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The 2010 spring drought reduced primary productivity in southwestern China

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Abstract
Many parts of the world experience frequent and severe droughts. Summer drought can significantly reduce primary productivity and carbon sequestration capacity. The impacts of spring droughts, however, have received much less attention. A severe and sustained spring drought occurred in southwestern China in 2010. Here we examine the influence of this spring drought on the primary productivity of terrestrial ecosystems using data on climate, vegetation greenness and productivity. We first assess the spatial extent, duration and severity of the drought using precipitation data and the Palmer drought severity index. We then examine the impacts of the drought on terrestrial ecosystems using satellite data for the period 2000–2010. Our results show that the spring drought substantially reduced the enhanced vegetation index (EVI) and gross primary productivity (GPP) during spring 2010 (March–May). Both EVI and GPP also substantially declined in the summer and did not fully recover from the drought stress until August. The drought reduced regional annual GPP and net primary productivity (NPP) in 2010 by 65 and 46 Tg C yr^{-1}, respectively. Both annual GPP and NPP in 2010 were the lowest over the period 2000–2010. The negative effects of the drought on annual primary productivity were partly offset by the remarkably high productivity in August and September caused by the exceptionally wet conditions in late summer and early fall and the farming practices adopted to mitigate drought effects. Our results show that, like summer droughts, spring droughts can also have significant impacts on vegetation productivity and terrestrial carbon cycling.

Keywords: drought, primary productivity, vegetation greenness, EVI, GPP, NPP, MODIS

1. Introduction

The Earth's land surface has experienced frequent and severe droughts over the past century (Dai *et al* 1998, Zeng and Qian 2005, Della-Marta *et al* 2007, Xiao *et al* 2009, Zhao and Running 2010). The global land area affected by drought has significantly increased during the last five decades, particularly in the northern hemisphere (Easterling *et al* 2000, Hoerling and Kumar 2003, Meehl and Tebaldi 2004). Droughts are also projected to become more frequent and more severe during the remainder of the 21st century under different climate change scenarios (IPCC 2007). Drought has

profound impacts on ecosystem carbon exchange (Law *et al* 2001, Rambal *et al* 2003, Krishnan *et al* 2006). It can reduce gross primary productivity (GPP) and net ecosystem exchange (NEE) by suppressing photosynthetic activity and altering ecosystem respiration. Drought can also indirectly influence carbon cycling by inducing fire (Westerling *et al* 2006, Xiao and Zhuang 2007), tree mortality (Hogg *et al* 2008, Allen *et al* 2010) and insect outbreaks (Kurz *et al* 2008).

Severe and extended droughts can affect terrestrial carbon budgets at regional, continental and global scales. Globally, Zhao and Running (2010) showed that large-scale droughts reduced global net primary productivity (NPP). Regionally, researchers have studied the effects of droughts on carbon dynamics in different regions, such as Amazonia, Europe and North America. For instance, the 2005 and 2010 droughts over the Amazon tropical rainforest caused the loss of large amount of biomass and carbon (Phillips *et al* 2009, Lewis *et al* 2011, Potter *et al* 2011). In Europe, the drought and heatwave in 2003 substantially reduced GPP and led to a large net carbon release into the atmosphere (Ciais *et al* 2005, Reichstein *et al* 2007). In the US, Xiao *et al* (2010, 2011) reported that the 2002 and 2006 droughts substantially reduced the net carbon uptake of terrestrial ecosystems. In the central United States, studies have found that the drought reduced GPP and NEE and limited ecosystems' carbon sequestration capacity (Kwon *et al* 2008, Zhang *et al* 2011). In China, severe and extended droughts during the 20th century substantially reduced ecosystem carbon sequestration, or even switched terrestrial ecosystems from being a carbon sink to a source (Xiao *et al* 2009). Similar impacts of droughts on vegetation productivity and carbon budgets have also been investigated in other regions, such as the grassland ecosystems of southern Portugal (Pereira *et al* 2007), temperate forest ecosystems in East Asia (Saigusa *et al* 2010) and boreal forest ecosystems in the Arctic (Welp *et al* 2007). Most of these studies, however, focused on summer droughts. Few studies have investigated the impacts of spring droughts on ecosystem carbon dynamics (Kwon *et al* 2008, Noormets *et al* 2008, Scott *et al* 2009).

