which can be used to estimate the effect of typical drought events in grassland productivity loss. For example, as shown in Fig. 3 (b), there presentative moderate, severe, and extreme droughts (Table 2)occurred in 1998, 1965, and 1968 at Hailar station, respectively. At Hailar station, moderate drought about started in July and about ended in the end of December, lasting approximately 5 months just over the late growing season, which resulted (Table 3) in influence on ecosystem. Severe drought about started in June and about ended in the end of October, lasting approximately 5 months just occurred in the growing season, which resulted in serious impact on ecosystem. Extreme drought about started in February and about ended in the end of December, lasting approximately 10 months just over the growing season, which resulted in more serious impact on ecosystem.

At the same time, drought conditions were identified based on 12-month SPI from 1961 to 2009 at six weather stations in Inner Mongolia, as shown in Fig. 4. Also, the presentative moderate, severe, and extreme drought occurred in 1998, 1965, and 1968 at the six sites of Inner Mongolia, respectively. For example, the moderate, severe, and

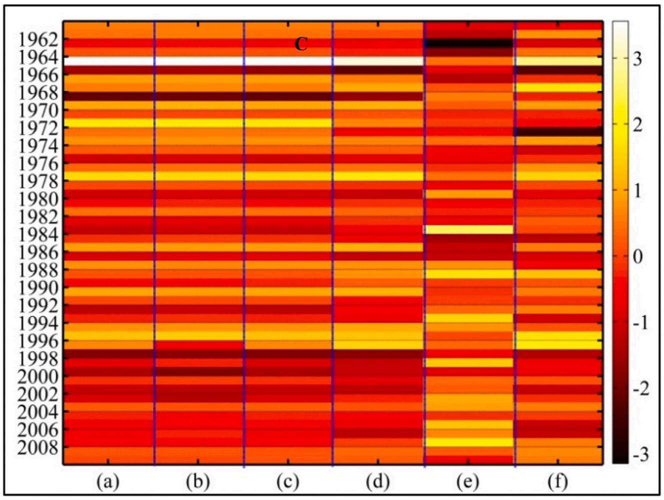

Fig. 4. Drought conditions and levels of drought events identified based-on 12-month SPI at representative stations in Inner Mongolia ((a) Hailar, (b) Tongliao, (c) Xilinhot, (d) Abaga, (e) Alxa Right, and (f) Sonid Left). The blue short dash line was the boundary of each site. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

extreme drought occurred representatively in 1998, 1965, and 1968 at Xilinhot station in typical steppe, respectively. Furthermore, the moderate, severe, and extreme drought occurred representatively in 1979, 1971, and 1962 at Alxa Right station in Desert steppe, respectively. The other study revealed historical drought conditions, including the national extreme droughts in 1961, 1965, 1972, 1978, 1986, 1992, 1994, 1997, 1999 and 2000, but various drought severity levels were classified for each drought event in Inner Mongolia over 1961–2013 (Yao et al., 2018).

3.2. Correlation between drought and NPP analysis

The calibrated result of the Biome-BGC model was successful and the R^2 of meadow, typical and desert steppe were 0.79, 0.71 and 0.83, respectively. Thus, Biome-BGC model had good applicability and reliability to simulate productivity in Inner Mongolia grasslands. Based on the calibrated Biome-BGC model, we simulated the NPP from 1961 to 2009 at six stations of Inner Mongolia grassland. As shown in Fig. 5, NPP was significantly correlated with the average rainfall and drought conditions and the correlation coefficients of the average rainfall and drought were more than 0.5 ($p < 0.001$) based-on LRM. The highest NPP value appeared in the wettest years, and the lowest NPP value appeared in the driest years (Chen et al., 2012). We found that 12-month SPI and NPP had similar trends. The correlation coefficients of NPP and

