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# Climate extremes and grassland potential productivity

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**Abstract**
The considerable interannual variability (IAV) (~5 PgC $yr^{-1}$) observed in atmospheric $CO_2$ is dominated by variability in terrestrial productivity. Among terrestrial ecosystems, grassland productivity IAV is greatest. Relationships between grassland productivity IAV and climate drivers are poorly explained by traditional multiple-regression approaches. We propose a novel method, the perfect-deficit approach, to identify climate drivers of grassland IAV from observational data. The maximum daily value of each ecological or meteorological variable for each day of the year, over the period of record, defines the 'perfect' annual curve. Deficits of these variables can be identified by comparing daily observational data for a given year against the perfect curve. Links between large deficits of ecosystem activity and extreme climate events are readily identified. We applied this approach to five grassland sites with 26 site-years of observational data. Large deficits of canopy photosynthetic capacity and evapotranspiration derived from eddy-covariance measurements, and leaf area index derived from satellite data occur together and are driven by a local-dryness index during the growing season. This new method shows great promise in using observational evidence to demonstrate how extreme climate events alter yearly dynamics of ecosystem potential productivity and exchanges with atmosphere, and shine a new light on climate–carbon feedback mechanisms.

**Keywords:** climate extremes, gross photosynthetic production (GPP), dryness, grasslands, perfect-deficit approach

S Online supplementary data available from stacks.iop.org/ERL/7/035703/mmedia

## 1. Introduction

Understanding how extreme climate events affect the potential of grassland ecosystems to absorb carbon is critical to developing policies for mitigating greenhouse gas emission and undesirable climate change. This is because: (1) the frequencies and intensities of droughts and extreme temperature events are increasing (Min *et al* 2010, Huntington 2006, Alexander *et al* 2006, Meehl and Tebaldi 2004, Easterling *et al* 2000) in a warming world; and (2) grassland ecosystems are quite vulnerable to extreme climate events that may turn these ecosystems from carbon sinks into sources (Zhang *et al* 2010, Fang *et al* 2001, Nemani *et al* 2003). However, our ability to quantify the response of an ecosystem to extreme climate events is limited. Although it is well known that grasslands are water-controlled ecosystems, a simplistic approach of linking precipitation with concurrent ecosystem production data masks important relationships between physical and ecological processes.

Three major disadvantages of using precipitation as an index to predict daily dynamic responses of semiarid grassland ecosystems to water availability are: (1) precipitation is a discontinuous input; (2) precipitation occurs stochastically (Noy-Meir 1973); and (3) its influence on ecosystem activities is not only immediate but can extend for days to months. To overcome these disadvantages and quantify the ecological consequences of drought events, we are in an imperative need of developing new concepts and approaches. In this letter, we proposed a new drought index and a new perfect-deficit approach, which can be used to identify the dynamic relationship of carbon absorption of grassland ecosystems with drought stresses. These new concepts and approaches are described in section 2. The results and discussion are given in section 3.

## 2. Method

### *2.1. Local dryness*

We define a property termed 'local dryness' ($D_L$) consisting of weighted values of the last 100 days' precipitation and net radiation:

$$D_L = \sum_{i=1}^{100} w(i) R_n(i) \Bigg/ \left(2500 \sum_{i=1}^{100} w(i) P(i)\right), \qquad (1)$$

where $P(i)$ and $R_n(i)$ are daily precipitation (mm $d^{-1}$) and net radiation (kJ $m^{-2}$ $d^{-1}$) at $i$ days ago, $w(i)$ is a linear weight function with a maximum at reference day ($i = 1$) and a minimum at 100 days ago ($i = 100$), and 2500 is a conversion factor for latent heat. The nature of $D_L$ is not sensitive to the chosen time period when $i$ is longer than 30 days (supplementary figure 1 available at stacks.iop.org/ERL/7/035703/mmedia). For longer time periods (>30 days), the magnitude of $D_L$ is smaller. For simplicity, we show results using 100 days as defined in equation (1).

