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Key Points:

- Northern China experienced a multi-year precipitation reduction from 1999-2011
- The multiyear drought changed the regional carbon sink to source
- Maize yield decreased in the study region responded to drought

Supporting Information:

- Readme
- Table S1 and Figures S1–S3

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Multiyear precipitation reduction strongly decreases carbon uptake over northern China

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Abstract Drought has been a concern in global and regional water, carbon, and energy cycles. From 1999 to 2011, northern China experienced a multiyear precipitation reduction that significantly decreased water availability as indicated by the Palmer Drought Severity Index and soil moisture measurements. In this study, a light use efficiency model (EC-LUE) and an ecosystem physiological model (IBIS) were used to characterize the impacts of long-term drought on terrestrial carbon fluxes in northern China. EC-LUE and IBIS models showed the reduction of averaged GPP of 0.09 and 0.05 Pg C yr^{-1} during 1999–2011 compared with 1982–1998. Based on the IBIS model, simulated ecosystem respiration experienced an insignificant decrease from 1999 to 2011. The multiyear precipitation reduction changed the regional carbon uptake of 0.011 Pg C yr^{-1} from 1982 to 1998 to a net source of 0.018 Pg C yr^{-1} from 1999 to 2011. Moreover, a pronounced decrease in maize yield in almost all provinces in the study region was found from 1999 to 2011 versus the average of yield from1978 to 2011. The largest maize yield reduction occurred in Beijing (2499 kg ha^{-1} yr^{-1}), Jilin (2180 kg ha^{-1} yr^{-1}), Tianjing (1923 kg ha^{-1} yr^{-1}), and Heilongjiang (1791 kg ha^{-1} yr^{-1}), and the maize yield anomaly was significantly correlated with the annual precipitation over the entire study area. Our results revealed that recent climate change, especially drought-induced water stress, is the dominant cause of the reduction in the terrestrial carbon sink over northern China.

1. Introduction

As a major issue in global environmental changes, drought has attracted widespread attention from both scientists and policy makers over the past few decades [*IPCC*, 2007]. The global total of very dry land areas has increased from 12 to 30% since 1972 as indicated by the Palmer Drought Severity Index [*Dai et al*., 2004]. Recent large-scale and severe droughts have occurred in Europe in 2003 [*Ciais et al*., 2005], western North America from 1999 to 2004 [*Schwalm et al*., 2012], and the Sahel region of Africa from the 1960s to the present [*Dai et al*., 2004]. Given the strong relationship between carbon and water cycles, such drying may have significant impacts on terrestrial carbon dynamics and atmospheric carbon dioxide concentrations, leading to positive feedback in the global climate system. An extreme drought in Europe during 2003, for example, not only led to a crop shortfall (more than 20%) in southern Europe but also caused approximately 0.5 Pg of carbon to be lost from terrestrial ecosystems, which corresponds to net ecosystem carbon sequestration of 4 years [*Ciais et al*., 2005].

Northern China has experienced frequent severe droughts during the second half of the 20th century [*Wang and Zhai*, 2003; *Zou et al*., 2005]. Studies based on climate station data showed that much of northern China has experienced droughts since the 1950s, and the most severe and prolonged droughts have occurred since 1990 [*Zhai et al*., 2010]. Moreover, drought variations displayed multiple time scales and seasonal differences [*Wang and Zhai*, 2003]. Consistent with *Dai et al*. [2004], increases in drought areas were found in much of northern China (but not in northwest China) [*Zou et al*., 2005], aggravated by warming and decreasing precipitation.

Several studies have reported the impacts of drought on terrestrial ecosystems in northern China. For instance, the 2008/2009 winter drought in northeastern China, which was one of the worst in the past 50 years, resulted in an estimated $2.3 billion in economic losses and subjected more than 10 million people to water shortages [*Gao and Yang*, 2009]. Continuous multiyear precipitation deficit has resulted into a trend of substantial decreases in the water available within terrestrial ecosystems. Observations of soil moisture at 16 sites in northeast China indicated that the surface soil mositure during the crop growth period of 1980–2005 displayed a decreasing trend and tended to be drier, especially in the western and southern regions of northeast China [*Jiang et al*., 2009]. Using satellite-derived normalized difference vegetation index (*NDVI*) data for northern China, the analysis concluded that the growing season *NDVI* significantly decreased after the 1990s due to drought stress that was strengthened by warming and reduced precipitation [*Peng et al*., 2011].

However, there are a limited number of studies on the effects of drought on ecosystem carbon uptake in northern China. The overarching goal of this study is to conduct an assessment of the impacts of severe extended droughts on the carbon balance of terrestrial ecosystems. Specific objectives are to (1) evaluate the long-term spatial and temporal distributions of annual precipitation changes across northern China, and (2) investigate the magnitude and mechanism of the impacts of drought on the carbon budget of terrestrial ecosystems.

2. Data and Method

2.1. Study Area and Data

The study area for this research encompasses 11 provinces in northern China (Figure 1), which covers approximately 2.90 million km^2 and accounts for 30% of the territory of China. The study area is predominantly composed of various temperature forests, grasslands, croplands, and deserts, including 41% of all forests, 36% of grasslands, and 57% of croplands in China, and this area is one of the most important carbon storage and crop production areas in China.

To examine climate change in this region, we collected meteorology data of 185 stations from the National Climate Center of China Meteorological Administration. The locations of the stations can be seen in Figure 1. The thin plate smoothing splines method was used to generate the daily mean air temperature (T_m), relative humidity (R_h), precipitation (P_{rec}), wind speed (W_s), and daylight hours (S_h) for all of China at a spatial resolution of 25 km of latitude and longitude for the period of 1960–2011 [*Yuan et al*., 2014]. The fitted trivariate splines incorporated a spatially varying dependence on ground elevation and automatically adapted to the large variation in station density throughout China. A comprehensive introduction to the technique of thin plate smoothing splines is given in *Wahba* [1990]. Moreover, an Angstrom-type correlation method was used to calculate downward solar radiation (R_g) from the daylight hours data [*Angstrom*, 1924; *Almorox and Hontoria*, 2004], and Rg was converted to photosynthetically active radiation (PAR) using a ratio of 0.5.

The Palmer Drought Severity Index (PDSI) at 2.5° resolution was used to investigate long-term drought trends in northern China [*Jacobi et al*., 2013]. The PDSI is the most prominent index of meteorological drought used worldwide. The PDSI incorporates antecedent and current moisture supply (precipitation) and demand (evapotranspiration) in a hydrological accounting system. The PDSI has been additionally used to quantify long-term changes in global drought events in the 20th and 21st centuries [*Dai et al*., 2004; *Burke et al*., 2006].

