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Severe Long-Lasting Drought Accelerated Carbon Depletion in the Mongolian Plateau

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Key Points:
- The recent decade (2000–2009) has been identified as one of the driest periods on the Mongolian Plateau over the most recent ~2,000 years
- This long-duration drought shortened the C sequestration season, increased the summer C source, and led to a net annual C release
- The NEP amplitude in this dry decade increased due to reduced C uptake and increased C emissions, implying an accelerated C depletion

Supporting Information:
- Supporting Information S1

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Abstract Paleoclimate records identified a severe drought lasting approximately a decade on the Mongolian Plateau during the 2000s, the severity of which was only exceeded by a single drought during the last two millennia. Under high-emission scenarios, arid and semiarid areas are projected to continue to experience a drying trend over the coming decades; therefore, understanding how ecosystems respond to long-lasting drought has global implications. Here we used a process-based ecosystem model to examine the interannual and intra-annual variations in net ecosystem productivity in response to climate extremes across the Mongolian Plateau. We find that the recent-decade drought caused Mongolian terrestrial ecosystems to shift from a carbon (C) sink to a C source, canceling 40% of climate-induced C accumulation over the entire twentieth century. Our study details a shortened C sequestering season, increased summer C source, and accelerated C depletion during the 2000s drought.

Plain Language Summary Multiple lines of evidence have shown detrimental effects of drought events on ecosystem production and carbon dynamics, but it remains uncertain how arid and semiarid ecosystems respond to long-lasting drought. Here we reveal that a severe drought during the first decade of the 2000s on the Mongolian Plateau considerably weakened C sequestration capacity and accelerated C depletion. This work has broad implications for understanding impacts of persistent droughts on terrestrial C dynamics as a drying trend, in many arid and semiarid areas, is projected to continue over the coming decades.

1. Introduction

Global climate models predict that more frequent and intense droughts will occur in dry regions by the end of the 21st century under the scenario of high greenhouse gas emissions (Pachauri et al., 2014). Drought can strongly affect terrestrial ecosystem carbon (C) balance by altering C uptake through photosynthesis and C release through autotrophic and heterotrophic respiration (Meir et al., 2008). Severe drought, in particular, has been widely documented to convert various terrestrial ecosystems from a net C sink to a net C source (Chen et al., 2012; Hao et al., 2008; Lund et al., 2012; Rajan et al., 2013). Much effort has been invested to examine diverse responses of biological systems (crops, natural vegetation, etc.) to water shortage and their contrasting capabilities in recovering from drought events (Beguería et al., 2010; Schwalm et al., 2017; Yu et al., 2017). However, arid and semiarid ecosystems have received less attention as they only account for a small portion of terrestrial C fluxes and storage. It remains unknown how long-lasting drought has altered the capability of arid and semiarid ecosystems in sequestering C, and whether there is a tipping point beyond which an ecosystem cannot recover. A previous study reported that semiarid ecosystems played a pivotal, and increasingly important role, in determining the interannual variability of the global Csink (Poulter et al., 2014). Therefore, it is of critical global importance to understand how sensitive C cycling in arid and semiarid ecosystems is when severe long-lasting droughts occur, especially as it impacts land-atmosphere feedbacks. Here we address these questions using the Mongolian Plateau as a testbed.

The Mongolian Plateau, encompassing Inner Mongolia in China and the country of Mongolia, is mainly covered by grasslands, forests, and deserts (Figure S1.1 in the supporting information), under an arid and semiarid climate. Paleoclimate reconstructions from Mongolian tree rings indicate that the climate system in this region experienced a major shift from a 5-year pluvial in the 1990s to a 12-year drought around the 2000s, both exceeding the estimated 900-year return time (Hessl et al., 2018; Pederson et al., 2014). This implies that, in less than two decades, the Mongolian Plateau has experienced one of the wettest periods and one of the driest periods over ~2,000-year history. The drying trend in the Mongolian Plateau is projected to continue until at least the middle of the 21st century (Hessl et al., 2018). All of these make the Mongolian Plateau an ideal region to investigate the sensitivity and resilience of terrestrial C dynamics to long-lasting droughts.