### *2.2. Canopy photosynthetic capacity (CPC)*

The daily maximum potential carbon storage capacity of an ecosystem is termed the canopy photosynthetic capacity (CPC). For a given year, the daily CPC of ecosystems monitored by eddy-flux towers is defined by the maximum gross photosynthetic production (GPP) derived from $CO_2$ flux measurements with 30 min resolution (www.fluxnet.ornl.gov) by eddy-covariance techniques (Gu *et al* 2009). A yearly CPC curve is constructed from daily observation data and algorithmically smoothed (see supplementary materials available at stacks.iop.org/ERL/7/035703/mmedia). This CPC curve forms an upper boundary for the instantaneous canopy photosynthetic rates, and the area under the CPC curve (red curve in figure 1) represents ecosystem carbon assimilation

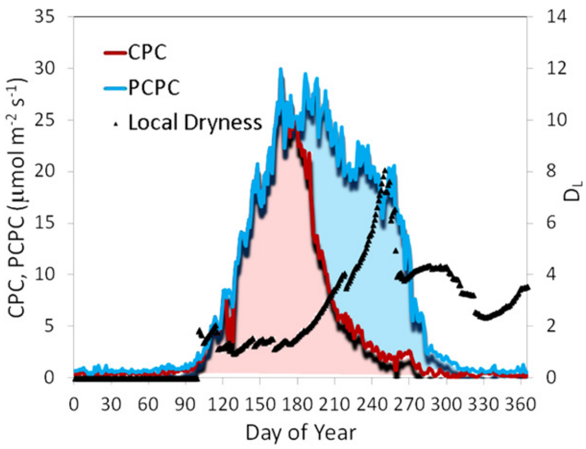


**Figure 1.** Illustration of the perfect-deficit concept: canopy photosynthetic capacity (CPC, red curve), perfect CPC (PCPC, blue curve), CPC deficit (blue area), and local dryness (filled triangle). The CPC values are the maximum values of half-hourly data of GPP derived from eddy-flux measurements in each day in 2003 at the CA-Let site in Canada. The PCPC values are the maximum values of CPC in each day across all years from 1999 to 2005. The CPC deficit is the difference between PCPC and CPC. The local dryness is calculated by equation (1). The data sources are the same as figure 3(g).

potential—how much carbon dioxide potentially can be assimilated by an ecosystem at a site in an individual year (Gu *et al* 2009). The dynamic relationship between the CPC and $D_L$, as well as other climate conditions, can therefore be examined from observation data.

### *2.3. Perfect CPC*

We hypothesize that ecosystem carbon assimilation potential (total area under a CPC curve) is constrained mainly by the climate conditions of a given year. We define a perfect CPC (PCPC) curve as a measure of the maximum carbon assimilation potential for a site given 'perfect' climate conditions for a particular day of the year, over the years for which data are available. This assumes that long-term trends are insignificant and that interannual variability is well sampled; therefore, only sites with at least 4 yr of data are used. Direct evidence indicating that a minimum of 4 yr of data is an adequate amount was provided by long-term climate and forage production data collected for the Central Plains Experimental Range (CPER) in north-central Colorado from 1939 to 1990 (Lauenroth and Sala 1992). Lauenroth and Sala (1992) concluded 'The climate at the CPER is representative of sites in semiarid regions with relatively high variability in precipitation from year to year ($cv = 30\%$) and relatively low variability in temperature ($cv = 7\%$). Twenty-three of 52 observations of annual precipitation were below the mean with no more three of the low values occurring in consecutive years.' A fundamental reason for the '3 yr rule' may be that semiarid ecosystems strongly depend on precipitation that has a random nature as emphasized by Noy-Meir (1973).

The perfect CPC values are calculated for each day of the year as the maximum CPC recorded on that day across