Soil moisture observations were used to investigate the impacts of precipitation changes on available water. The soil moisture data for five different layers (0–10, 10–20, 20–30, 30–40, and 40–50 cm) over a 10 day interval from 1982 to 1999 were obtained from the National Meteorological Information Center of the China Meteorological Administration. We excluded irrigation stations because the primary objective of this paper is to study the effects of precipitation on soil moisture. The annual mean soil moisture was calculated based of

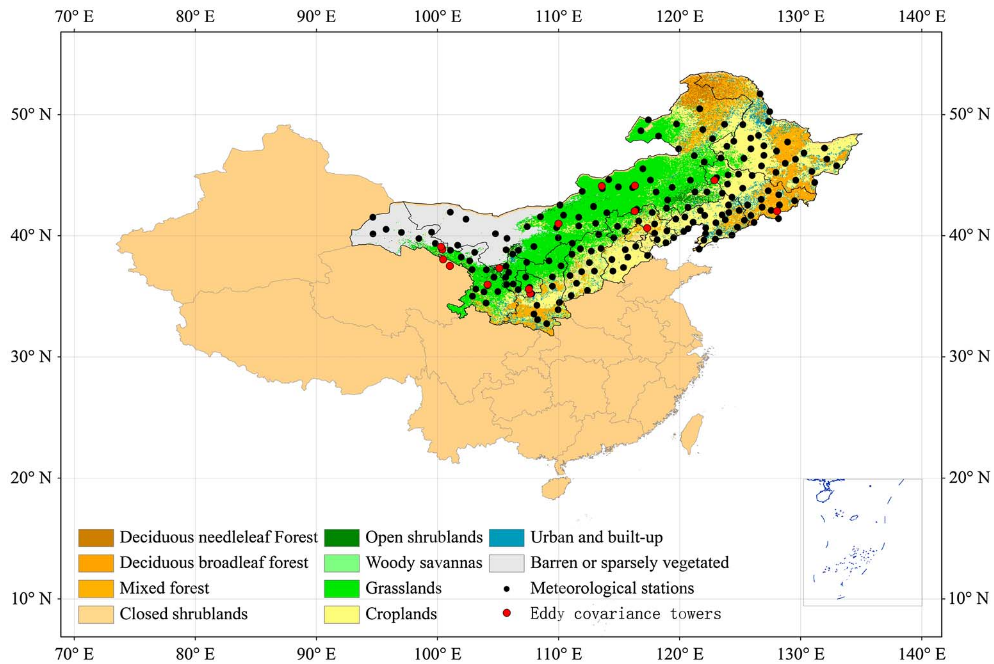

Figure 1. Spatial domain of the study area, vegetation distribution, meteorological stations, and eddy covariance towers location along with the remaining portion of China and its provincial boundaries.

the average of soil moisture data for each 10 day interval from May to September. If more than 20% of annual data were missing from a site, we did not consider the corresponding year at this site to be available. In total, there were 49 soil moisture sites with at least 20 year measurements and more than five annual measurements after 1999, and these measurements were used to characterize change of soil moisture over the study region. At each site, annual soil moisture anomalies were calculated based on long-term mean soil moisture, and then we calculated the site fraction with a negative soil moisture anomaly over the study area for a given year and examined the interannual variability of site fraction and the relationship with precipitation. Moreover, we also investigated the long-term trends of soil moisture at these 49 sites.

Maize harvest data from province-level statistics from 1982 to 2011 were used to analyze drought impacts on the study areas [*Ministry of Agriculture*, 2009, 2010, 2011, 2012]. Maize is one of the most widely cultivated crop types in northern China, and maize in the study area is cultivated without irrigation; therefore, the maize yield can be used to reflect drought impact on crop production. The crop yield is influenced by various biotic, abiotic, and anthropogenic factors (e.g., environment and management) and shows trends due to improvements in genetics, and fertilizer application policies. The crop yield time series were detrended using the best fit least squares regression method as recommended by *Goldblum* [2009]. In order to avoid the effects of drought on maize yield from 1999 to 2011, we used the data series from 1982 to 1998 to construct detrended regression equation. The residuals after detrending can be assumed to reflect the impact of climatic factors.

We use the biweekly *NDVI* data with an 8 km spatial resolution from the third Global Inventory Monitoring and Modeling Studies data set (GIMMS NDVI3g). GIMMS NDVI3g has been recently produced for the period July 1981 to December 2011 with AVHRR sensor data. This version of the data set is corrected through a series of processing steps to alleviate known limitations of the AVHRR measurements induced by intersensor calibration, orbital drift, cloud cover, solar angle differences, volcanic eruptions, and other atmospheric contaminations.

2.2. Carbon Cycle Models

In this study, a satellite-based light use efficiency (LUE) model (EC-LUE, Eddy Covariance Light Use Efficiency) and an ecosystem physiological model (IBIS, Integrated BIosphere Simulator), which have been widely validated and applied at global scales, were selected to examine the impact of drought events on vegetation gross primary production (GPP) and carbon uptake in northern China.

The EC-LUE model is driven by only four variables: the normalized difference vegetation index (*NDVI*), photosynthetically active radiation (*PAR*, MJ m^{-2}), air temperature (*T*, °C), and the Bowen ratio of sensible to latent heat flux [*Yuan et al*., 2007, 2010a]. The GPP was computed from the fraction of *PAR* absorbed by the vegetation canopy (*fPAR*), *PAR*, and down-regulators that represent plant stresses due to suboptimal temperature (T_s) and water (W_s).

IBIS is hierarchically organized to allow explicit coupling among ecological biophysical and physiological processes at different timescales [*Foley et al*., 1996]. IBIS uses a mechanistic Farquhar model for the treatment of canopy photosynthesis [*Farquhar et al*., 1980]. The CO_2 production models are established for ecosystem respiration processes on the principle of mass balance of carbon in ecosystems, which generally share a common structure that partitions carbon input into several pools from which carbon is released via respiratory processes.

Fifteen eddy covariance (EC) sites in northern China, covering various ecosystem types such as forests, grasslands, and croplands, were included in this study to verify the ability of EC-LUE and IBIS models to reproduce the observed GPP, Ecosystem Respiration (TER), and Net Ecosystem Production (NEP) (Figure 1). Averages representing half hour or hourly readings of solar radiation (R_g), photosynthetically active radiation (*PAR*), air temperature (*T*), and friction velocity ($u*$) were used with the net ecosystem exchange of CO_2 (NEE) in this study. Data analyses procedures were presented in *Yuan et al.* [2010a, 2010b], *Li et al*. [2012], and *Zhang et al*. [2012]. In brief, daily NEE, TER, and meteorological variables were synthesized based on half hour or hourly values. As a result, the tower-based GPP was calculated as the result of NEE and TER. Daytime TER is usually developed from nighttime NEE measurements that equal night respiration and estimated by daytime temperature and a linear equation to describe the temperature dependence of respiration [*Reichstein et al*., 2005]. The daily values were indicated as missing when more than 20% of all data on a given day were missing. Otherwise, daily values were calculated by multiplying the averaged hourly rate by 24 h [*Yuan et al*., 2009].

We simulated the changes in carbon fluxes from 1982 to 2011 using an interpolated climate data and satellite-based leaf area index (*LAI*) and *NDVI*. AVHRR GIMMS *LAI* and *NDVI* during 1982–2006 and MODIS *LAI* and *NDVI* during 2000–2011 series were used to generate a single, continuous *LAI* and *NDVI* records. A linear regression method was used to combine these two data sets [*Zhang et al*., 2008]. MODIS land cover product (MOD13) was used to indicate land cover types.

In order to examine the model performance for simulating the impacts of drought, we selected 12 eddy covariance sites that experienced the severity drought of 2003 in Europe (Table 1) [*Ciais et al*., 2005]. We compared the observed and simulated differences of GPP, TER, and NEP between 2002 and 2003.

2.3. Analyses

The relative deviation of carbon cycle variables were defined as the standardized departure (*SD*) from mean values

$$SD = (x - \bar{x})/\sigma \quad (1)$$

where x was the variable values for a given year or period and $\bar{x}$ and σ were average values and standard deviation of climate and carbon cycle variables for a long-term period, respectively.