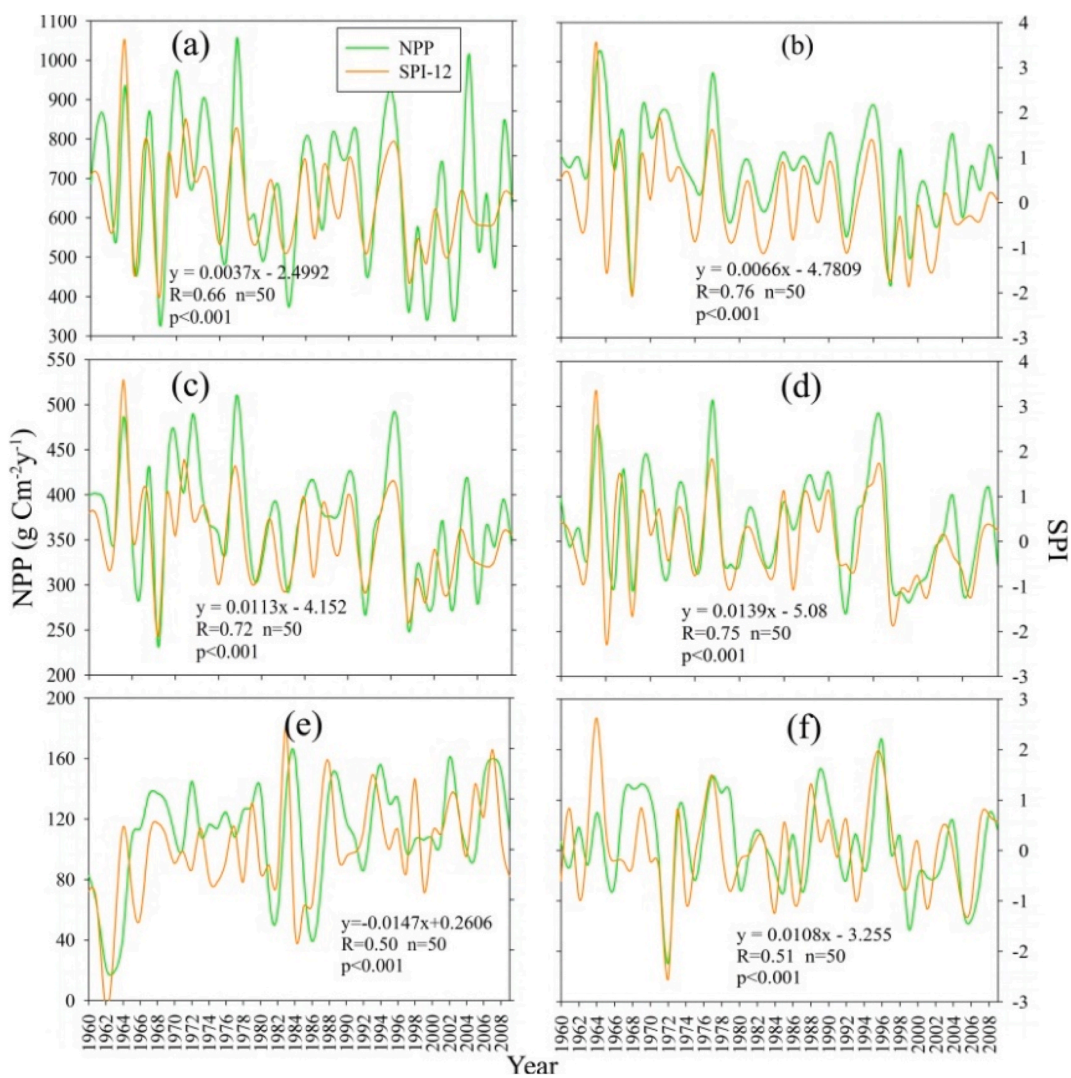

Fig. 5. The correlation between NPP and 12-month SPI ((a) Hailar, (b) Tongliao, (c) Xilinhot, (d) Abaga, (e) Alxa Right, (f) Sonid Left).

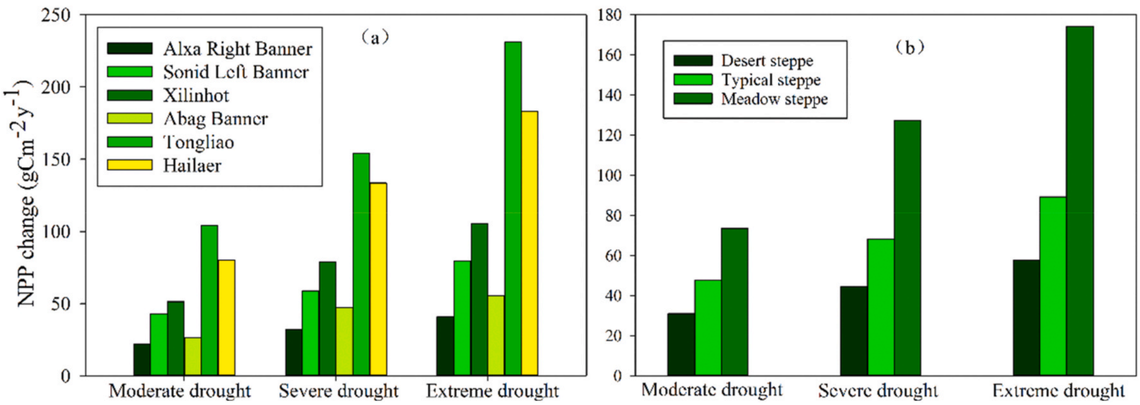

Fig. 6. NPP losses of different levels of drought (a) and different grassland types (b) at typical weather stations in Inner Mongolia.

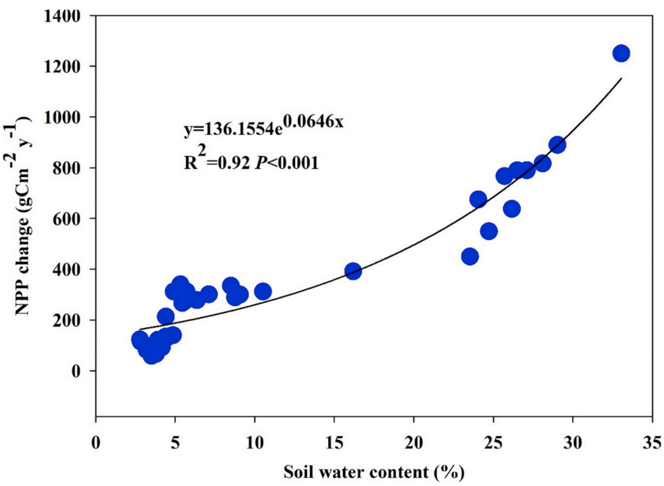

Fig. 7. The relationship between NPP and soil moisture content in different grassland types.

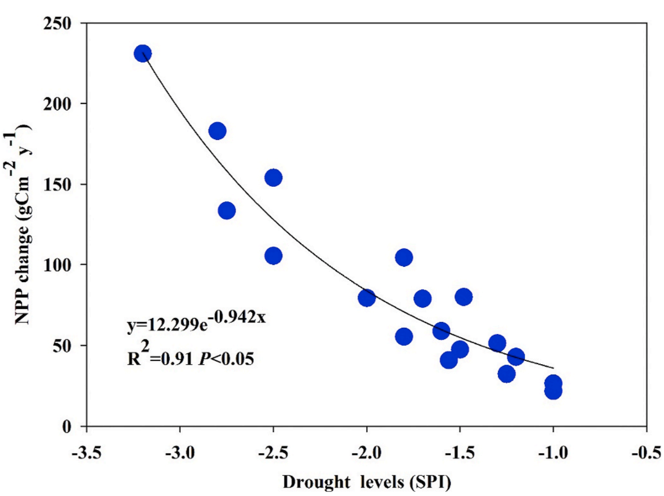

Fig. 8. The response of NPP change in three grassland types to same drought-level.

12-month SPI in typical steppe were the highest (R > 0.72), followed by meadow steppe (R > 0.66), and desert steppe (R > 0.5). The results were consistent with the effect of precipitation gradient change in meadow-typical-desert steppe, indicating that the stability of desert steppe resistance to drought was relatively high (Guo et al., 2012). We

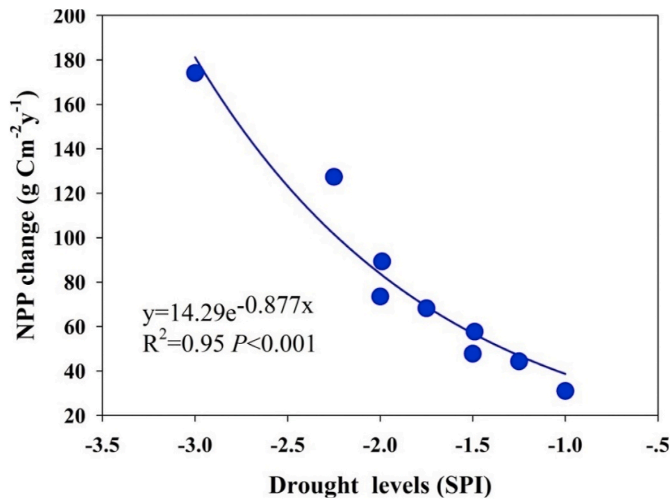

Fig. 9. The response of NPP change to different drought levels.

found that when the degree of drought gradually increased, the plant NPP gradually decreased and the plant growth potential became worse. Some scholars found that the degree of change in productivity depends on the physiological response of plants to the acquisition of available water and the change of vegetation structure during the drought period (Meir et al., 2008). Therefore, drought was the main trigger of inter-annual variation of NPP.