A few studies have documented the impacts of drought either in part of this region or over part of this period, including the impacts on humans and animals (Lu et al., 2009; Sternberg et al., 2011), grassland degradation, reduction in vegetation cover (John et al., 2013), and reduced number and size of lakes (Tao et al., 2015). By creating water stress for plants and livestock and increasing the odds of dust storms, the drought event in the 2000s threatened ecosystem stability as well as the economic and social benefits in this region (John et al., 2013; Y. Lu et al., 2009; Rao et al., 2015; Yu et al., 2018). Additional work has also explored C dynamics in response to drought at the site level. For example, one study compared the net primary production (NPP) from field survey and model analysis from 2005–2007 and found that water stress was a stronger regulator of NPP than temperature in desert-steppe, steppe, and forest-steppe in Mongolia (Bat-oyun et al., 2010). Similarly, using eddy covariance measurements, another study showed that the summer and spring drought in 2005 reduced both gross ecosystem photosynthesis and respiration (Fu et al., 2009). However, none of the previous studies assessed C dynamics across the Mongolian Plateau during this dry decade. Rainfall manipulation experiments, often carried out at local study sites, cannot reflect the ecosystem responses to drought across a large spatial scale (Beier et al., 2012; Wu et al., 2011). A modeling approach can serve as an effective tool to assess regional C budget and distinguish and quantify the contributions of climate and nonclimate drivers at various spatial scales (Dangal et al., 2016; Lu et al., 2009).

Here we used a well-evaluated process-based ecosystem model, Dynamic Land Ecosystem Model (DLEM, Tian et al., 2011), to simulate the spatial and temporal changes in net ecosystem productivity (NEP) in response to climate variability and extremes on the Mongolian Plateau from 1901 to 2012, covering the dry decade from 2000 to 2009. We specifically aim to answer the following questions: (1) To what extent have ecosystem C dynamics changed in response to the 2000s drought? (2) How has the seasonal pattern of C uptake and release been altered by the 2000s drought? (3) Has this drought changed the seasonal amplitude of NEP?

2. Methods

2.1. Ecosystem Model

The DLEM is a highly integrated process-based terrestrial ecosystem model that simulates daily C, water, and nitrogen cycles as forced by climate conditions (temperature, precipitation, shortwave radiation, and relative humidity), atmospheric CO_2 concentration, nitrogen deposition, land use and cover patterns, and management practices (e.g., agricultural fertilizer use, irrigation, rotation, and harvesting). DLEM has been used to study the water balance and fluxes (such as evapotranspiration and surface and subsurface runoff) in various ecosystems (e.g., grasslands and forests; Liu et al., 2013), and ecosystem productivity and carbon dynamics in response to water stress in arid ecosystems (Tian et al., 2011; Yu et al., 2018; Zscheischler et al., 2014). A cohort structure is designed in the DLEM for characterizing land cover pattern in each simulation grid. Up to four natural plant functional types (PFTs) and one cropping system in each grid, and the area percentage of each component is allowed to change annually following the prescribed land use history data. Basic calculation of C dynamics is conducted for each PFT and crop type (Collatz et al., 1991; Farquhar et al., 1980; Oleson et al., 2004). The model-estimated C, water, and nitrogen cycling processes have been well evaluated against abundant observation data in forests, grasslands, and agricultural lands across the world (Dangal et al., 2016; Lu & Tian, 2013). In this study, we use additional site-level CO_2 flux measurements and global eddy covariance measurements-derived NEP products to validate DLEM's performance in capturing the interannual variation of NEP on the Mongolian Plateau. More details about the DLEM can be found in supporting information S2.

2.2. Input Drivers

We used time-series gridded data to characterize changes in climate (warming and climate variability), land use, atmospheric CO_2 concentration, and nitrogen deposition in the Mongolian Plateau during 1901 to 2012. All the input data have been resampled to a quarter degree (about 30 km × 30 km at the equator) and span the whole study period. Daily climate data, including daily maximum, minimum, and average temperature, precipitation, and shortwave radiation were derived from input data for the AsiaMIP project, which is based on the product of National Center for Environmental Prediction/National Center for Atmospheric Research Reanalysis 1 (Kalnay et al., 1996), and further corrected with the climate product of the Climate Research Unit (Mitchell & Jones, 2005). Using this climate dataset, we calculated the monthly Palmer Drought Severity Index (PDSI) for the Mongolian Plateau following the approach in Dai et al. (2004). The land use history was depicted by annual changes in area percentage of natural PFTs and crops in each grid (Figure S1.1 in the supporting information). Annual land use maps were developed from cropland percentage resampled from HYDE 3.2 (Goldewijk et al., 2017) and global potential vegetation map from SYNMAP (Wei et al., 2014). Monthly data of atmospheric CO_2 concentration was derived from the GLOBALVIEW-CO_2 2011 data product, and annual data of atmospheric nitrogen deposition (NH_x-N and NO_y-N) were resampled from the global database (Wei et al., 2014).