3. Results

3.1. Climate Change Over the Northern China

Northern China experienced a multiyear precipitation anomaly since 1999 (Figure 2). Except for 2003 and 2010, 11 of the 13 years from 1999 to 2011 showed 3–21% reductions compared with long-term averages from 1960 to 2011 from all meteorology stations (Figure 2). More than 84% stations in the study area showed a decreased annual mean precipitation during 1999–2011, and significant decreased trends were found at 27% of stations (Figure 3). A general decrease in precipitation days has been observed in over 89% of stations (Figure 3), and a 4% decrease in precipitation days for 1999–2011 was observed in comparison with the long-

Table 1. Name, Location, Vegetation Type, and Available Years of the Study Sites Used for the Model Validation

Site Name	Latitude, Longitude	Vegetation Type	Available Period[a]
	Sites in the Study Area		
Arou	38.04°N, 100.46°W	Grassland	2008–2009 (8)
Changbaishan	42.40°N, 127.09°W	Forest	2004–2005 (6)
Changwu	35.20°N, 107.67°W	Grassland	2008–2009 (7)
Dongsu	44.09°N, 113.57°W	Grassland	2008–2009 (7)
Duolun	42.04°N, 116.29°W	Grassland	2005–2006 (6)
Haibei	37.50°N, 101.02°W	Grassland	2004–2005 (6)
Miyun	40.63°N, 117.32°W	Cropland	2008–2009 (8)
Qingyang	35.59°N, 107.54°W	Grassland	2009 (2)
SiziwangFence	41.23°N, 111.57°W	Grassland	2010 (3)
SiziwangGraze	41.28°N, 111.68°W	Grassland	2010 (3)
Tongyu	44.57°N, 122.88°W	Grassland	2008–2009 (5)
Xilinhaote	44.13°N, 116.31°W	Grassland	2006 (4)
Yingke	38.86°N, 100.41°W	Cropland	2008–2009 (6)
Yuzhong	35.95°N, 104.13°W	Cropland	2008–2009 (7)
Zhangye	39.09°N, 100.30°W	Grassland	2008 (3)
	European Sites for Model Validation		
DK-Sor	55.49°N, 11.65°E	Forest	2002–2003
FR-Hes	48.67°N, 7.06°E	Forest	2002–2003
IT-Ro1	42.41°N, 11.93°E	Forest	2002–2003
FR-Pue	43.74°N, 3.60°E	Forest	2002–2003
DE-Tha	50.96°N, 13.57°E	Forest	2002–2003
ES-Es1	39.35°N, 0.32°W	Forest	2002–2003
BE-Vie	50.31°N, 6.00°E	Forest	2002–2003
DE-Hai	51.08°N, 10.45°E	Forest	2002–2003
FR-LBr	44.72°N, 0.77°W	Forest	2002–2003
IT-Sro	42.39°N, 11.92°E	Forest	2002–2003
FI-Hyy	61.85°N, 24.88°E	Forest	2002–2003
IT-Cpz	41.71°N, 12.38°E	Forest	2002–2003

[a]At the most sites in the study area, the available period was from July to September. The numbers in the parentheses indicate the number of available months.

term average (1960–2011) (Figure 2). Seasonal changes in precipitation patterns are additionally apparent, and precipitation shows the obvious decrease in summer and autumn (Figure 2). In stark contrast, winter and spring experienced an increase in precipitation (Figure 2).

A strong warming throughout the past decade in northern China is firmly supported by continuous measurements. The mean annual temperature has increased at a rate of 0.258°C per decadal years since the 1960s (Figure 2), which is quite higher than the 0.074°C mean level across the entire world [*IPCC*, 2007]. A total of 98% of stations show a significant higher temperature from 1999 to 2011 compare with the past five decades (Figure 3a). The results show a significant reduction of relative humidity from 1999 to 2011 (Figure 3b).

Reduced precipitation and increased temperature clearly impacted the water balance on a regional scale. We collected the soil moisture measurements of 49 sites with more than 20 annual measurements. During 1999–2009, more soil moisture sites showed a negative anomaly of annual mean soil moisture compared with the previous 17 years (i.e., from 1982 to 1998) (Figure 4a). From 1999 to 2009, soil moisture at the 56% sites was less than 30% of the long-term mean values. Mean annual precipitation over the study region presented a very good explanation for the increased number of drought soil moisture sites (Figure 4b). Moreover, 71% sites showed decreased soil moisture over the study period compared with the baseline period (1982–1998) (Figure 5a).

The PDSI was used to identify the severity of droughts in northern China. Negative PDSI values indicate drought events. The differences in the annual PDSI between the two periods of 1999–2011 and 1960–1998 are shown in Figure 5. An increased drought magnitude as indicated by PDSI has occurred in northern China (Figure 5b). Moreover, the mean PDSI values from 1999 to 2011 indicated a severe drought (Figure 5c).

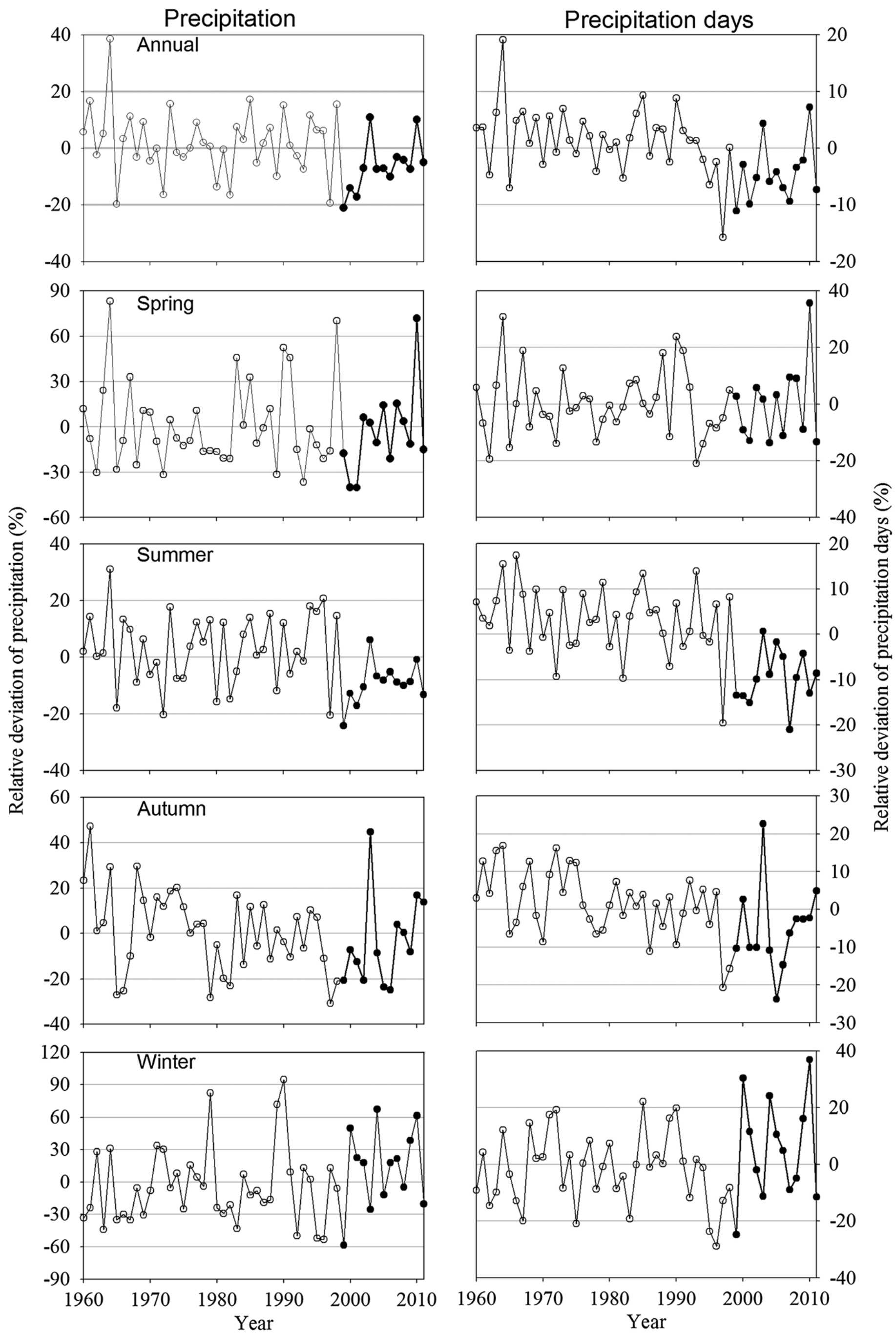

Figure 2. Observed trends of (left) annual precipitation and (right) precipitation days from 1960 to 2011 in northern China. (top to bottom) Mean values for the entire year, spring, summer, autumn, and winter. The open dots show the study period of 1960 to 1998, and the solid dots show the study period of 1999 to 2011. The relative deviation was the ratio of the absolute differences and the long-term average, and the former was calculated by difference between the mean values of each year and the long-term average (1960–2011).

