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A new framework for evaluating the impacts of drought on net primary productivity of grassland

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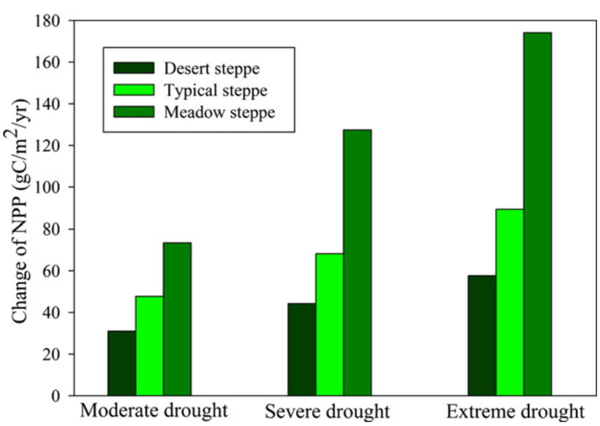
HIGHLIGHTS

- A framework was presented to assess drought impacts on NPP of grassland ecosystem.
- Total and mean NPP losses are different in different grasslands during drought years.
- NPP loss of different drought levels was assessed and significantly different.
- Same drought-level displayed markedly different NPP-loss in different grasslands.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presented a valuable framework for evaluating the impacts of droughts (single factor) on grassland ecosystems. This framework was defined as the quantitative magnitude of drought impact that unacceptable short-term and long-term effects on ecosystems may experience relative to the reference standard. Long-term effects on ecosystems may occur relative to the reference standard. Net primary productivity (NPP) was selected as the response indicator of drought to assess the quantitative impact of drought on Inner Mongolia grassland based on the Standardized Precipitation Index (SPI) and BIOME-BGC model. The framework consists of six main steps: 1) clearly defining drought scenarios, such as moderate, severe and extreme drought; 2) selecting an appropriate indicator of drought impact; 3) selecting an appropriate ecosystem model and verifying its capabilities, calibrating the bias and assessing the uncertainty; 4) assigning a level of unacceptable impact of drought on the indicator; 5) determining the response of the indicator to drought and normal weather state under global-change; and 6) investigating the unacceptable impact of drought at different spatial scales. We found NPP losses assessed using the new framework were more sensitive to drought and had higher precision than the long-term average method. Moreover, the total and average losses of NPP are different in different grassland types during the drought years from 1961–2009. NPP loss was significantly increased along a gradient of increasing drought

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levels. Meanwhile, NPP loss variation under the same drought level was different in different grassland types. The operational framework was particularly suited for integrative assessing the effects of different drought events and long-term droughts at multiple spatial scales, which provided essential insights for sciences and societies that must develop coping strategies for ecosystems for such events.

1. Introduction

Global change may intensify the hydrological cycle and increase the frequency of extreme weather events such as droughts (Jentsch and Beierkuhnlein, 2008). On a global scale, the frequency, duration and severity of droughts have increased substantially in recent decades (Dai, 2011), especially in arid and semi-arid regions (Solomon, 2007). Meanwhile, droughts can have serious and damaging effects on human society and natural ecosystems (Lambers et al., 2008; Meehl et al., 2000). Multiple pieces of evidence assert that future droughts, characterized by stronger magnitudes, longer durations, and higher frequencies, are out of synchrony with the stress thresholds of ecosystems and are expected to influence the biogeochemical cycle more strongly in the future (Parmesan, 2006; Sheffield and Wood, 2012).

In fact, droughts result in significant impacts on plant growth, productivity, structure, composition, and ecosystem functions, such as C-fixation as well as fluxes and pools (Jentsch et al., 2011; Xia et al., 2014). However, due to changing spatial and temporal characteristics of drought and complex ecosystem attributes, it is difficult to monitor and assess the potential impacts of droughts on ecosystems (Wang et al., 2014). Numerous studies have used many methods to measure the impacts of drought on carbon cycling, such as flux tower measurements and other field experiments (Baldocchi et al., 2001; Baldocchi, 2003), remote sensing (Asner et al., 2004; Zhao and Running, 2010), ecosystem models (Ciais et al., 2005; Woodward and Lomas, 2004) or integrating tower fluxes, satellite data and ecosystem modeling (Reichstein et al., 2007; Running et al., 1999). In the real world, however, there are many global-change drivers that alter the relationship between drought and carbon cycling via complicated mechanisms, such as elevated CO_2 concentrations, global warming, nitrogen deposition, grazing, and land-use change (Heimann and Reichstein, 2008). Global-change drivers can more or less change the impacts of droughts on carbon cycling, either singly or in combination.