3.3. NPP loss of different drought-levels in grasslands

Aiming to differentiate the impacts of different drought events in different types of grassland productivity, we studied the quantitative impacts of different drought events on NPP. As shown in Fig. 6, for the meadow steppe, the average loss resulted from moderate, severe and extreme drought was 57.66, 89.29 and 174.13 gC/m^2/yr, respectively. As a representative of meadow steppe, NPP loss reduced by moderate, severe, and extreme drought was 79.95, 133.53 and 182.91 gC/m^2/yr at Hailaer site, respectively. For the typical steppe, the average loss resulted from moderate, severe and extreme drought was 44.29, 68.21 and 127.38 gC/m^2/yr, respectively. As a representative of typical steppe, NPP loss caused by moderate, severe, and extreme drought was 26.45, 47.45 and 55.40 gC/m^2/yr at Abag Banner site, respectively. For the desert steppe, the average loss reduced by moderate, severe and extreme drought was 31.02, 47.75 and 73.45 gC/m^2/yr, respectively. As a representative of desert steppe, NPP loss reduced by moderate, severe, and extreme drought was 21.75, 32.3 and 40.8 gC/m^2/yr at Alxa Right Banner site, respectively. NPP decreased significantly with the increase

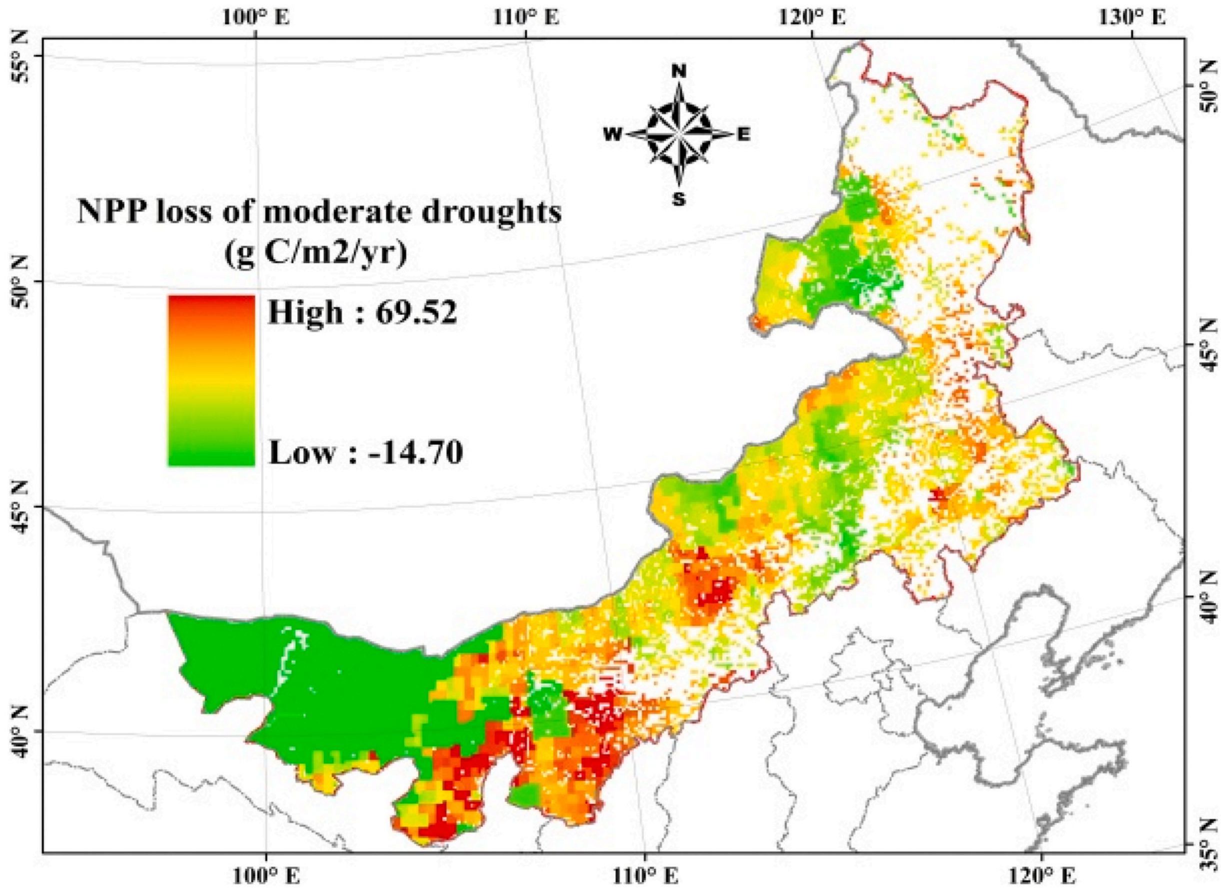

Fig. 10. NPP loss of different grassland types caused by moderate drought.

of drought severity (Chen et al., 2012).

For moderate drought, NPP loss in meadow, typical and desert steppe was 57.66, 44.29, and 31.02 gC/m^2/yr, respectively, as shown in Fig. 6(b). For severe drought, NPP loss in meadow, typical and desert steppe was 89.29, 68.21, and 47.75 gC/m^2/yr respectively. For extreme drought, NPP loss in meadow, typical and desert steppe was 174.13, 127.38, and 73.45 gC/m^2/yr, respectively. Therefore, the response of NPP to different drought levels was different, and NPP loss variation in different grassland types under the same level of drought was dramatically different. At the same time, average productivity of different grasslands was decreased in meadow steppe, typical steppe, desert steppe, respectively. The determinant coefficient of 0.62, 0.60, and 0.47 between NPP change and drought decreased in desert steppe, typical steppe, meadow steppe, respectively. It was indicated that the effect of drought on NPP of different grassland types gradually decreased with the increase of precipitation from west to east in Inner Mongolia.