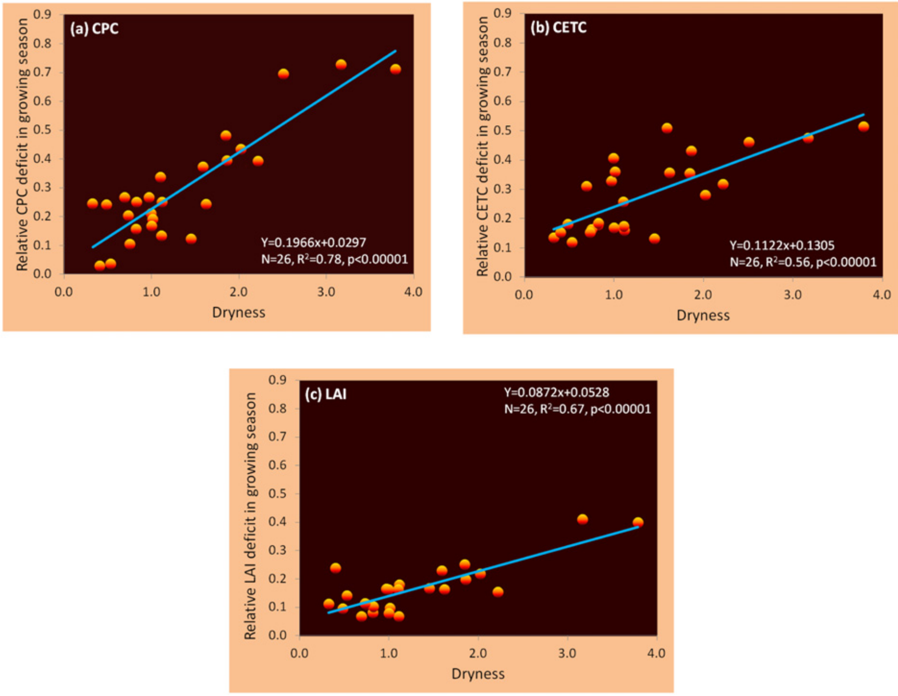


**Figure 2.** The deficits of CPC, CETC and LAI versus dryness. CETC refers to canopy evapotranspiration (ET) capacity that was derived by taking the maximum values of half-hourly data of latent heat fluxes measured at the eddy-flux tower site for each day in a year. The latent heat fluxes are converted into ET fluxes by dividing a latent constant (2500 kJ $kg^{-1}$). The values of perfect CETC (PCETC) are given by the maximum values of CETC in each day across all years in the studied time period at the studied site. The deficits of CETC are the differences between PCETC and CETC. LAI data are derived from the leaf area index product (LAI) MOD15A2 of the moderate resolution imaging spectrometer (MODIS) measurements with 8-day resolution (see supplementary materials available at stacks.iop.org/ERL/7/035703/mmedia). The values of perfect LAI (PLAI) are the maximum values of LAI from each 8-day period across all years in the study period at the study site. The LAI deficits are the differences between PLAI and LAI. The dryness was calculated by the formula (Yi *et al* 2010), $\mathcal{R}_n/(LP)$, where is $\mathcal{R}_n$ annual net radiation, $P$ is annual precipitation, and $L$ is a latent heat constant. The values of deficits of CPC, CETC and LAI were normalized by the total area of their perfect curve integration over time, respectively.

all available years of site data. Thus, a perfect CPC curve of maximized carbon assimilation potential can be constructed and smoothed by the same algorithm (blue curve in figure 1). Our hypothesis assumes that the features of a perfect CPC curve reflect ideal growing conditions determined by the characteristics of local climate during the studied time period. For example, a dip in a perfect CPC curve may reflect drought conditions occurring at the same time every year. In our analysis, therefore, we treat such events as a normal local climate condition that limits productivity in the studied time period rather than as an episodic extreme climate event.

### *2.4. Deficit CPC*

A CPC deficit is defined as the difference between the CPC measured on a particular day and the perfect CPC (blue area in figure 1). Therefore, dynamic relationships between CPC deficits and extreme climate events can be readily discerned. This perfect-deficit concept can be applied to any ecosystem or climate variable with continuous time series data measured or derived from measurements for a long enough time periods (≥4 yr). In addition to CPC deficits, we have conducted the analysis of the deficits of evapotranspiration (ET) fluxes, sensible heat ($H$) fluxes, air temperature (Ta), net radiation (Rn) and photosynthetic active radiation (PAR). The data used in this study are from five grassland eddy-covariance flux sites with a total of 26 site-years of data (supplementary table 1 available at stacks.iop.org/ERL/7/035703/mmedia).

## 3. Results and discussion

We found that the growing season deficits of grassland ecosystem CPC were strongly correlated ($R^2 = 0.78$, $p < 0.000\,01$) with dryness (figure 2(a)), but not correlated with the other climate variables (Ta, Rn and PAR). This robust correlation with dryness suggests that the ability to absorb carbon from the atmosphere is limited by water availability in the case of the grasslands explored here. However, we also discovered that dryness is the best indicator of water availability contributing to the interannual variability (IAV) of grassland potential productivity, as the correlation of the CPC deficits with annual precipitation is much lower ($R^2 = 0.31$) (supplementary figure 2 available at stacks.iop.org/ERL/7/035703/mmedia) than with dryness ($R^2 = 0.78$, figure 2(a)). Precipitation, as an index characterizing water availability, only reflects one aspect (input) of soil water budget, but evapotranspiration, as an output driven by available energy, is also important. The dryness index reflects both as a ratio of potential evapotranspiration to precipitation (Yi *et al* 2010, Budyko 1974) (see the legend of figure 2). Theoretically,