2.3. Simulation Experiment

After equilibrium run and model spin-up, we set up two major experiments for the transient run: In experiment I (*Climate*), only climate drivers were allowed to change over time while other drivers were kept constant at the level of 1900. In experiment II (*Climate plus Others*), all the environmental drivers (including climate, land use, CO_2 concentration, and nitrogen deposition) were turned on to allow changes. Results from experiment II can be viewed as our “best estimate” of C dynamics on the Mongolian Plateau, with which the field observations and data synthesis results have been compared. Here we mainly focus on NPP (net primary productivity, a difference of gross primary productivity and autotrophic respiration, indicative of net ecosystem capacity to assimilate C), Rh (heterotrophic respiration), and the resultant NEP (the difference between NPP and Rh) at annual and monthly time steps.

We used z scores (ratio of NEP anomaly to 30-year standard deviation, SD) to assess the deviation of NEP from the long-term average. Negative (positive) z score indicate how many SDs that modeled or observed NEP lies below (above) the mean. We adopted cluster analysis (Churkina et al., 2005; supporting information S2) to test whether the ecosystem response to summer drought changed over time from 1980 to 2012. The clustering was applied to the summer (June, July, and August) average of NEP, computed as a spatially averaged net ecosystem carbon dynamics for each year.

3. Results and Discussion

3.1. Lasting Drought on the Mongolian Plateau During the 2000s

A severe drought occurred across the Mongolian Plateau during the 2000s (2000–2009), with growing season (March–October) average PDSI below -2 (i.e., moderate to severe drought), and the length of drought (PDSI ≤ -1) reaching 12 months in 8 out of 10 years (Figure 1). Since 1990, regional average PDSI declined by 0.15 per year (referring to the slope of the linear regression line, $p < 0.05$). This is primarily attributed to the combination of all-season temperature increase and precipitation decrease in summer and autumn in most of the years across the Mongolian Plateau (supporting information Figure S1.6). In the 2000s, areas exposed to drought averaged 82% of the entire land area of the plateau, among which nearly 20% suffered from extreme drought (PDSI ≤ -4), 25% severe drought ($-4 <$ PDSI ≤ -3), and the rest experienced mild and moderate drought ($-3 <$ PDSI ≤ -1; Figures S1.2 and S1.3 in the supporting information). Before 2000, the duration of extreme drought only spanned 2–3 months per year, but it grew to 5–6 months per year in the 2000s, indicating an extended duration of severe drought, while mild and moderate droughts were relatively stable since 1980 (see Figure S1.2 in the supporting information).

3.2. Mongolian C Dynamics in Response to Drought

The DLEM estimate at the site level (Figure 2a) captures the interannual variability in NEP demonstrated by eddy covariance measurements (Li et al., 2005). The NEP reduction of ~2 SD documented by eddy covariance in 2007 was well reproduced by DLEM. In addition, across the Mongolian Plateau, the

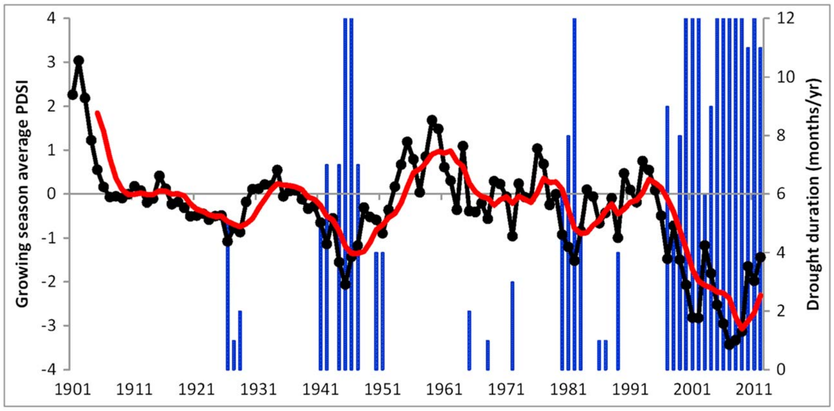

Figure 1. Growing season (March–October) average Palmer Drought Severity Index (PDSI) index (black dotted line) and drought duration (blue line, months with PDSI below −1 within a year) across the Mongolian Plateau in the period 1901–2012. Red line is a 5-year moving average of growing season PDSI.

