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# Drought-induced dynamics of carbon and water use efficiency of global grasslands from 2000 to 2011

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ABSTRACT

Drought is frequently recorded as a result of climate warming and elevated concentration of greenhouse gases, which affect the carbon and water cycles in terrestrial ecosystems, particularly in arid and semi-arid regions. To identify the drought in grassland ecosystems and to determine how such drought affects grassland ecosystems in terms of carbon and water cycles across the globe, this study evaluated the drought conditions of global grassland ecosystems from 2000 to 2011 on the basis of the remotely sensed Drought Severity Index (DSI) data. The temporal dynamics of grassland carbon use efficiency (CUE) and water use efficiency (WUE), as well as their correlations with DSI, were also investigated at the global scale. Results showed that 57.04% of grassland ecosystems experienced a dry trend over this period. In general, most grassland ecosystems in the northern hemisphere (N.H.) were in near normal condition, whereas those in the southern hemisphere (S.H.) experienced a clear drying and wetting trend, with the year 2005 regarded as the turning point. Grassland CUE increased continually despite the varied drought conditions over this period. By contrast, WUE increased in the closed shrublands and woody savannas but decreased in all the other grassland types. The drought conditions affected the carbon and water use mainly by influencing the primary production and evapotranspiration of grass through photosynthesis and transpiration process. The CUE and WUE of savannas was most sensitive to droughts among all the grassland types. The areas of grassland DSI that showed significant correlations with CUE and WUE were 52.92% and 22.11% of the total grassland areas, respectively. Overall, droughts sufficiently explained the dynamics of grassland CUE, especially in the S.H. In comparison with grassland CUE, the grassland WUE was less sensitive to drought conditions at the global scale.



## 1. Introduction

Water resources are essential for society and ecosystems. Increasing evidence indicates that the recent climate change has exacerbated the water resources stress by increasing water demand and shrinking water supplies. This condition has strong adverse effects on food security and poses great challenges to the sustainability of life (Vörösmarty et al., 2000; Rosegrant et al., 2003). Drought is an important adverse climate disturbance that is occurred globally, and it is expected to intensify in this century (IPCC, 2007, 2012). Droughts affect the terrestrial carbon and water cycles by reducing the carbon sequestration ability and aggravating the evaporation rate of ecosystems (Ciais et al., 2005; Van der Molen et al., 2011; Battipaglia et al., 2014). Carbon use efficiency (CUE), which is the ratio of net primary productivity (NPP) to gross primary productivity (GPP), and water use efficiency (WUE), which is the ratio of NPP to evapotranspiration (ET), are important indicators for addressing the interactions between the water and carbon cycles of terrestrial ecosystems (Webb et al., 1978; LeHouerou, 1984; Delucia et al., 2007). Several studies have evaluated the effects of climate variables on the CUE and WUE of ecosystems at

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multiple scales (Keenan et al., 2013; Adiredjo et al., 2014; Rowland et al., 2014; Zhang et al., 2014). Knowledge has advanced since the development of remote sensing technology with respect to the potential effects of climate change and other drivers on carbon and water cycles at large scales. Although the severity of droughts has been investigated extensively, its subsequent influences on terrestrial CUE and WUE are not well explored. Therefore, monitoring the extent and duration of droughts accurately and consistently is necessary, especially when assessing impacts and mitigating the distresses at global and regional scales.

Many indices have been developed to assess and monitor the occurrence of droughts from regional to global scale, e.g. the Standardized Precipitation Index (SPI) (McKee et al., 1995), the Palmer Drought Severity Index (PDSI) (Palmer, 1965), the Temperature-Vegetation Dryness Index (TVDI) (Sandholt et al., 2002), the Vegetation, Water and Thermal Stress Index (VWTCI) (Shakya and Yamaguchi, 2010). Developed by Mu et al. (2013), the Drought Severity Index (DSI), is an index that combines the meteorological and agricultural drought conditions. It is calculated on the basis of MODIS-derived Normalized Difference Vegetation Index (NDVI) and evapotranspiration/potential evapotranspiration (ET/PET) data with fine resolution at the global scale (Mu et al., 2013). The available DSI dataset extends from 2000 to 2011, and has been validated to capture the major droughts over the last decade worldwide (Zhao and Running, 2010; Mu et al., 2013; Zhang and Yamaguchi, 2014). Given on this, in the present study, the DSI data were used to monitor the extent and duration of drought spread in grassland ecosystems, as well as the effects of such drought spread on the water and carbon cycles of grassland ecosystems at the global scale.