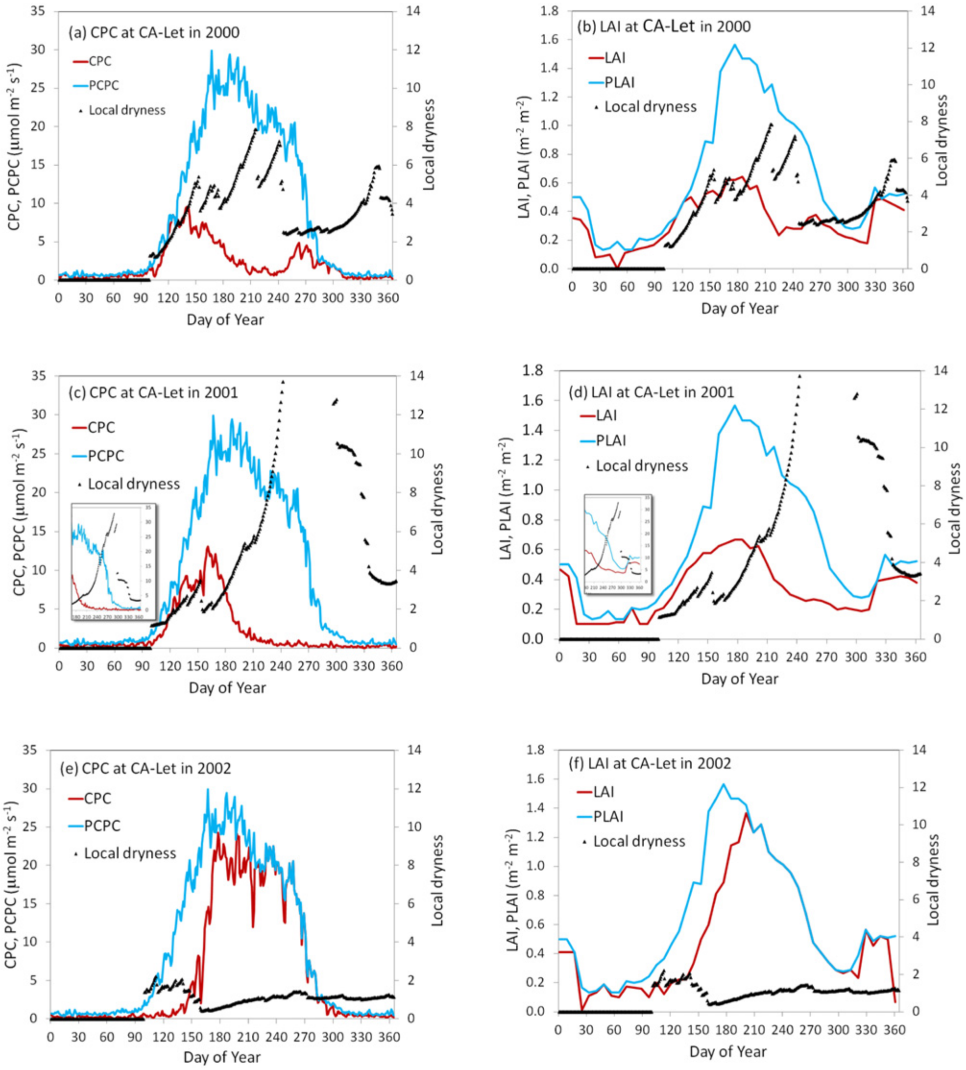


**Figure 3.** Left column: CPC and perfect CPC (PCPC) versus local dryness; right column: LAI and perfect LAI (PLAI) versus local dryness. The time series of CPC, PCPC and local dryness are derived from eddy-covariance measurements at CA-Let tower site in Canada. The curves of CPC and PCPC are algorithmically smoothed (see supplementary materials available at stacks.iop.org/ERL/7/035703/mmedia). LAI data are derived from NASA MOD15A2 data (http://daac.ornl.gov/). Perfect LAI values were calculated for each 8-day period for the year as the maximum LAI recorded during that 8-day period across all years of the site data. The CPC deficit is the difference between CPC and PCPC, while the LAI deficit is the difference between LAI and PLAI. The CPC deficits and LAI deficits co-vary and all are driven by local dryness. It is noted that the maximum value of local dryness in 2001 is 33. The insets in (c) and (d) indicate that the local dryness approached near 35 in 2001.