DLEM-estimated continuous growing-season NEP decline in the 2000s (*z* score shown in Figure 2b) was consistent with the MTE (Multi-Tree Ensemble) data product, an empirical global up-scaling estimate derived from eddy covariance measurements (Jung et al., 2017). We found that the negative magnitude of NEP deviation from the long-term mean was closely related to PDSI in both the data synthesis product and ecosystem modeling. In both cases, the drier climate is, the further NEP goes below the long-term mean.

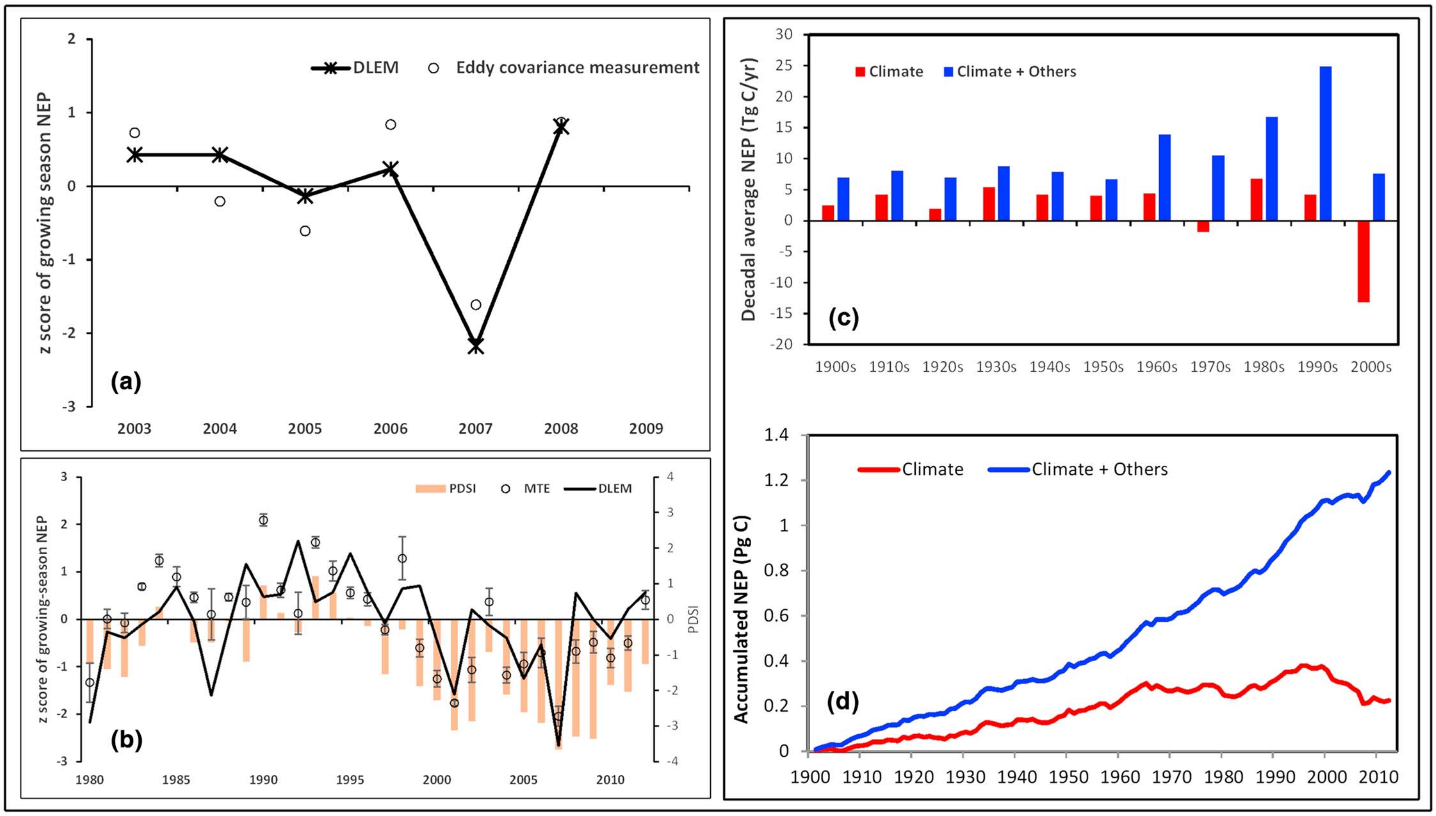

Figure 2. *Z* score of growing-season net ecosystem productivity (NEP) estimated by (a) flux tower measurement and Dynamic Land Ecosystem Model (DLEM) in the site of Kherlenbayan Ulaan (47°12′50.3″N, 108°44′14.4″E, measurements downloaded from AsiaFlux, http://www.asiaflux.net/) and (b) by Multi-Tree Ensemble (MTE; Jung et al., 2017) and DLEM in the Mongolian Plateau. Error bars in (b) indicate the standard deviation of