For the same grassland type, NPP loss also increased gradually by an exponential growth relationship from moderate drought, severe drought to extreme drought (Hu, 2010). At the same time, we used the measured data and long-term observation data of animal husbandry meteorological station to assess the effect mechanism of drought levels. Meanwhile, we found that the NPP also showed a significant exponential change with soil moisture content in different grassland types ($R^2 = 0.92$, $P < 0.001$), as shown in Fig. 7. On the whole, the responded fastest of NPP change under different drought-levels in meadow steppe, typical steppe, and desert steppe was 0.848,1.034, and 1.083, respectively. When drought levels were moderate and severe drought, the responsive rate of the NPP of desert steppe to moderate and severe drought was lower than that of the NPP of meadow and typical steppe. However, when drought level was extreme drought, the responsive rate of the NPP of desert steppe to extreme drought was higher than that of the NPP of meadow and typical steppe. Thereby, it was not the gradual increase or decrease of drought responsive rate along the gradient change of meadow, typical and desert steppe, but the more complex responsive relationship. The relationship showed that there was also a significant exponential relationship between NPP change and drought in different grasslands. Moreover, NPP changes exponentially with annual precipitation (Chou et al., 2008). Also, Peng found that the annual precipitation decreased by 10%, 20% and 30% respectively in Inner Mongolia grassland, while NPP decreased by 27%, 42% and 54%, respectively (Peng et al., 2013). Some scholars also found that the annual precipitation of NPP changed exponentially (LeHouerou, 1984). When drought intensity reached the peak, the correlation between drought and NPP anomalies was the highest (Pei et al., 2013). In the precipitation simulation experiment, 5%, 10%, 20%, 30%, 50% and 75% of the precipitation deficit were designed to represent different degrees of drought, and it was found that NPP loss became more and more serious with the aggravation of drought in the relationship of exponential change (Lei et al., 2015).

Meanwhile, mean grassland productivity loss induced-by the total drought events among meadow, typical and desert steppe reduced by 128.31, 49.56, 39.95 gC/m^2/yr over nearly 50 years, respectively. This result was consistent with the distribution of drought condition, rainfall and grassland types. And also, NPP loss was lower in typical steppe and greater in meadows and desert steppes. As the results showed that typical steppe had higher stability and adaptability to drought than extreme dry (desert steppe) or wet areas (meadow steppe). That was a very significant phenomenon. The relationship of the results with the species diversity in different grassland types and the environmental adaptability of different species was close (Tilman et al., 1996). Due to different species had different respond to these fluctuations and led to functional compensations among species, the plant diversity of grassland could provide a buffer against environmental fluctuations (Smith,

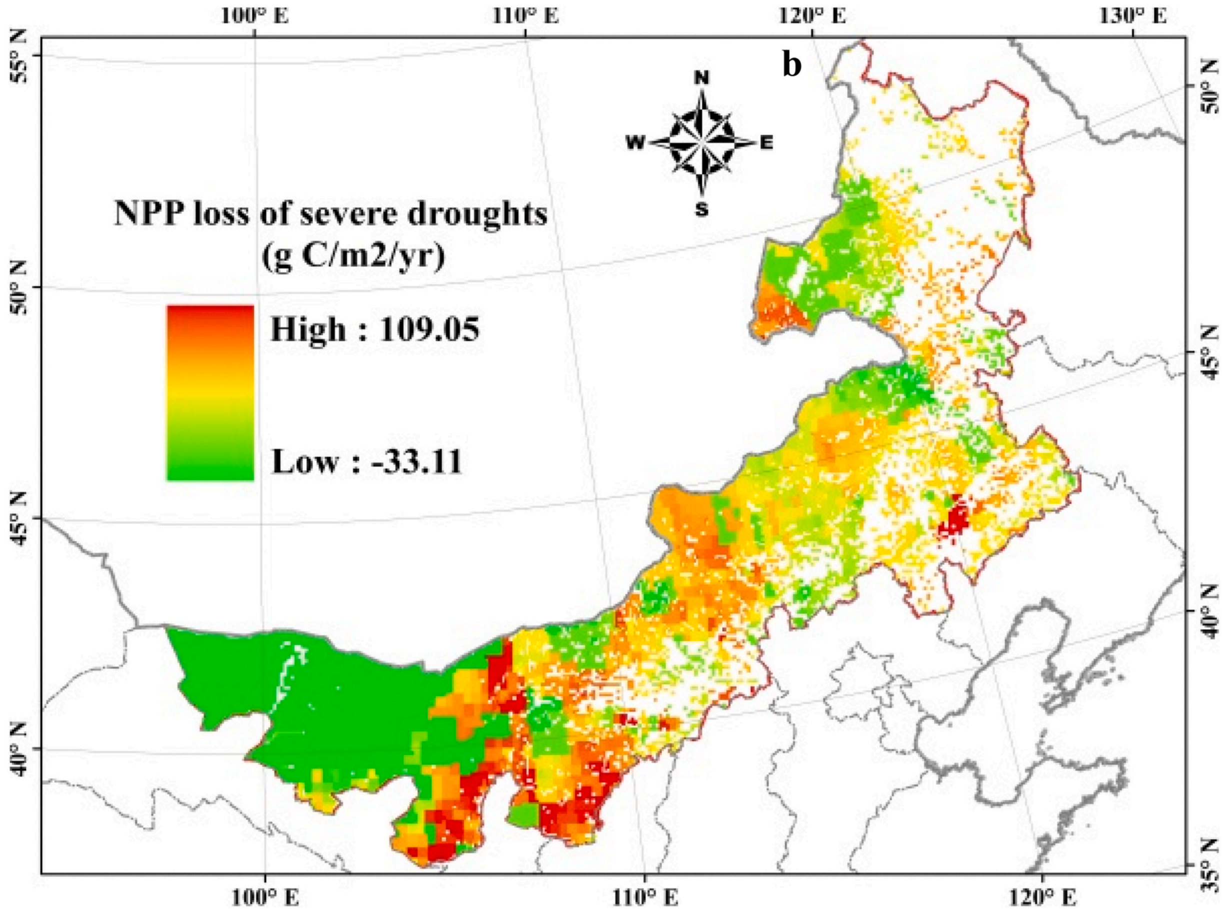

Fig. 11. NPP loss of different grassland types caused by severe drought.

2011). Therefore, the effects of drought in different grassland types were noticeably different.