3.2. Impacts of Decreased Precipitation on Carbon Uptake

The estimated GPP from EC measurements taken at 15 sites was used to validate the EC-LUE and IBIS models. The EC-LUE model successfully predicted the magnitudes and monthly variations of GPP and explained approximately 69% of the variation in the month-averaged GPP at all sites (Figure 6a). The results showed good IBIS model performance for simulating GPP, ecosystem respiration (TER), and NEE, and the RMSE (root

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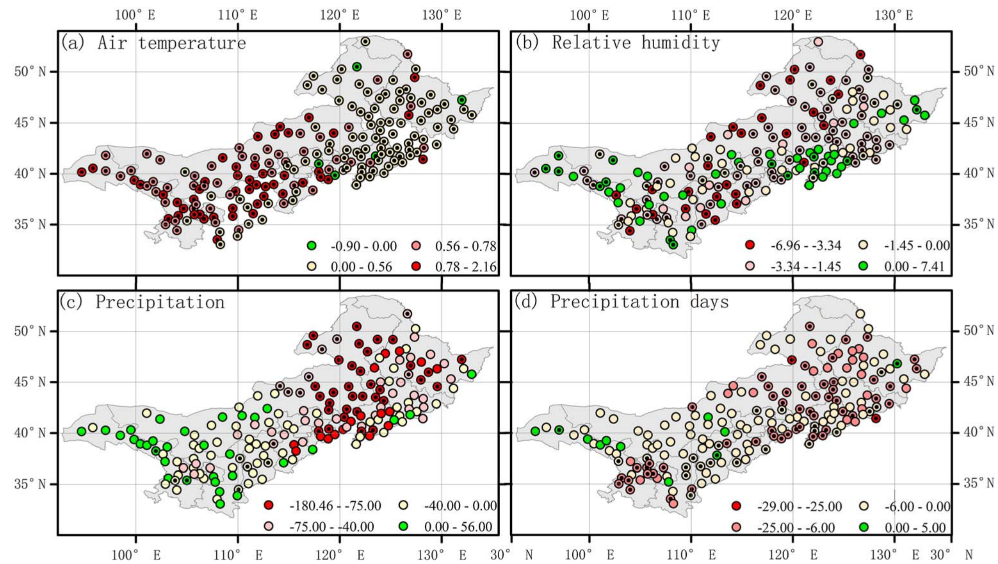

Figure 3. Observed differences in the mean values from 1999 to 2011 compared with the long-term average (1982–1998) in China. (a) Air temperature, (b) relative humidity, (c) annual precipitation, and (d) Precipitation days. The black dots indicate the significant differences ($p < 0.05$).

mean square error) of the simulations were 1.48, 1.41, and 0.96 g C m^{-2} day^{-1}, respectively (Figures 6b–6d). Moreover, in order to examine the model performance for simulating the impacts of drought, we selected 12 eddy covariance sites that experienced the severity drought of 2003 in Europe (Table 1) [*Ciais et al*., 2005]. We compared the observed and simulated differences of GPP, TER, and NEP between 2002 and 2003. The results showed that EC-LUE and IBIS can simulate the impacts of drought very well (Figure 7).

Although there were still large differences in the simulated GPP between these two models, however, both of the models showed a pronounced GPP decrease ranging from 1999 to 2011 versus the average for 1982–1998 over the study region (Figure 8). The simulations of the entire study region showed a significant reduction in average GPP from 1999 to 2011 compared with 1982 to 1998, and the decreased magnitude of annual mean GPP was 0.09 Pg C yr^{-1} and 0.05 Pg C yr^{-1} for the EC-LUE and IBIS model, respectively (Figures 8a and 8c). Similar spatial patterns of GPP anomaly were found in the two models (Figures 9a and 9b). Increased GPP was only found in the small areas mainly located at the northern and eastern study area, and other most regions showed decreased GPP trends. From 1999 to 2011, the simulated TER in China decreased by 0.019 Pg C yr^{-1}. The larger reduction in GPP compared with TER in China caused an anomalous source from 1999 to 2011 to the atmosphere of 0.018 Pg C yr^{-1} according to the IBIS simulations, which changed the

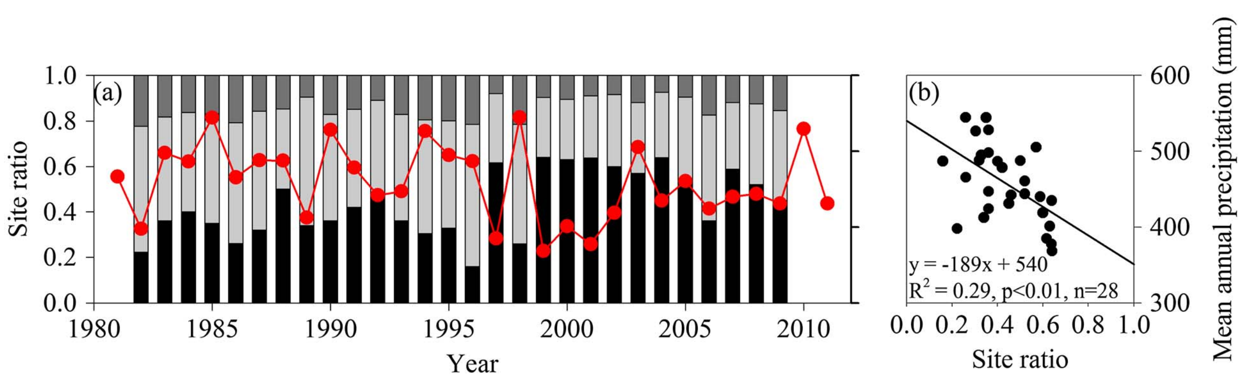

Figure 4. Changes in soil moisture and precipitation in northern China. (a) Interannual variability on the site fractions of drought (black bars), normal (light gray bars) and wet (dark gray bars), and mean annual precipitation (red line); (b) the relationship between drought site ratio with mean annual precipitation. Drought and wet were defined as the soil moisture less or larger than 33% of mean soil moisture, and the other was defined as the normal.