both plant photosynthesis and transpiration are controlled by leaf stomatal opening and closing dynamics. This logical link was observed between CPC deficits and the deficits of canopy evapotranspiration capacity (CETC) ($R^2 = 0.60$, supplementary figure 3 available at stacks.iop.org/ERL/7/035703/mmedia). For CETC deficits 56% of the variance was well explained by the dryness index (figure 2(b)). The fact that correlation between CETC deficits and dryness is less than the correlation between CPC deficits and dryness may be attributable to the fact that ET observed by the eddy-covariance method includes both transpiration from plants with stomatal control and evaporation from soil. The correlations of grassland CPC and CETC deficits with dryness were independently verified by remote sensing data of the leaf area index (LAI) measured by the Moderate Resolution Imaging Spectroradiometers (MODIS) onboard NASA's Terra and Aqua satellites (figure 2(c)). The LAI deficits were also calculated by the perfect-deficit approach illustrated in figure 1.

We examined daily dynamics of the deficits of CPC, CETC, and LAI with local dryness defined in equation (1) for all 26 site-years (supplementary table 1 available at stacks.iop.org/ERL/7/035703/mmedia). As illustrated in figure 3 for the CA-Let tower site in Canada, all these deficits followed the dynamics of local dryness closely, i.e. daily CPC (or CETC or LAI) decreased as local dryness was increasing. This new concept, local dryness, reflects the historical integration effect of the tight coupling of separate rain events and energy inflow. The critical time periods or drought events in a year can be clearly identified by the perfect-deficit chart illustrated