Moreover, NPP loss in desert, typical and meadow steppe of the same drought level increased gradually in exponential relationship, as shown in Fig. 8. In arid and semi-arid areas, NPP was controlled by water factors strongly (Ni, 2004). Some scholars found that different grassland ecosystems have different species and utilization efficiency of resources (Lei et al., 2015). Also, community structure and species diversity were important determinants of community productivity (Zheng et al., 2010). There were significant differences in response of different species composition or community structure to external disturbance (drought) (Huxman et al., 2004; Kahmen et al., 2005). Thereby, the effects of same drought level in different grassland types were significantly difference.

Furthermore, we found that the change of NPP showed a significant exponential change with drought intensity levels ($R^2 = 0.95$, $p < 0.001$), as shown in Fig. 9. Moreover, some scholars found that NPP (Bloor and Bardgett, 2012) decreased significantly (Chimner and Welker, 2005) with increasing drought intensity (Chen et al., 2012). Other scholars also found that the difference in (Knapp and K, 2002) the impact of (LeHouerou, 1984)drought on regional NPP in (Oo et al., 2020) China was mainly due (Ryan and Law, 2005)to drought intensity, duration and different vegetation types (Pei et al., 2013). Therefore, there were significant differences in the effects of different grades of drought on the same grassland type, and the effects of the same level of drought on different grassland ecosystems were also various, due to the different responsive rate of the NPP in different grasslands.

However, the percentage of NPP loss in desert, typical and meadow steppe reduced by 20.5%, 13.1% and 17.5%, respectively. The percentage of NPP loss in meadow, typical and desert steppe was U-shaped, and NPP loss percentage of meadow and desert steppe was nearly close. NPP loss in meadow, typical and desert steppe showed the phenomenon of high at both ends and low in the middle. The results were consistent with the conclusion that precipitation plays a more important role in determining NPP of desert and meadow steppe than that of typical steppe (Guo et al., 2012). The responsive rate of NPP change to drought in typical steppe may be higher than that of meadow steppe under the same condition, although NPP loss of meadow grassland was relatively more. Under moderate and severe drought conditions, the responsive rate of NPP change to drought in typical steppe was higher than that of desert steppe to drought. It was indicated that the response of NPP to drought was closely related to the types of ecosystems, the severity (intensity and duration) of drought events, and the base of ecosystem productivity. Peng et al. found that annual precipitation, seasonal distribution and frequency significantly regulated the basic process of grassland carbon cycle in Inner Mongolia. The uncertainty of drought impact on productivity in Inner Mongolia was mainly determined by drought intensity, duration and affected area, and the cumulative and lagging effects of vegetation on precipitation deficit (Pei et al., 2013). Uncertainty of grassland productivity change may also be mainly controlled by interannual climate fluctuations and biomass dynamics (Flanagan et al., 2002).

The effect of drought on grassland productivity was closely related to vegetation type and its growing environment (Zhang et al., 2014). The desert steppe had high resistance stability and low resilience stability due to few species in desert steppe. It was difficult to recover once drought damaged, which had a serious impact on NPP. The typical steppe had medium resistance and resilience stability, so NPP loss caused by drought was in the middle of the loss between meadow and desert steppe, because NPP can quickly return to the level close to that before drought after drought. The meadow steppe had low resistance

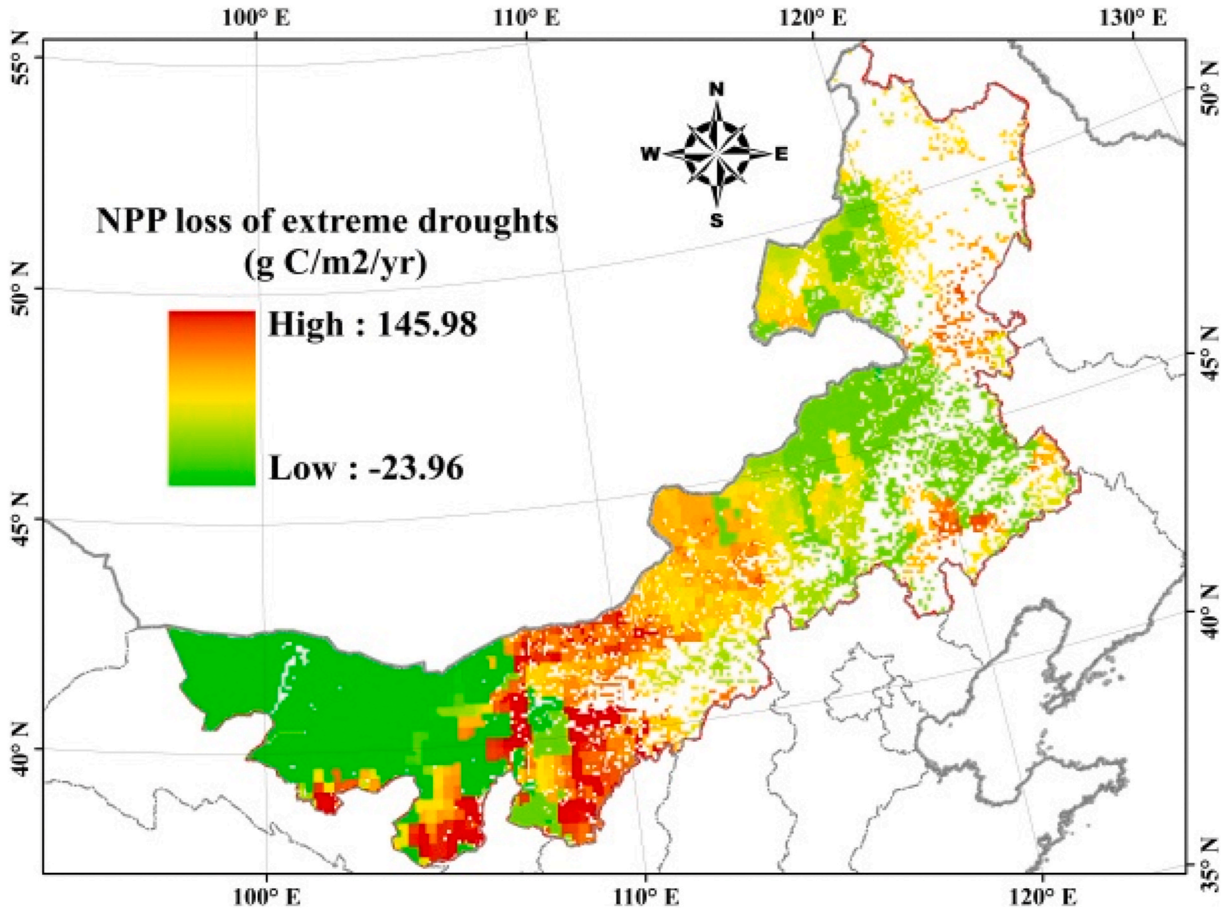

Fig. 12. NPP loss of different grassland types caused by extreme drought.

stability and high resilience stability. Although drought had a great impact on ANPP, it had no impact on the huge BNPP. After drought, NPP can quickly recover to pre-drought conditions after the end of drought, avoiding the serious impact of drought on productivity (Shinoda et al., 2010). Thus, the resistance of meadow grassland to drought was lower, but the resilience was higher than that of typical steppe and desert steppe.