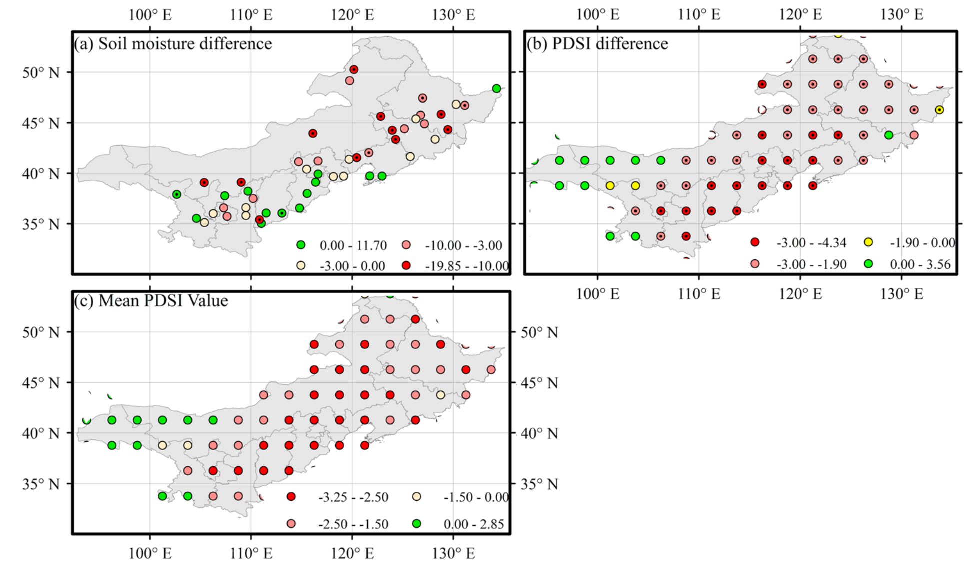

Figure 5. Difference in the soil moisture and PDSI after 1999 (1999–2009 for soil moisture and 1999–2011 for PDSI) with the (a and b) long-term average (1982–1998) in northern China and (c) mean PDSI values from 1999 to 2011. The black dots indicate the significance differences ($p < 0.05$).

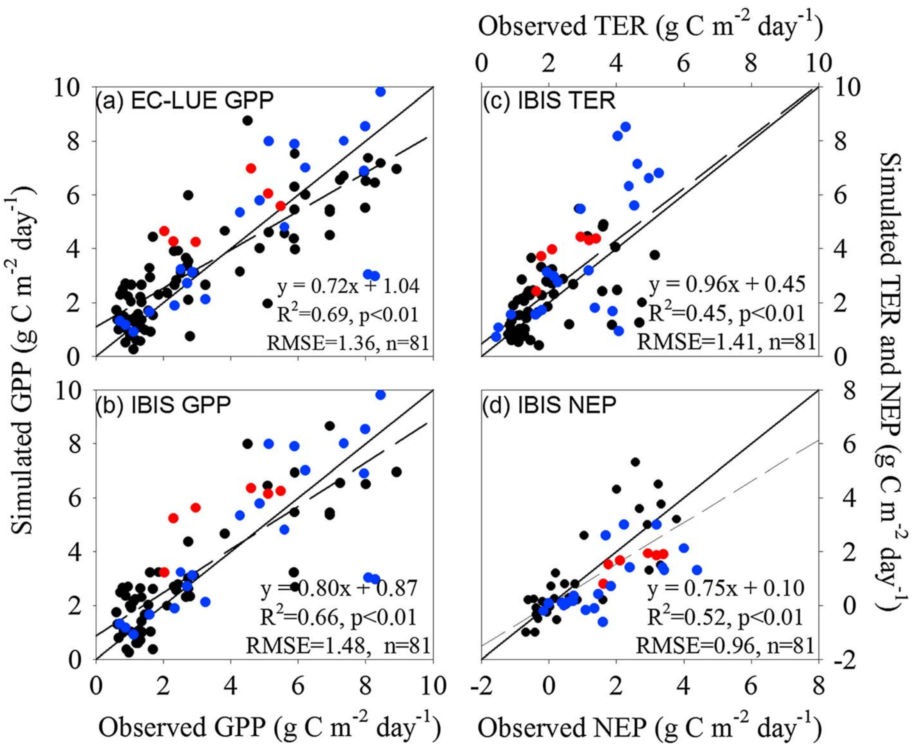

Figure 6. Observed versus modeled monthly gross primary production (GPP) across 15 eddy covariance towers from the (a) EC-LUE and (b) IBIS models, (c) TER (ecosystem respiration), and (d) NEP (net ecosystem production) from the IBIS model. The solid lines represent the 1:1 line, and the long dash lines represent the regression lines. The black, blue, and red dots indicate the grassland, cropland, and forest sites, respectively. RMSE is the root mean square error (g C m^{-2} day^{-1}). In total, we have 81 site-months measurements at all 15 sites in the study area (Table 1).

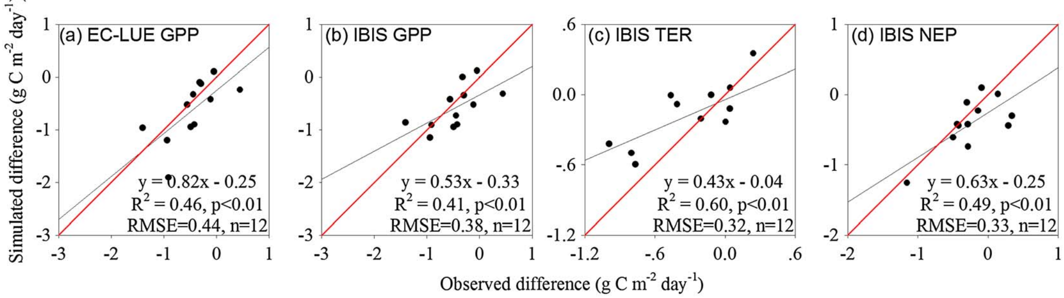

Figure 7. Observed versus modeled difference of (a and b) mean daily gross primary production (GPP), (c) ecosystem respiration (TER), and (d) net ecosystem production between 2002 and 2003 at 12 European sites. The red lines are 1:1 line, and the black lines are linear regression line. RMSE is the root mean square error (g C m^{-2} d^{-1}).

regional carbon uptake of 0.011 Pg C yr^{-1} averaged from 1982 to 1998 to a net source. This suggests that the multiyear drought decreased carbon sequestration of 0.029 Pg C yr^{-1} and cumulated 0.37 Pg C during the 13 years (1999 to 2011), which was much larger than the long-term mean annual carbon uptake over the entire China (0.19 to 0.26 Pg C yr^{-1}) [*Piao et al.*, 2009].

Similarly, the maize yield significantly decreased after 1999 (Figure 8b). The average maize yield from 1999 to 2011 was reduced by 440 kg ha^{-1} yr^{-1} compared with linear trend yields. The largest crop yield reduction was found in Beijing (2499 kg ha^{-1} yr^{-1}), Jilin (2180 kg ha^{-1} yr^{-1}), Tianjing (1923 kg ha^{-1} yr^{-1}), and Heilongjiang (1791 kg ha^{-1} yr^{-1}) (data not shown).

Over the entire study period, precipitation strongly regulated the carbon cycle fluxes (Figure 10). The simulated GPP by EC-LUE and IBIS increased significantly with precipitation during the growing season (May to September) (EC-LUE GPP: $y = 0.0008x + 1.75$, $R^2 = 0.17$, $p < 0.05$; IBIS GPP: $y = 0.0005x + 1.29$, $R^2 = 0.21$, $p < 0.05$) (Figures 10a and 10b), but we were unable to detect a significant relationship between TER simulations and precipitation ($y = 0.0003x + 1.04$, $R^2 = 0.04$, $p = 0.71$) (Figure 10c). Consequently, there was a