Grassland ecosystems are among the largest distributed biomes, which occupy more than 30% of the Earth's land surface. Grasslands contribute significantly to food security by providing food for ruminants, which serve as sources of meat and milk for human consumption (Scurlock and Hall, 1998; O'Mara, 2012). Grassland ecosystems play a key role in balancing the global atmospheric greenhouse gases through the carbon and water cycles (French, 1979; O'Mara, 2012). Given that grassland ecosystems are mainly distributed in arid and semi-arid regions, temperature and precipitation are two key factors that control the growth and productivity of grass (Gang et al., 2015a,b). With the increasing frequency of climate extremes in recent decades, the effects of droughts on the structure, composition, and function of grassland ecosystems have been widely studied (Wolf et al., 2013; Bollig and Feller, 2014; Burri et al., 2014; Koerner and Collins, 2014; Manea and Leishman, 2014). Short-term droughts are likely to induce the plastic adjustment of the resident plants, whereas long-term progressive droughts would cause the species turnover within plant communities (Helmuth et al., 2005; Jung et al., 2014). However, most of these studies were conducted at the stand or local scale, hence, the understanding on how droughts affect the carbon and water use of grassland ecosystems, especially at the global scale, remain limited. This lack of extensive research represents an important knowledge gap.

The past decade was the warmest 10 years since the instrumental measurements of temperatures began in the 1880s (Zhao and Running, 2010). To address the aforementioned scientific problems during the "warmest decade", the present study primarily aims: (i) to characterize the extent and duration of drought occurred in global grassland ecosystems from 2000 to 2011 by using the remotely sensed DSI data; (ii) to quantify the annual changes in grassland GPP, NPP, ET, CUE, and WUE at the global scale during this period; and (iii) to calculate the correlations between grassland CUE, WUE and DSI, as well as the mean annual temperature (MAT) and mean annual precipitation (MAP), to reflect the how the grassland carbon and water use is controlled by environmental variables. The outcomes of this study do not only elucidate the extent and duration of droughts in global grassland ecosystems in recent years but also provide baselines for enhancing the sustainable carbon and water use in grasslands across the globe. In addition, the findings of this study may serve as guidelines for government and policy makers in initiating adaptation strategies to respond to the climate change and to manage grassland production.

## 2. Materials and methods

### 2.1. MODIS DSI, GPP, NPP, and ET data

Annual MODIS DSI, GPP, NPP and ET data (~1 km resolution) extending from 2000 to 2011 were obtained from the Numerical Terra dynamic Simulation Group at the University of Montana (http://www.ntsg.umt.edu/). These dataset are in TIFF format and the WGS84 geographic coordinate system, and were converted into a grid format.

For the remotely sensed DSI data, the ET/PET and snow-free growing season NDVI products of MODIS for all vegetated land areas from 2000 to 2011 were integrated with a 0.05° spatial resolution. The MODIS NDVI is sensitive to vegetation drought responses and associated water stress, especially in the water-limited regions. This situation provides a link between climate change and vegetation responses through greenness changes (Atkinson et al., 2011; Mu et al., 2013). The NDVI product has been successfully used to monitor the global vegetation photosynthetic activities (Huete et al., 2002; Justice et al., 2002). DSI is calculated as a standardized value, which is expressed as follows:

$$A_{\mathrm{NDVI}} = \frac{\mathrm{NDVI} - \overline{\mathrm{NDVI}}}{\delta_{\mathrm{NDVI}}} \tag{1}$$

$$A_{\mathrm{EVA}} = \frac{(\mathrm{ET/PET}) - \overline{(\mathrm{ET/PET})}}{\delta_{(\mathrm{ET/PET})}} \tag{2}$$

$$A = A_{\mathrm{NDVI}} + A_{\mathrm{EVA}} \tag{3}$$

$$\mathrm{DSI} = \frac{A - \overline{A}}{\delta_A} \tag{4}$$

where $A_{\mathrm{NDVI}}$ is the standardized anomaly of the NDVI, which is calculated using the long-term mean value of $\overline{\mathrm{NDVI}}$ and the standard deviation $\delta_{\mathrm{NDVI}}$ of the period 2000–2011; $A_{\mathrm{EVA}}$ is the standardized anomaly of ET/PET, which is calculated as the long-term mean value of $\overline{\mathrm{ET/PET}}$ and a standard deviation $\delta_{(\mathrm{ET/PET})}$; ET/PET is the ratio of ET to PET; $A$ is a sum of $A_{NDVI}$ and $A_{EVA}$; the DSI is a standardized anomaly of $A$; $\overline{A}$ is the long-term mean value of $A_{\mathrm{NDVI}}$ and $A_{(\mathrm{ET/PET})}$; $\delta_A$ is the standardized deviation. The categories of drought conditions based on DSI value is shown in Table 1 (Mu et al., 2013).

**Table 1**
The categories for drought conditions of the global DSI (Mu et al., 2013).

| Category | Description | DSI |
|---|---|---|
| D5 | Extremely drought | <−1.50 |
| D4 | Severe drought | −1.49 to −1.20 |
| D3 | Moderate drought | −1.99 to −0.9 |
| D2 | Mild drought | −0.89 to −0.60 |
| D1 | Incipient drought | −0.59 to −0.30 |
| WD | Near normal | −0.29 to 0.29 |
| W1 | Incipient wet | 0.30 to 0.59 |
| W2 | Slightly wet | 0.60 to 0.89 |
| W3 | Moderately wet | 0.90 to 1.19 |
| W4 | Very wet | 1.20 to 1.50 |
| W5 | Extremely wet | >1.50 |