3.4. Spatial distribution of NPP loss under drought levels

Furthermore, we evaluated the quantitative impact of drought on regional NPP, especially on moderate, severe and extreme drought. As shown in Fig. 10, the average NPP loss was 22.18 gC/m^2/yr and the maximum loss was 69.52 gC/m^2/yr caused by moderate drought events in Inner Mongolia grassland. The results showed that the average NPP loss of meadow, typical and desert steppe caused by moderate drought was 21.15, 20.38 and 9.51 gC/m^2/yr, respectively. However, we found that the moderate drought in the northeast of typical steppe and the west of desert steppe results in the increase of NPP (when NPP is negative), while the NPP loss was more serious in the southwest of meadow steppe, the middle and southwest of typical steppe and the southeast of desert steppe. As shown in Fig. 11, the average NPP loss was 36.07 gC/m^2/yr and the maximum loss was 109.05 gC/m^2/yr caused by severe drought events in meadow steppe. The results showed that the average NPP loss of meadow, typical and desert steppe caused by severe drought events was 32.99, 36.29 and 14.57 gC/m^2/yr, respectively. Severe drought also resulted in the increase of NPP in the middle of meadow steppe, the west and northeast of typical steppe and the west of desert steppe, while NPP loss in the southwest and southeast of meadow steppe, the middle and southwest of typical steppe and the southeast of desert steppe was relatively serious. As shown in Fig. 12, the average NPP loss was 52.62 gC/m^2/yr and the maximum loss was 145.98 gC/m^2/yr caused by extreme drought events in Inner Mongolia. According to the analysis of different steppe types, the average NPP loss in meadow, typical and desert steppe caused by extreme drought was 49.16, 52.61 and 59.82 gC/m^2/yr, respectively. Extreme drought resulted in the increase of NPP in the east of typical steppe, the south of meadow steppe and the west of desert steppe, NPP loss was relatively large in the southwest and middle of meadow steppe, the middle and southwest of typical steppe and the south of desert steppe. Generally, drought was mostly mild or moderate, and NPP sometimes increased because of a smaller increase in GPP relative to ecosystem respiration (Liu et al., 2014). The water-use efficiency and net carbon uptake capacity were increased following a drought without changes in respiration, thereby promoting a net carbon uptake into the system (Baldocchi and Ryu, 2011). Moreover, elevated atmospheric CO_2 concentrations may more or less reduce the vulnerability of grassland productivity to drought (Soussana and Lüscher, 2007). Inversely, droughts had not been alleviated by increasing biodiversity richness. Intriguingly, frequent mild droughts did not change the productivity patterns, and with increasing biodiversity richness that did not enhance resistance to severe droughts (Zavalloni et al., 2008).

4. Conclusions

Drought that is one of the natural hazards affect human life and nature ecosystems widely. How to quantitatively estimate the impacts of drought on grassland ecosystem has been a hard work for a long time. Based on the ecological process model (Biome-BGC) and SPI, a quantitative assessment method to assess quantitatively different drought levels on productivity in different grasslands was proposed based-on model-data fusion. Also, drought was the main trigger of interannual variation of NPP. In addition, NPP loss caused by moderate, severe and extreme drought was dramatically different in grasslands, and NPP loss showed a significant exponential change with gradient of different drought-levels. Furthermore, NPP loss variation in different grassland types under the same drought level was significantly different and the influences of different drought-levels in same grassland type was also different. Besides, the effect of drought on NPP gradually decreased in desert, typical and meadow steppe. For the same grassland type, NPP loss also increased gradually by an exponential growth relationship from moderate drought, severe drought to extreme drought. However, the percentage of NPP loss in meadow, typical and desert steppe was U-shaped, and NPP loss percentage of meadow and desert steppe was nearly close. The response of NPP to drought was closely related to the types of ecosystems, the severity (intensity and duration) of drought events, and the base of ecosystem productivity. Meanwhile, our results can offer scientific basis to improve assessment impact of extreme climate events used by ecosystem model and data, and cope with carbon cycling management and climate change.

Author contributions

Tianjie Lei, Juan LV and Jiabao Wang designed the draft framework and wrote the initial draft. Tianjie Lei, Jiabao Wang and Hongquan Song revised the draft framework. The other authors modified and supplemented the ideas, examples and references for the final draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research received financial support from National Key R&D Program of China (2018YFC0407706 & 2017YFC1502404), National Natural Science Foundation of China (41601569 & 51779269), and IWHR Research & Development Support Program (JZ0145B612016).

References

Abdulrazzaq, Z.T., Hadi, R., Aziz, N.A., 2019. Integrated TRMM data and standardized precipitation index to monitor the meteorological drought. Civ. Eng. J. 5 (7), 1590–1598. https://doi.org/10.28991/cej-2019-03091355.

Abudu, S., Sheng, Z., Sabzi, H.Z., et al., 2018. Drought scenario analysis using RiverWare: a case study in Urumqi River Basin, China. Civ. Eng. J. 4 (8), 1837–1860. https://doi.org/10.28991/cej-03091118.

Acharya, B.S., Rasmussen, J., Eriksen, J., 2012. Grassland carbon sequestration and emissions following cultivation in a mixed crop rotation. Agric. Ecosyst. Environ. 153 (24), 33–39. https://doi.org/10.1016/j.agee.2012.03.001.

Baldocchi, D.D., Ryu, Y., 2011. A synthesis of forest evaporation fluxes–from days to years–as measured with eddy covariance. In: Forest Hydrology and Biogeochemistry. Springer, Dordrecht, pp. 101–116. https://doi.org/10.1007/978-94-007-1363-5_5.