MTE-NEP among three approaches (ANN, MARS, and RF). *Z* score is calculated as the ratio of NEP anomaly (deviation from 1961–1990 average) to 30-year standard deviation. The model-estimated decadal average NEP (c) and accumulated NEP (d) driven by climate variability alone and climate plus other environmental drivers (including land use history, atmospheric CO_2 concentration and N deposition) across the Mongolian Plateau during the period 1901–2012. PDSI = Palmer Drought Severity Index.

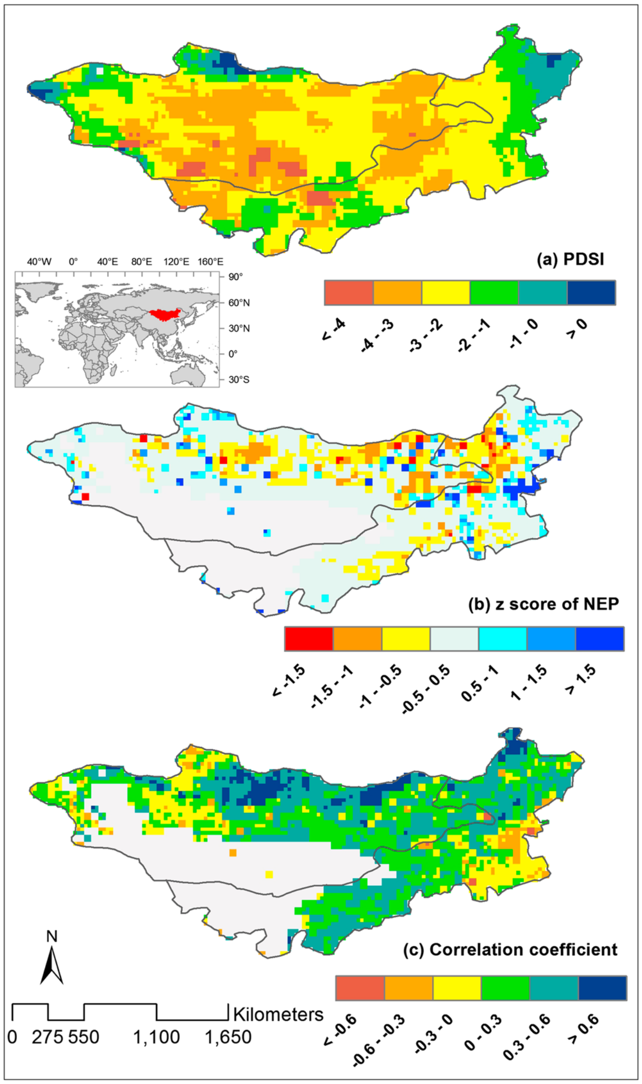

Figure 3. Spatial patterns of (a) average Palmer Drought Severity Index (PDSI), (b) *z* score of DLEM-estimated net ecosystem productivity (NEP) in the Mongolian Plateau during the 2000s drought, and (c) Pearson correlation coefficient between PDSI and *z* score of modeled NEP since 1980. Inset figure shows the spatial location and boundary of the study area. The above boundary line demonstrates the country of Mongolia and Inner Mongolia, China.