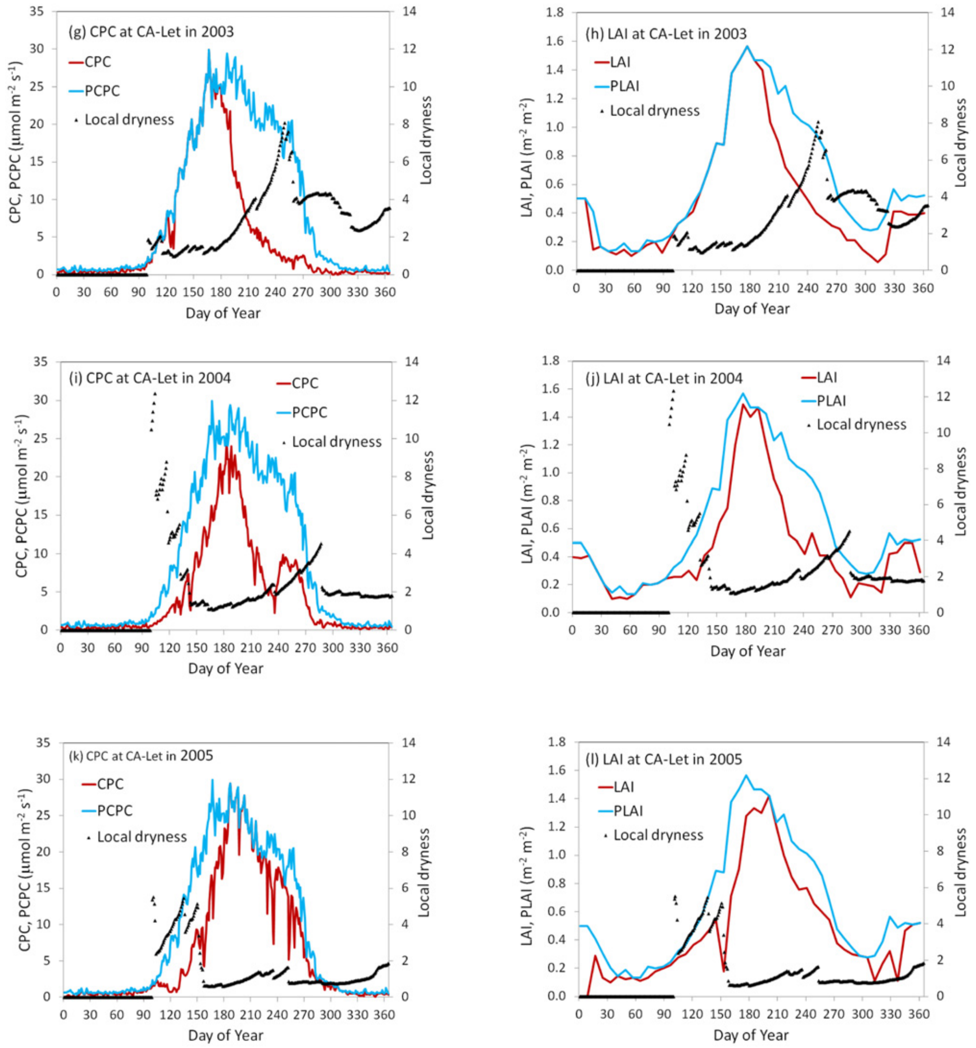


**Figure 3.** (Continued.)

in figure 3, when CPC deficits are larger with higher local dryness. Severe drought occurred in years 2000 and 2001, and the CPCs for those years were reduced by greater than 70% of their perfect CPCs (figures 3(a) and (c)). The ecosystem production was severely impacted after July in 2001 with extreme high local dryness (figure 3(c)). The extreme drought events recognized by the perfect-deficit charts at the CA-Let tower site were: in the earlier stage of growing season in 2002 (figures 3(e) and (f)), in 2004 (figures 3(i) and (j)), and in 2005 (figures 3(k) and (l)); in the late stage of growing season in 2003 (figures 3(g) and (h)) and in 2004 (figures 3(i) and (j)). These drought events can be cross-verified by the same perfect-deficit approach with independent data sources (e.g. comparing eddy-flux tower data with remote sensing data).

The increase of climate extremes has been predicted by theories and confirmed by observational data (Huntington 2006, Alexander *et al* 2006, Meehl and Tebaldi 2004, Easterling *et al* 2000). These increased climate extremes significantly disturb terrestrial carbon pools (Ciais *et al* 2005, Piao *et al* 2008, Knapp and Smith 2001, Zhao and Running 2010, Flanagan and Adkinson 2011, Dai *et al* 2004), especially for the most vulnerable grassland ecosystems and contribute to the large atmospheric $CO_2$ IAV (Peters *et al* 2007, Polley *et al* 2010). How to identify these climate extremes and their ecological consequences is a major challenge to understanding climate–ecosystem dynamics. The novel perfect-deficit approach provides a theoretical and operational basis for examining these relationships. Extreme climate events and their impacts on ecosystem productivity can be readily identified by the logical links between the deficits of ecosystem potential (CPC or CETC) and the deficits of climate factors (maximum Ta, Rn, PAR) or the amplitudes of climate factors (minimum Ta, local dryness). The approach of perfect-deficit analysis can be applied to any temporally continuous dataset in ecosystem–climate interactions. Therefore, the same extreme events can be cross-verified by different independent datasets, e.g. drought events verified by both eddy-flux tower data and MODIS remote sensing data. The data-based nature of the approach requires coexistence of both ecosystem and climate data. Large declines in the perfect CPC (or CETC) curve determined by this approach reflect persistent characteristics displaying the effects of local climate on the CPCs of ecosystem variables such as phenology or persistent drought stress during the study years, and are treated as results of normal local climate conditions over the period of observation. Local dryness is a good predictor of drought events and can also be used to predict daily dynamics of ecosystem–precipitation interaction.

In conclusion, our cross-site analysis shows that carbon sequestration capacities of grassland ecosystems were severely reduced by increased dryness associated with extreme drought events. Grassland ecosystems, which cover 40% of the earth's land surface, are fundamental to the support of plant, animal and human life. However, the world's grasslands have been declining in their extent and in their overall health (White *et al* 2000). Our results suggest that the decline of world's grasslands may result in large part from positive feedback between warming-associated drought events and grasslands CPC reduction: anthropogenic warming of the climate leads to more frequent and severe drought events (Huntington 2006, Alexander *et al* 2006, Meehl and Tebaldi 2004, Dai *et al* 2004, Easterling *et al* 2000) that weaken grasslands' carbon sink function, possibly turning grasslands into carbon sources.

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### Author Contributions

CY created new concept of local dryness and perfect-deficit approach and carried out data analysis, interpretation and wrote the paper. GR performed $CO_2$ flux data analysis, and carried out data interpretation and writing. XX performed $H_2O$ flux data analysis. AD performed leaf area index data analysis. JW contributed to the mathematical smoothing approach. SW contributed to the data processing method. DR, GH, TM, ZN and KP contributed to the interpretation of the results and the writing of the paper.

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