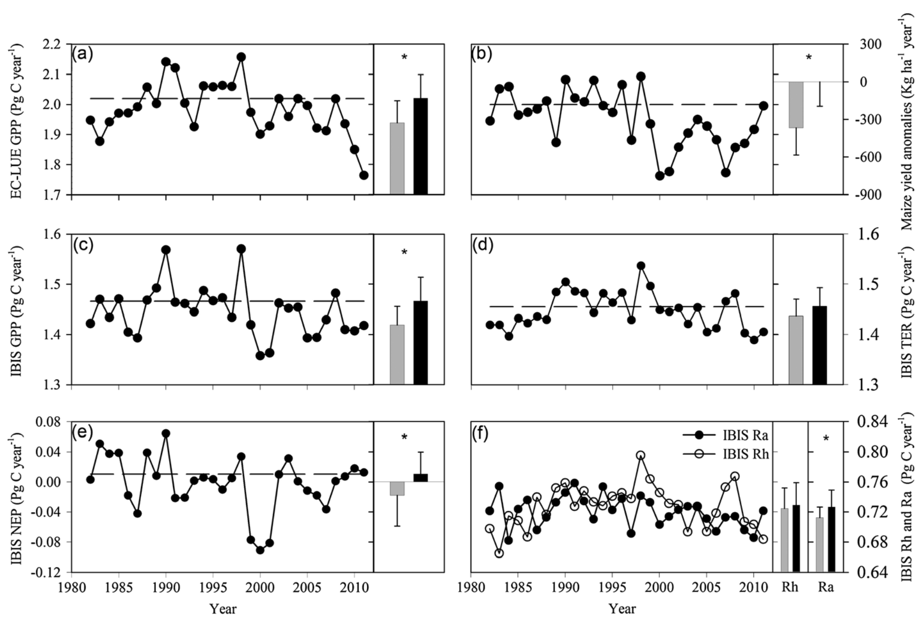

Figure 8. Interannual variability of the regional GPP, maize yield anomalies, ecosystem respiration (TER), net ecosystem production (NEP), autotrophic respiration (R_a), and heterotrophic respiration (R_h). (a and b) EC-LUE GPP, (c and d) IBIS GPP, and (e and f) IBIS NEP. The dashed black lines indicate the mean values from 1982 to 1998. The comparisons of the mean values of various variables from 1982 to 1998 and 1999 to 2011 were shown at right sides of each panel, the black and gray bars indicate the mean values of 1982–1998 and 1999–2011, respectively, and the asterisk indicated the significant differences between the mean values of two periods.

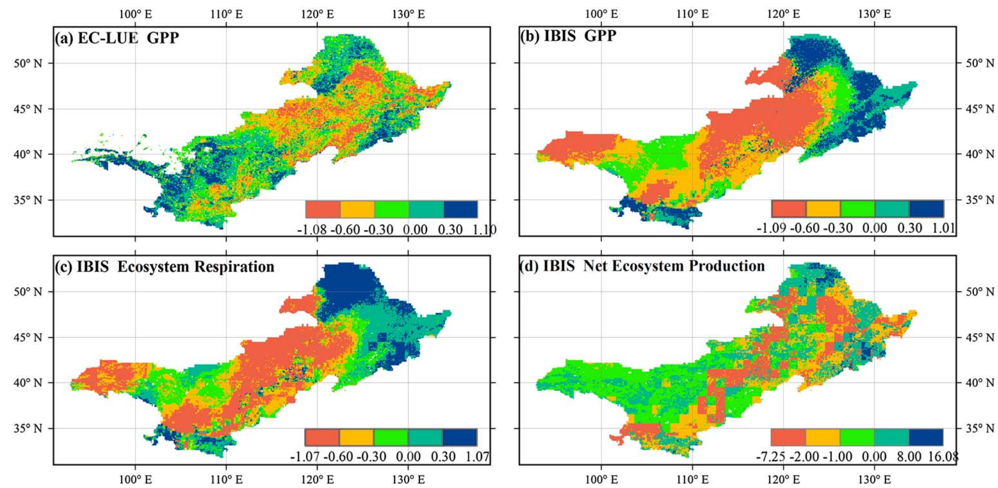

Figure 9. Spatial patterns of the (a and b) relative deviation of GPP, (c) TER, and (d) NEP from 1999 to 2011 compared with the mean values from 1982 to 2011.

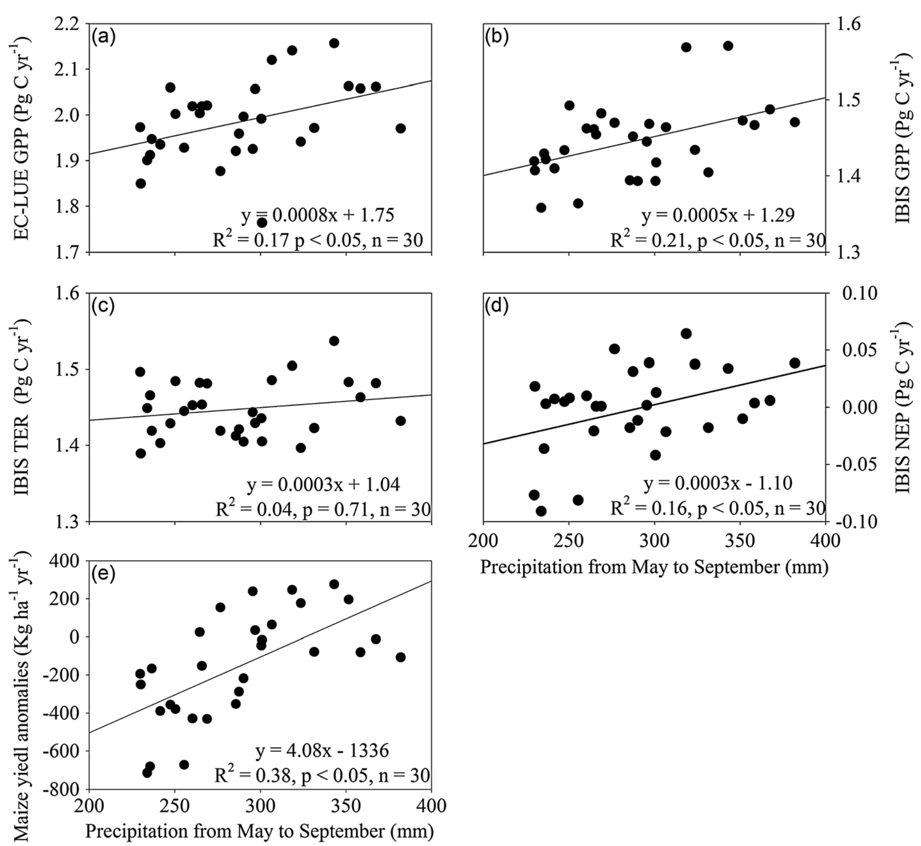

Figure 10. Relationship between the (a and b) simulated vegetation gross primary production (GPP), (c) ecosystem respiration (TER), (d) net ecosystem production (NEP), and (e) maize yield with precipitation of May to September from 1982 to 2011 in the entire study area. To remove the effects of improved agriculture, a linear trend has been generated from the data that indicates the yield trend. The crop yield records show the difference between the observed crop yield and the trend value.

significant positive correlation between NEP and precipitation ($y = 0.0003x - 1.10$, $R^2 = 0.16$, $p < 0.05$). The corn yield anomaly was significantly correlated with the May and September precipitation in the entire study area from 1982 to 2011 ($y = 4.08x - 1336$, $R^2 = 0.38$, $p < 0.05$) (Figure 10e), indicating the dominant role of water limitations.

4. Discussion

4.1. Precipitation Reduction Over the Northern China

Terrestrial ecosystems have been experiencing frequent extreme drought events that have already exerted profound impacts on global economy, food security, and terrestrial ecosystems [*Dai et al.*, 2004]. In this study, the results showed decadal-scale precipitation reduction since 1999 in northern China. Other lines of evidence support our findings that precipitation shows a decreasing trend in the study region. A recent study used the Standardized Precipitation Evapotranspiration Index at 609 locations in China during the period of 1951–2010. This study revealed that severe and extreme droughts throughout China have become more serious since the late 1990s, and persistent multiyear severe droughts were more frequent in northern China due to a decrease in precipitation coupled with a general increase in temperature [*Yu et al.*, 2013]. Reconstructed precipitation data based on tree-rings records from the past 232 years do not indicate any apparent long-term decreasing or increasing trend of precipitation in northern China during the last 100 years; however, a strong decreasing trend was found during the most recent decade [*Chen et al.*, 2011b].