Across the Mongolian Plateau, model simulations showed that century-long average NEP was nearly neutral when driven by climate variability alone in the 20th century, but it turned into a large C source (NEP−13.2 Tg C/year) due to the recent decade-long drought in the 21st century (Fig. 2c). Comparing with the period of 1961 to 1990, the NEP anomaly of the dry decade was −17.0 Tg C/year. Grassland and shrubland nearly equally contributed to this source, while other land cover types (i.e., cropland, forest) contributed minimally to this decline. Even considering the alleviating effects of non-climate drivers (i.e., land use, rising CO_2, and elevated nitrogen deposition), the Mongolian Plateau acted as a small C sink (7.6 Tg C/year) over the 2000s, only equivalent to 55% of the long-term average NEP (i.e., 13.7 Tg C/year during 1961–1990). We estimated that there was 1.2 Pg C accumulated in this region in the period 1901–2012, during which the climate contribution (red line in Figure 2d) dropped from 34% by the year 2000 to 18% by 2010. Importantly, the decade-long drought in the 2000s canceled 40% of climate-induced C accumulation in the entire 20th century. Spatially, the largest NEP reduction (negative *z* score in Figure 3b) was found in the northern Mongolian Plateau, in which terrestrial C release during the 2000–2009 period was predominantly caused by drought (as shown by positive correlation between PDSI and NEP anomaly in Figure 3c).

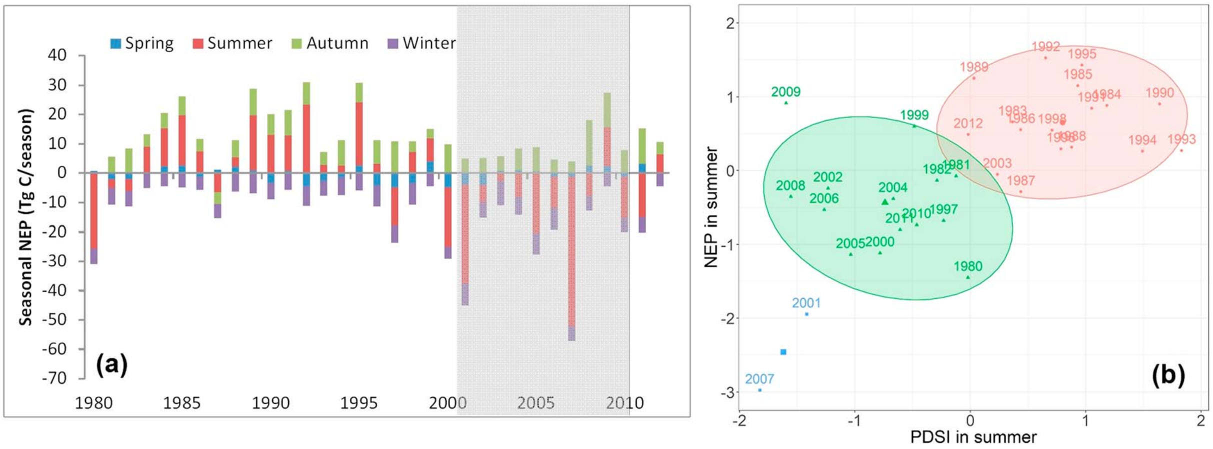

Figure 4. The DLEM-simulated seasonal net ecosystem productivity (NEP) driven by climate variability alone in the Mongolian Plateau during 1980–2012 (a), and the relationship between average NEP and Palmer Drought Severity Index (PDSI) during summer season (b). The ellipses are drawn for the groups as derived from K-means cluster analysis. The green triangle, red dot, and blue square represent the centroid of each cluster.

3.3. Seasonal Variation in C Dynamics in Response to Drought

Here, we found the drought-induced C release was closely related to anomalous seasonal variations in C dynamics in arid and semiarid ecosystems. In drought-absent years, terrestrial ecosystems in the Mongolian Plateau took up C from the atmosphere (i.e., C sink, NPP is larger than Rh) in summer and autumn due to rapid plant growth (Figure S1.4 in the supporting information). However, when drought occurred, NPP was more suppressed than Rh in summer and on annual time scale (Figure S1.5), which therefore shifted the Mongolian Plateau from a C-absorbing system to a C-releasing system (Figure 4a). The modeled higher drought sensitivity of NPP than that of Rh is consistent with the synthesis result based on FLUXNET, a global network of eddy covariance measurements (Schwalm et al., 2010). In contrast, drought-induced reduction in NPP and Rh were similar in autumn, during which Mongolian Plateau acted as a small C sink. Overall, C release in dry summers overwhelmed the C uptake in autumns of the 2000s, leading to a strong net C source driven by climate alone.