However, few studies have investigated how much carbon loss is caused by the single-factor drought and different drought events. As yet, there is no unified framework to assess drought effects compared to different assessment criteria. Above all, an integrated modeling framework or methods should be established to integratively analyze the quantitative linkages between drought and carbon loss. Therefore, the primary objectives of this paper are to (1) develop an integrated assessment framework of drought-impact on ecosystems, and (2) estimate the quantitatively unacceptable-impact of different drought events.

2. Study area and data

We chose representative grassland ecosystems as the research subjects, using the framework to assess the quantitative impact of drought on carbon cycling. Grassland plays a significant role in water and carbon cycles (Abberton et al., 2010). Grassland comprises approximately 40.5% of the Earth's land area and accounts for approximately 34% of total terrestrial ecosystem carbon (Kemp et al., 2013). Admittedly, water is a limiting factor for grassland vegetation growth in arid and semi-arid regions (Knapp et al., 2002). In addition, grasslands are more susceptible to droughts than other ecosystems (Coupland, 1958). Therefore, we chose six weather sites in Inner Mongolia to represent meadow, typical and desert steppe as the study area, as shown in Fig. 1.

Inner Mongolia grasslands (located at 97°12′–126°04′E, 37°24′–53°23′N) in China are dominated by three major types of ecosystems: meadow, typical and desert steppe. The terrain in the study area is mainly plateau, including the Hulunbuir Plateau, Xilingole Plateau and the Ordos Plateau. The study area belongs to a typical temperate continental monsoon climate. The study area is located in the temperate semi-arid and semi-humid regions, with annual average temperature varying from 5–9 °C and annual average precipitation ranging from 150 to 500 mm, mainly concentrated from May to September. Meadow steppe located in the sub-humid zone of the eastern part of the study area is composed of mainly dominant herbaceous perennial mesophytic and xerophytic species, such as *Stipa baicalensis*, *Filifolium sibiricum*, and *Leymus chinensis*. A typical steppe spreads from the middle part of the region and is mainly composed of perennial typical xerophytic herbs, such as *S. grandis*, *S. krylovii*, and *L. chinensis*. The desert steppe is distributed in the western region, with dry–tolerant, dominant short grasses, such as *S. klemenzii* and *S. breviflora* (Sui and Zhou, 2013). In addition, the meadow, typical and desert steppes are mainly associated with chernozem, chestnut and brown calcic soil types, respectively (Ma et al., 2008).

In this paper, meteorological, soil, vegetation types and NPP of field observation data were used to drive and calibrate the BIOME-BGC model. Six sites from the China meteorological data sharing network (*http://cdc.cma.gov.cn*) provided nearly 50 (1961–2009) years of meteorological data, including daily maximum temperature, daily minimum temperature, average daily temperature, total daily rainfall, average vapor pressure, average short-wave radiation flux density and length of day. Monthly precipitation was used for the calculation of SPI in each month from 1961–2009. Vegetation types in the study area were compiled from the editorial board of Chinese vegetation type map at the scale of 1:1,000,000, which can be a very good expression of vegetation distribution (Chinese vegetation map editor committee of the Chinese academy of sciences, *http://www.geodata.cn*). Vegetation types in the study area include meadow steppe, typical grassland, and desert steppe, as shown in Fig. 1.

Soil texture (sand, silt and clay content) and depth data came from the International Soil Reference and Information Centre (ISRIC, *http://www.isric.org*). CO_2 data were obtained from Pro Oxygen from the Mauna Loa Observatory/NASA, Hawaii (*http://www.co2now.org*). Nitrogen-deposition data came from the UK Air Pollution Information System (APIS: *http://www.apis.ac.uk*). In this paper, NPP data were derived 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*). Also, NPP data was obtained from experimental stations that are mainly located in Inner Mongolia grassland, including Hailar (meadow steppe: 1980–2006), Xilinhot (typical steppe) and Urat banner sites (desert steppe). The details of those sites are described in Table 1.

3. Method

The critical loads and critical climate approaches are important means to evaluate the response of NPP to environmental changes. Critical loads is defined as “the quantitative assessment of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to current knowledge” (Nilsson, 1988). Critical loads are broadly used to evaluate emissions of pollutant deposition (acid,