China is located in the East Asian monsoon region, which is highly vulnerable to any anomalous monsoon rainfall that yields droughts or floods. A strong summer monsoon generally produces floods in northern China, whereas droughts can occur during the years where the summer monsoon is weak in most of northern China [*Guo*, 1994]. Previous studies showed a weakening summer monsoon in recent years [*Ding et al.*, 2008]. It has been suggested that El Niño-like warming in the tropical Pacific could lead to weakened summer monsoons and thus severe drought in East China [*Li et al.*, 2010b]. Analysis of prediction data from the IPCC AR4 multimodel ensemble-mean under the SRES A1B scenario indicates that soil moisture worldwide is generally drying, warned of a worldwide drought by the late 21st century [*IPCC*, 2007], and especially showed that the recently observed drying in northern China may further intensify [*Wang*, 2005].

A continuous multiyear precipitation deficit has resulted in the trend of substantially decreased water available within the terrestrial ecosystems. Our results showed the presence of more soil moisture sites with drier trends compared with sites with wetter trends (Figure 5). Other lines of evidence support our conclusions that soil moisture and river runoff in the study region have showed significant reduction trends [*Han et al.*, 2009; *Li et al.*, 2010a; *Li et al.*, 2011].

4.2. Impacts of Drought on Carbon Budget

Severe extended droughts during the 20th century showed significant impacts on terrestrial carbon cycling, suggesting that severe extended droughts should be considered in regional carbon budget studies [*Zhao and Running*, 2010]. The magnitude of the terrestrial carbon sink could be substantially overestimated without considering extreme climate events. Based on observations and models, previous studies showed the impacts of drought on vegetation production across various geographical and climate regions at regional to continental scales. For example, severe drought in moist tropical forests results into large carbon emissions by suppressing tree growth [*Nepstad et al.*, 2004]. The benefits of larger growing seasons due to global warming for middle- and high-latitude terrestrial ecosystem are being weakened by severe droughts [*Zeng et al.*, 2005; *Yuan et al.*, 2007; *Ma et al.*, 2012].

In this study, we used a satellite-based model (EC-LUE) and ecosystem physiological model (IBIS) to investigate the impacts of drought and reduce uncertainties in the individual model. Although both models indicated a significant reduction in average GPP from 1999 to 2011 throughout the entire study region, the magnitude of decreased GPP substantially differed between the two models (Figure 8). The discrepancy in model structure is major cause for model differences. The EC-LUE model is a satellite-based model that does not integrate ecosystem physiological processes and cannot characterize important plant physiological responses to alleviate drought stresses [*Yuan et al.*, 2010b]. On the contrary, IBIS is an ecosystem physiological model that can represent several adaptive mechanisms, such as large carbon allocation to roots and the closure of stomatal conductance, which can actuate plants to absorb more soil water, reduce water

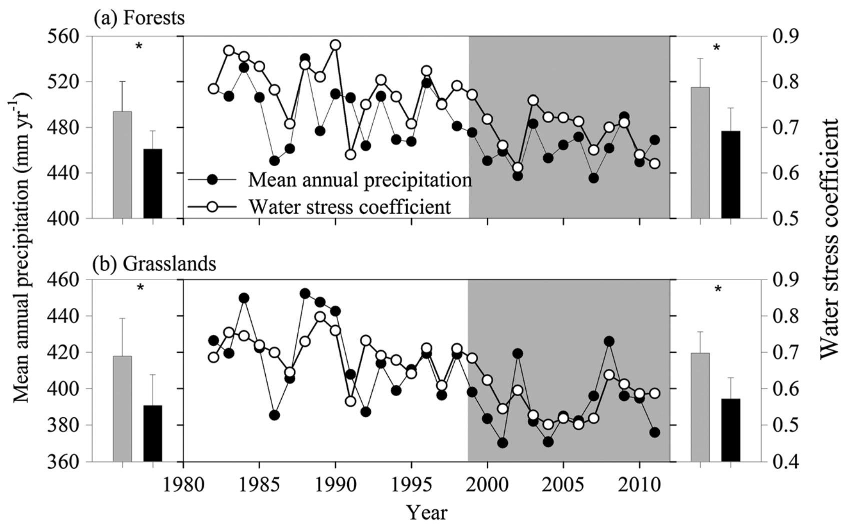

Figure 11. Comparison on the changes of water stress coefficient over (a) all forests and (b) grasslands at the study area. The comparison of mean annual precipitation and water stress coefficient through two periods (gray bars: 1982–1998; black bars: 1999–2011) is shown as well as the variations of mean annual precipitation (black dots) and water stress coefficient (white dots); the gray area show the period from 1999 to 2011. The asterisk indicates the significant difference at the $p < 0.05$.

transpiration, and ultimately weaken the impacts of drought on vegetation production [*Li et al*., 2012]. Therefore, the EC-LUE model theoretically has more sensitivity to drought compared with IBIS model that integrates physiological adaptation processes. Differences in the model structure are the major causes for large differences of GPP estimates between two models. The EC-LUE model simulated a 0.09 Pg C yr^{-1} reduction of GPP, which is higher compared with IBIS (0.05 Pg C yr^{-1}), and the EC-LUE identified larger regions with decreased GPP compared with the data derived from the IBIS model (Figure 9).

The two models consistently identified an increase in the vegetation production in forest ecosystems throughout the northern and eastern study areas, unlike other ecosystem types. It has been suggested that forests may be more resilient to drought than other ecosystems due to deeper forest root system compared with grasslands [*Teuling et al*., 2010]. IBIS model integrates the root vertical distribution equation of *Jackson et al*. [1996], which was developed based on a database of 250 root studies at the 11 biomes globally. Compared with the forest types, grasslands showed the shallower rooting profiles, and 95% of roots existed in the top 50 cm of soil at grasslands (Figure S2). The water stress coefficient was calculated by aggregating soil moisture of all soil layers weighted by root distribution fraction (see supporting information). The soil moisture at deep layer showed smaller variations than that of top soil layer (Figure S1). Therefore, the water stresses at the forest areas were much less than those of grasslands according to the model simulations (Figure S3). At both forests and grasslands, precipitation strongly regulated the interannual variation of water stress coefficient, and especially the decreased precipitation exacerbated soil moisture stresses from 1999 to 2011 (Figure 11). However, on average, water stress coefficient showed the different decreased magnitude at forests (10.45%) and grasslands (19.68%) of 1999–2011 compared with the means of 1982–1998 (Figure 11).

Satellite-based *NDVI* observations supported our conclusion that forests experienced the relatively mild impacts of drought. Based on long-time series of *NDVI* data, we found the larger annual mean *NDVI* values from 1999 to 2011 compared with that of 1982–1998 over the forest dominated regions and the decreased *NDVI* at grassland ecosystems (Figure 12). Drought stress may not limit forest growth in northern China, and the forest could possibly benefit from a warming-induced earlier spring onset and higher solar radiation [*Black et al*., 2000; *Richardson et al*., 2009]. Moreover, anthropogenic activities (such as afforestation and reforestation) may partly contribute to the expansion of positive vegetation greenness in these forested regions in the 2000s [*State Forestry Administration of China*, 2009].