The cluster analysis demonstrates that the relationship between NEP and summer drought fell into three groups (Figure 4b), with years of high NEP and positive PDSI clustering mostly between 1980 and 1998 (except 1980–1982 and 1997) and years of low NEP and negative PDSI occurring after 1999 (except 2003 and 2012). A third cluster was identified for the years 2001 and 2007, which were more extreme, with summer PDSI values below −1.5 and NEP values below −2.0 Tg C per summer. While most years of the drought occurred in either cluster 1 or 2, 2009 was an exception during which the ecosystem in the Mongolian Plateau still took up C as estimated by both ecosystem modeling and MTE data product. This was likely caused by the fact that the drought area during 2009 was spatially limited (mainly concentrated in the western Gobi Desert ecosystem) in 2009 (Figure S1.3), accompanied by reduced drought severity in the spring and the previous winter, compared to other dry years.

Existing studies suggest that abrupt changes in ecosystems may lead to the transition between alternative stable states, such as a transition from grassland to desert, but abrupt changes can also reflect a proportional and reversible ecological response to rapid or gradual changes in external drivers (Bestelmeyer et al., 2011). Regimes shift in the Mongolian Plateau has mainly attributed to enhanced grazing pressure and human-induced land use change (Sankey et al., 2009). However, no study has yet quantified climate-induced regime shift across this region. In arid grassland ecosystems, below-ground biomass is typically several times of aboveground biomass (Ni, 2004). The large root system in a Mongolian steppe allows for the possibility of a rapid recovery of above-ground productivity after an intense drought event and keeps the ecosystem from shifting to a drier equilibrium state, however, the time scales of responses to drought differed among species (Shinoda et al., 2010). Both our simulation and MTE data product showed summer NEP returned to positive in 2009, despite the drought remaining pervasive. The magnitude of CO_2 sequestration and release is heavily dependent on where and when drought occurred in that year, and how resilient the ecosystem was.

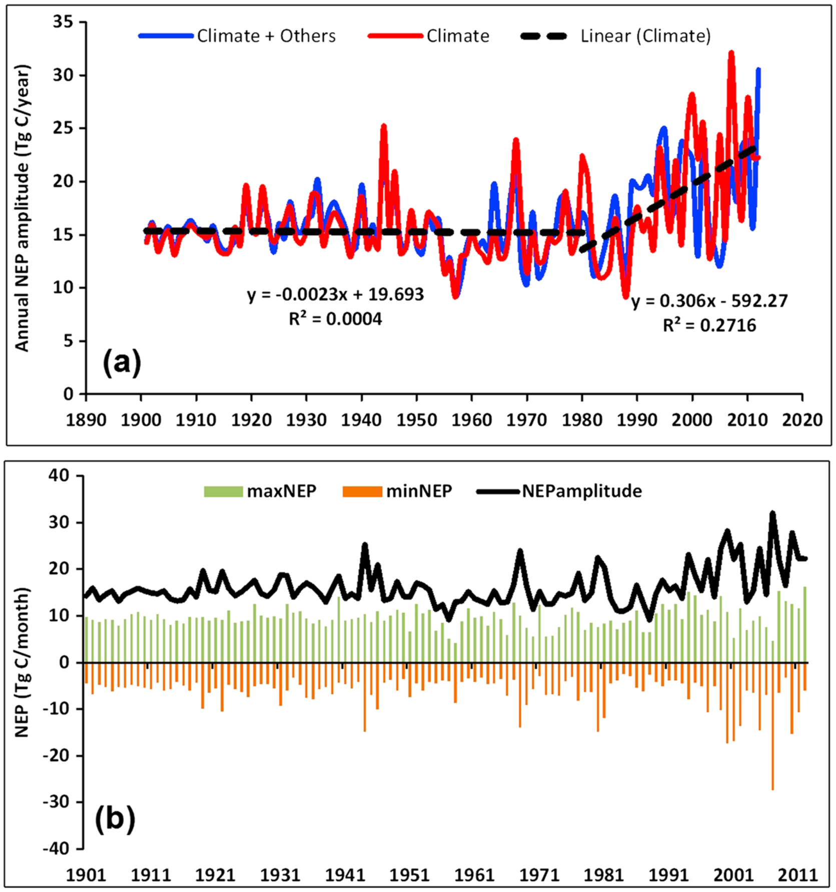

Figure 5. The simulated annual net ecosystem productivity (NEP) amplitude driven by climate alone and climate plus other drivers (a). The dash lines indicate a linear trend of NEP amplitude before and after 1980, respectively. The maximum and minimum monthly NEP and annual NEP amplitude driven by climate variability alone in the Mongolian Plateau during 1901–2012 (b).