Bloor, J.M.G., Bardgett, R.D., 2012. Stability of above-ground and below-ground processes to extreme drought in model grassland ecosystems: interactions with plant species diversity and soil nitrogen availability. Perspect. Plant Ecol. Evol. Systemat. 14 (3), 193–204. https://doi.org/10.1016/j.ppees.2011.12.001.

Chen, G., Tian, H., Zhang, C., Liu, M., Ren, W., Zhu, W., et al., 2012. Drought in the southern United States over the 20th century: variability and its impacts on terrestrial ecosystem productivity and carbon storage. Clim. Chang. 114 (2), 379–397. https://doi.org/10.1007/s10584-012-0410-z.

Chimner, R., Welker, J., 2005. Ecosystem respiration responses to experimental manipulations of winter and summer precipitation in a Mixedgrass Prairie, WY, USA. Biogeochemistry 73, 257–270. https://doi.org/10.1007/s10533-004-1989-6.

Chou, W.W., Silver, W.L., Jackson, R.D., et al., 2008. The sensitivity of annual grassland carbon cycling to the quantity and timing of rainfall. Global Change Biol. 14 (6), 1382–1394. https://doi.org/10.1111/j.1365-2486.2008.01572.x.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., et al., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature (London) 437 (7058), 529–533. https://doi.org/10.1038/nature03972.

Costanza, R., Wilson, M.A., Troy, A., Voinov, A., Liu, S., D'Agostino, J., 2006. The Value of New Jersey's Ecosystem Services and Natural Capital. https://doi.org/10.1038/387253a0.

Fang, J., Yu, G., Liu, L., Hu, S., Chapin, F.S., 2018. Climate change, human impacts, and carbon sequestration in China. Proc. Natl. Acad. Sci. Unit. States Am. 115 (16), 4015–4020. https://doi.org/10.1073/pnas.1700304115.

Flanagan, L.B., Wever, L.A., Carlson, P.J., 2002. Seasonal and interannual variation in carbon dioxide exchange and carbon balance in a northern temperate grassland. Global Change Biol. 8 (7), 599–615. https://doi.org/10.1046/j.1365-2486.2002.00491.x.

Guo, Q., Hu, Z., Li, S., Li, X., Sun, X., Yu, G., 2012. Spatial variations in aboveground net primary productivity along a climate gradient in eurasian temperate grassland: effects of mean annual precipitation and its seasonal distribution. Global Change Biol. 18 (12), 3624–3631. https://doi.org/10.1111/gcb.12010.

Herbel, C.H., Ares, F.N., Wright, R.A., 1972. Drought effects on a semidesert grassland range. Ecology 53, 1084–1093. https://doi.org/10.2307/1935420.

Hu, Z., 2010. Precipitation-use efficiency along a 4500-km grassland transect. Energy Ecosyst. Environ. Chang. 19 (6), 842–851. https://doi.org/10.1111/j.1466-8238.2010.00564.x.

Huxman, T.E., Cable, J.M., Ignace, D.D., Eilts, J.A., English, N.B., Williams, W.D.G., 2004. Response of net ecosystem gas exchange to a simulated precipitation pulse in a semi-arid grassland: the role of native versus non-native grasses and soil texture. Oecologia 141 (2), 295–305. https://doi.org/10.2307/40005688.

Jentsch, A., Kreyling, J., Elmer, M., Gellesch, E., Glaser, B., Grant, K., et al., 2011. Climate extremes initiate ecosystem-regulating functions while maintaining productivity. J. Ecol. 99 (3), 689–702.

Kahmen, A., Perner, J., Buchmann, N., 2005. Diversity-dependent productivity in semi-natural grasslands following climate perturbations. Funct. Ecol. 19 (4), 594–601. https://doi.org/10.1111/j.1365-2435.2005.01001.x.

Kemp, D.R., Guodong, H., Xiangyang, H., Michalk, D.L., Yingjun, Z., 2013. Innovative grassland management systems for environmental and livelihood benefits. Proc. Natl. Acad. Sci. Unit. States Am. 110 (21), 8369–8374. https://doi.org/10.1073/pnas.1208063110.

Knapp, K, A., 2002. Rainfall variability, carbon cycling, and plant species diversity in a mesic grassland. Science 298 (5601), 2202–2205. https://doi.org/10.1126/science.1076347.

Kreyling, J., Beierkuhnlein, C., Elmer, M., Pritsch, K., Radovski, M., Schloter, M., et al., 2008. Soil biotic processes remain remarkably stable after 100-year extreme weather events in experimental grassland and heath. Plant Soil 308 (s1–2), 175–188. https://doi.org/10.1007/s11104-008-9617-1.

LeHouerou, H.N., 1984. Rain use efficiency: a unifying concept in arid-land ecology. J. Arid Environ. 7 (3), 213–247. https://doi.org/10.1016/S0140-1963(18)31399-5.

Lei, T., Pang, Z., Wang, X., Li, L., Fu, J., Kan, G., Shao, C., 2016. Drought and carbon cycling of grassland ecosystems under global change: a review. Water 8 (10), 460. https://doi.org/10.3390/w8100460.

Lei, T., Wu, J., Li, X., Geng, G., Shao, C., Zhou, H., et al., 2015. A new framework for evaluating the impacts of drought on net primary productivity of grassland. Sci. Total Environ. 536, 161–172. https://doi.org/10.1016/j.scitotenv.2015.06.138.

Liu, Y., Zhou, Y., Ju, W., Wang, S., Wu, X., He, M., et al., 2014. Impacts of droughts on carbon sequestration by China's terrestrial ecosystems from 2000 to 2011. Biogeosciences 11 (10), 2583–2599. https://doi.org/10.5194/bg-11-2583-2014.

Lloyd-Hughes, B., Saunders, M.A., 2002. A drought climatology for Europe. Int. J. Climatol. 22 (13), 1571–1592. https://doi.org/10.1002/joc.846.

Ma, Ruifang, 2007. Climate Change During the Past 50 Years and its Impact on the Production Ability in Inner Monglia Grassland. Chinese Academy of Agricultural Sciences Dissertation, pp. 5–79.

Meir, P., Metcalfe, D.B., Costa, A.C.L., Fisher, R.A., 2008. The fate of assimilated carbon during drought: impacts on respiration in amazon rainforests. Phil. Trans. Biol. Sci. 363 (1498), 1849–1855. https://doi.org/10.1098/rstb.2007.0021.

Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. J. Hydrol. (Amst.) 391 (1–2), 202–216. https://doi.org/10.1111/j.1399-3054.2005.00586.x.

Ni, J., 2004. Estimating net primary productivity of grasslands from field biomass measurements in temperate northern China. Plant Ecol. 174 (2), 217–234. https://doi.org/10.1023/B:VEGE.0000049097.85960.10.

Oo, H.T., Zin, W.W., Kyi, C.C.T., 2020. Analysis of streamflow response to changing climate conditions using SWAT model. Civ. Eng. J. 6 (2), 194–209.

Pei, F., Li, X., Liu, X., Lao, C., 2013. Assessing the impacts of droughts on net primary productivity in China. J. Environ. Manag. 114 (Complete), 362–371. https://doi.org/10.1016/j.jenvman.2012.10.031.

Peng, S., Piao, S., Shen, Z., Ciais, P., Sun, Z., Chen, S., et al., 2013. Precipitation amount, seasonality and frequency regulate carbon cycling of a semi-arid grassland ecosystem in inner Mongolia, China: a modeling analysis. Agric. For. Meteorol. 178–179 (Complete), 46–55. https://doi.org/10.1016/j.agrformet.2013.02.002.

Pereira, J.S., Mateus, J.A., Aires, L.M., Pita, G., Rodrigues, A., 2007. Net ecosystem carbon exchange in three contrasting mediterranean ecosystems - the effect of drought. Biogeosciences 4 (5). https://doi.org/10.5194/bg-4-791-2007.

Raich, J.W., Tufekciogul, A., 2000. Vegetation and soil respiration: correlations and controls. Biogeochemistry 48 (1), 71–90. https://doi.org/10.1023/A:1006112000616.

Ryan, M.G., Law, B.E., 2005. Interpreting, measuring, and modeling soil respiration. Biogeochemistry (Dordrecht) 73 (1), 3–27. https://doi.org/10.1007/s10533-004-5167-7.

Scott, R.L., Hamerlynck, E.P., Jenerette, G.D., Moran, M.S., Barron-Gafford, G.A., 2010. Carbon dioxide exchange in a semidesert grassland through drought-induced vegetation change. J. Geophys. Res. 115, G03026. https://doi.org/10.1029/2010JG001348.

Shi, Z., Thomey, M.L., Mowll, W., et al., 2014. Differential Effects of Extreme Drought on Production and Respiration: Synthesis and Modeling Analysis. https://doi.org/10.5194/bgd-10-16043-2013.

Shinoda, M., Nachinshonhor, G.U., Nemoto, M., 2010. Impact of drought on vegetation dynamics of the Mongolian steppe: a field experiment. J. Arid Environ. 74 (1), 63–69. https://doi.org/10.1016/j.jaridenv.2009.07.004.

Smith, M.D., 2011. The ecological role of climate extremes: current understanding and future prospects. J. Ecol. 99 (3), 651–655. https://doi.org/10.1111/j.1365-2745.2011.01833.x.

Soussana, J.F., Lüscher, A., 2007. Temperate grasslands and global atmospheric change: a review. Grass Forage Sci. 62 (2), 127–134. https://doi.org/10.1111/j.1365-2494.2007.00577.x.

Spinoni, J., Naumann, G., Carrao, H., Barbosa, P., Vogt, J., 2014. World drought frequency, duration, and severity for 1951–2010. Int. J. Climatol. 34 (8), 2792–2804. https://doi.org/10.1002/joc.3875.

Tilman, D., Wedin, D., Knops, J., 1996. Productivity and sustainability influenced by biodiversity in grassland ecosystems. Nature (London) 379 (6567), 718–720. https://doi.org/10.1038/379718a0.

van der Molen, M.K., Dolman, A.J., Ciais, P., Eglin, T., Gobron, N., Law, B.E., Chen, T., 2011. Drought and ecosystem carbon cycling. Agric. For. Meteorol. 151 (7), 765–773. https://doi.org/10.1016/j.agrformet.2011.01.018.

Vicente-Serrano, S.M., 2007. Evaluating the impact of drought using remote sensing in a Mediterranean, semi-arid region. Nat. Hazards 40 (1), 173–208. https://doi.org/10.1007/s11069-006-0009-7.

White, M.A., Thornton, P.E., Running, S.W., Nemani, R.R., 2000. Parameterization and sensitivity analysis of the BIOME-BGC terrestrial ecosystem model: net primary production controls. Earth Interact. 4 (3), 1–84. https://doi.org/10.1175/1087-3562(2000)0042.0.CO.

Wilhite, D.A., 2005. Drought and Water Crises: Science, Technology, and Management Issues. CRC Press.

Wu, X., Kang, X., Liu, W., Cui, X., Hao, Y., Wang, Y., 2018. Using the DNDC model to simulate the potential of carbon budget in the meadow and desert steppes in Inner Mongolia, China. J. Soils Sediments 18 (1), 63–75. https://doi.org/10.1007/s11368-017-.

Yao, N., Li, Y., Lei, T., Peng, L., 2018. Drought evolution, severity and trends in mainland China over 1961–2013. Sci. Total Environ. 616, 73–89. https://doi.org/10.1016/j.scitotenv.2017.10.327.

Zavalloni, C., Gielen, B., Lemmens, C.M.H.M., Boeck, H.J.D., Blasi, S., Bergh, S.V.D., et al., 2008. Does a warmer climate with frequent mild water shortages protect grassland communities against a prolonged drought? Plant Soil 308 (1–2), 119–130. https://doi.org/10.1007/s11104-008-9612-6.

Zhang, L., Guo, H., Jia, G., Wylie, B., Gilmanov, T., Howard, D., et al., 2014. Net ecosystem productivity of temperate grasslands in northern China: an upscaling study. Agric. For. Meteorol. 184, 71–81. https://doi.org/10.1016/j.agrformet.2013.09.004.

Zhao, M., Running, S.W., 2010. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. Science 329 (5994), 940–943. https://doi.org/10.1126/science.1192666.

Zheng, X.X., Liu, G.H., Fu, B.J., Jin, T.T., Liu, Z.F., 2010. Effects of biodiversity and plant community composition on productivity in semiarid grasslands of Hulunbeir, Inner Mongolia, China. Ann. N. Y. Acad. Sci. 1195, E52–E64. https://doi.org/10.1111/j.1749-6632.2009.05405.x.