The very complex relationship between ecosystem respiration and drought involves numerous mechanisms and varies with regions and time scales. Drought can generally result in two contrary impacts on ecosystem

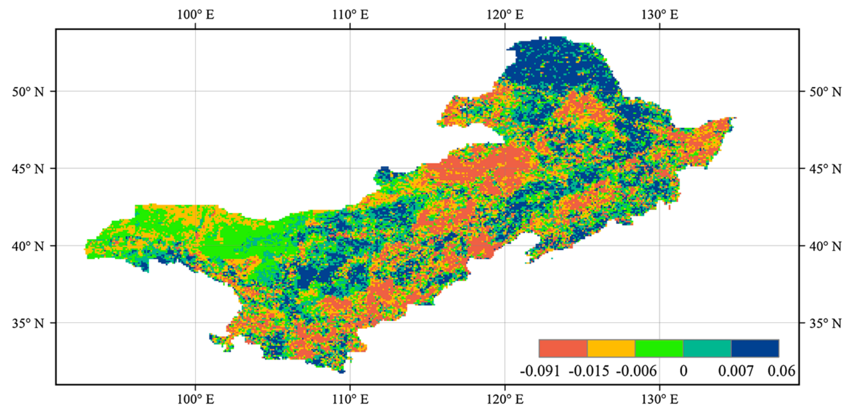

Figure 12. Spatial patterns on the difference of mean *NDVI* values during the growing season (April to October) between 1999–2011 and 1982–2011.

respiration. On the one hand, drought inhibited both plant growth and maintenance respiration due to depressed physiological processes [*Chapin et al*., 2012]. Low water availability decreased ecosystem vegetation production required to supply carbon substrate and decomposition [*Gärdenäs*, 2000] and induced dormancy in soil microorganisms [*Stark and Firestone*, 1995], which substantially limited soil respiration fluxes. On the other hand, decreased water moisture will increase the diffusion of soil CO_2 and O_2, which benefits soil organic matter decomposition [*Silver et al*., 1999]. Moreover, a high soil temperature coupled with drought events can stimulate litterfall and soil carbon decomposition [*Yuan et al*., 2009].

Previous studies show that ecosystem respiration responses to drought events have uncertain magnitude and direction. A manipulation experiment, investigating the effects of rainfall reductions on soil respiration, suggests that declines in precipitation could drive higher CO_2 fluxes to the atmosphere via increased soil O_2 availability and responses to elevated dissolved organic matter concentrations [*Cleveland et al*., 2010]. During the 2003 drought in Europe, *Reichstein et al*. [2007] found that nine of the 14 sites had negative flux anomalies relative to predrought conditions, and response magnitudes (predrought-postdrought flux value) ranged from -89 to 21 g C m^{-2} $month^{-1}$ for ecosystem respiration. The results of this study showed that both of ecosystem respiration and GPP fell in most regions during the study period; however, the regional mean TER showed an insignificant reduction from 1999 to 2011 compared with 1982 to 1998 (Figure 8b). It is worth noting that substantial decreases in TER did not appear from 1999 to 2001, which were the early years of this decadal drought event, while precipitation showed the largest reduction (Figure 8b). This result was supported by some control experiments and modeling analysis that showed low reduction of soil respiration at early years of drought [*Misson et al*., 2010; *Shi et al*., 2014]. Drought-induced reductions in vegetation production, soil water content, and soil organic material all contributed to the reduction in soil respiration. Vegetation production and soil moisture impacted soil respiration promptly, but their contributions were limited at the short term due to the lagged changes of soil moisture with precipitation and slight changes in soil organic materials [*Misson et al*., 2010]. In the long term, the decrease of the quantity and quality of organic material added to soil contributed significantly large reduction of soil respiration [*Misson et al*., 2010].

Carbon uptake is a balance of vegetation production and ecosystem respiration, and both factors will respond to varied water conditions when drought events occur. Our results indicated larger reductions in vegetation production than ecosystem respiration. Other studies showed similar conclusions. For example, the 2000–2004 drought of western North America reduced gross primary productivity (GPP) more than ecosystem respiration, resulting in a reduction in net CO_2 uptake [*Schwalm et al*., 2012]. A global analysis found that vegetation production was 50% more sensitive to a drought event than ecosystem respiration [*Schwalm et al*., 2010]. These results indicated that decreased ecosystem respiration cannot offset the loss of vegetation production during the drought episodes and highlighted the profound impacts of drought on terrestrial ecosystem carbon uptakes.

Northeast China, including the Heilongjiang, Jilin, Liaoning, and Hebei provinces, is one of the most important grain producing areas in China. The corn acreage in this region accounts for 26.3% of the corn area in the country, comprises approximately 29.4% of Chinese total corn grain productiony and plays a significant role in ensuring Chinese food security. Knowledge of the potential effects of climate change on corn production in Northeast China will be highly valuable for China and the world [*Sternberg*, 2012]. Although recent studies showed that climate change would increase corn yield in northern China due to a longer growing season [*IPCC*, 2007; *Chen et al*., 2011a], *Zhang et al*. [2010] reported opposite results indicating that average yields may decrease by approximately 2–3% without effective irrigation. Other studies highlighted the importance of drought impacts on crop yield, which is consistent with the conclusion in this study. For example, a lower yield and a higher temperature were accompanied by a positive correlation between yield and rainfall [*Chen et al*., 2011a]. Previous analysis shows that an increase in precipitation will increase crop yield, and crop yield is more sensitive to precipitation than temperature [*Droogers and Aerts*, 2005].

4.3. Model Limitations

A growing body of research used ecosystem models to investigate the effects of drought on ecosystem carbon cycling [*Ciais et al*., 2005; *Yuan et al*., 2010a, 2010b; *Schwalm et al*., 2012]. At present, most of the models, however, do not integrate the comprehensive equations to characterize the impacts of drought on ecosystem processes. First, previous studies have observed the quick and strong increases of soil respiration responding to a sudden increase in soil moisture from occasional rain pulses [*Xu et al*., 2004]. Especially at the arid and semiarid ecosystems, the carbon loss from those rain events is significant [*Xu et al*., 2004]. IBIS model used an early equation to simulate the impacts of soil moisture on soil respiration which assumed soil respiration increased with soil moisture until a given threshold (60% soil pore space filled by water) and then decreased (see supporting information). IBIS can capture partly the responses of soil respiration to rain pulses; however, the threshold still need explicitly be determined by combined the observations from eddy covariance towers.

Second, vegetation mortality is likely to occur if the drought is severe enough and can therefore have the substantial impacts on ecosystem carbon uptake [*McDowell et al*., 2008; *Liu et al*., 2012]. However, there are large uncertainties in our understanding of drought-induced plants mortality, particularly regarding the mechanisms, including moisture thresholds of plant death, which limited ecosystem models to accurately capture plant mortality [*McDowell et al*., 2013; *Reichstein et al*., 2013; *Xu et al*., 2013]. Mechanistic understanding of impacts of drought on plants mortality requires improved knowledge of belowground processes and soil moisture conditions [*Brunner et al*., 2009]; however, current models did not include detailed algorithms describing belowground physiological processes [*Allen et al*., 2010]. The failure of integrating vegetation mortality in the IBIS will result into the underestimation of carbon lost during the drought events.

5. Summary

Excluding fossil fuel emissions, northern China is presently an important carbon dioxide sink. Variations in this carbon sink are linked to hydroclimate variations that affect net ecosystem productivity. This study attempts to quantify the long-term consequences of extreme climate conditions on carbon cycles compared with other studies that focused on short-term impacts. Our results showed that continuous multiyear precipitation reductions have the potential to significantly alter long-term ecosystem water balances and carbon budgets. We further document a pronounced drying of the terrestrial biosphere during this period that is coupled with a reduction in soil moisture and a loss of cropland productivity. In China, more frequent extreme drought events may counteract the effects of the anticipated mean warming and lengthening of the growing season and erode the productivity of ecosystems, which reverses sinks to sources and contributes to positive carbon-climate feedbacks.

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