Meta-analysis showed that large biodiversity could help to stabilize grassland ecosystem productivity since high-diversity vegetation communities are more resistant to climate extremes (Isbell et al., 2015). Although species composition at a community level was not considered in this study, our simulations suggested C sequestration in the Mongolian Plateau could recover after severe droughts. Future modeling studies incorporating species composition and interactions are needed to determine how the magnitude and duration of drought events interact with diversity to prevent regime shifts in arid and semiarid grassland ecosystems like the Mongolian Plateau.

3.4. Increased NEP Amplitude During the Dry Decade

NEP amplitude, the difference between the maximum and minimum monthly NEP in one year, is an important indicator of terrestrial C dynamics. It regulates seasonal variations in atmospheric CO_2 concentration at the global scale. Before 1980, climate variability explained over 70% ($p < 0.05$) of interannual variation in NEP amplitude, but the importance of climate on NEP amplitude declined thereafter (i.e., increasing difference between model estimates of NEP magnitude driven by climate alone and climate plus other input drivers in Figure 5). This implies a growing role of anthropogenic drivers (such as elevated CO_2, increasing nitrogen deposition, and land use changes) in determining intra-annual NEP variations in this region after 1980. While the historical NEP amplitude in this region was relatively stable at 15 Tg C/year between 1901 and 1979, it increased by 0.31 Tg C/year^2 ($R^2 = 0.27$) with large interannual variations since 1980 (Figure 5a). We found that climate-induced increase in NEP amplitude in the 1980s and 1990s was mainly caused by elevated C sink (i.e., increased maximum NEP) and reduced C source (i.e., declined minimum NEP). It implies a faster C accumulation that likely resulted from the combination of wetter and cooler summers during those two decades, for example, the previously identified 1990s pluvial (Hessl et al., 2018). However, the increased NEP amplitude in the 2000s was attributed to the reduced C sink and enhanced C source (i.e., reduced maximum NEP and increased minimum NEP; Figure 4a), reflecting a faster C depletion due to the recent-decade drought (Figure 5).

Our study indicates that the accumulated NEP amplitude changes (i.e., 0.18 Tg C/year^2, totaling 9 Tg C/year during the period of 1961 to the 2000s) are equivalent to 41% of the NEP amplitude in the 2000s (22.0 Tg C/year) in the Mongolian Plateau. Such change doubles the global scale estimate (i.e., changing trend of 32.3±19.9 Tg C/year^2 in the same period, totaling 1.6 Pg C/year, which accounts for 20% of average NEP amplitude of 8.0 Pg C in the 2000s) reported by Ito et al. (2016). This implies the Mongolian Plateau is a hot spot with faster C dynamics (accumulation or depletion), characterized by enhancing intra-annual NEP variation and its higher changing trend relative to the global average. Contrary to the finding that climate contributed to the dampening seasonal cycle amplitude of NEP (Ito et al., 2016), our results revealed that NEP seasonal cycle amplitude in the Mongolian Plateau was increasingly amplified by climate, which was most remarkable after 1980, further emphasizing the sensitivity of arid and semiarid systems to climate variability.

4. Conclusion

Our study quantifies the interannual and intra-annual variations of NEP in response to drought across the Mongolian Plateau. We find that the record-breaking decade-long drought with an extensive area and long duration has reduced NPP more than Rh and therefore resulted in a climate-induced C source during 2000–2009. Both site-level and regional modeling estimates agree well with field observations and data synthesis product, respectively, revealing NEP decline in extremely dry years (e.g., 2007) can be over 2 times higher than interannual variation (measured by 30-year SD). Our modeling results also demonstrate that climate-induced NEP amplitude kept rising since 1980, indicating a faster C accumulation or depletion, although intensifying human activities (e.g., livestock husbandry) and anthropogenic environmental changes are proven to weaken the role of climate variability in shaping NEP amplitude in the same period. Our results suggest that long-lasting drought events are likely to shorten C-sequestering season, enlarge the size of summer C source, lead to a net C loss for years, and accelerate C depletion, which may take decades or longer for the ecosystem to recover its C storage. In addition, the drought-induced C emissions from the biosphere could form positive feedback to future drying trends in arid areas.

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