In spring 2010, large areas of southwestern China experienced a sustained and severe drought. Notably, this drought was the most severe spring drought during the last 50 years (Yang *et al* 2012) and was considered to be a 'once-in-a-century' drought. The drought initially started in September 2009 and was most severe from February to April 2010. Satellite observations showed that numerous small and medium-sized rivers and reservoirs dried up (Li *et al* 2010). This severe spring drought had substantial ecological (Wang 2010, Li *et al* 2010) and socioeconomic (Qiu 2010) impacts. It had large and destructive effects on agricultural production and the supply of drinking water to the inhabitants of the region (Qiu 2010, Wang 2010). In Yunnan, for instance, 8.1 million people (18% of Yunnan's population) were short of drinking water (Qiu 2010). According to a survey from the Office of State Flood Control and Drought Relief Headquarters, the cultivated land area affected by this spring drought accounted for 78% of the drought-affected area in China during the same period. Yunnan and Guizhou were the two most heavily impacted provinces in southwestern China, and winter wheat production in these two provinces decreased by 48% and 31%, respectively (Li *et al* 2010).

Here we use satellite data on vegetation greenness and primary productivity and climate data to examine the responses of terrestrial ecosystems to the 2010 spring drought in southwestern China. We first characterize the extent, duration, and severity of the drought using the Palmer drought severity index (PDSI) and then use satellite data products to assess the influence of the spring drought on vegetation greenness and primary productivity.

2. Data and methods

2.1. Study area

Our study region consists of four provinces: Yunnan, Guizhou, Guangxi and Sichuan and a municipality, Chongqing, in southwestern China, and covers the southeastern Tibetan Plateau, most of the Sichuan Basin and the Yunnan–Guizhou Plateau (figure 1). Drought occurs frequently in southwestern China and the terrestrial ecosystems in this region are highly fragile due to its special location, Karst landforms, climate and geology. This region is largely located in the subtropical climate area of China and is characterized by dry winters and wet summers. Annual precipitation is generally above 900 mm (Liu *et al* 2011) and is unevenly distributed over the year due to the influence of the subtropical monsoon climate and the hilly landscape (Zhu *et al* 2006). Karst landforms are widely distributed in the east with extensive exposure of limestone. Dry river valleys are broadly distributed in the west with sparse vegetation and severe water and soil loss, which can lead to the degradation of vegetation under disturbance (Wang *et al* 2010). Forest, savanna, cropland and grassland are the typical ecosystem types in this region, occupying 29.8%, 26.8%, 25.5% and 12.1% of the land area, respectively, according to the moderate resolution imaging spectroradiometer (MODIS) land cover map.

Most previous drought studies have focused on temperate and tropical ecosystems. However, few studies have paid attention to the subtropical zone. Southwestern China is largely located in the subtropical zone of China, which is a special region in the global biome due to the subtropical vegetation types and Asian monsoon climate. The 2010 spring drought that occurred in this region allows us to examine drought impacts in a typical subtropical zone.

2.2. Vegetation greenness and primary productivity products

We used enhanced vegetation index (EVI), GPP, and NPP data products derived from MODIS to characterize vegetation greenness and primary productivity during the drought period. MODIS has provided these data products globally at 1 km resolution since 24 February 2000.

Vegetation indices including the normalized difference vegetation index (NDVI) and EVI are important indicators of plant growth and vegetation productivity. These vegetation indices have been widely used to examine the spatial and temporal patterns of vegetation greenness and productivity

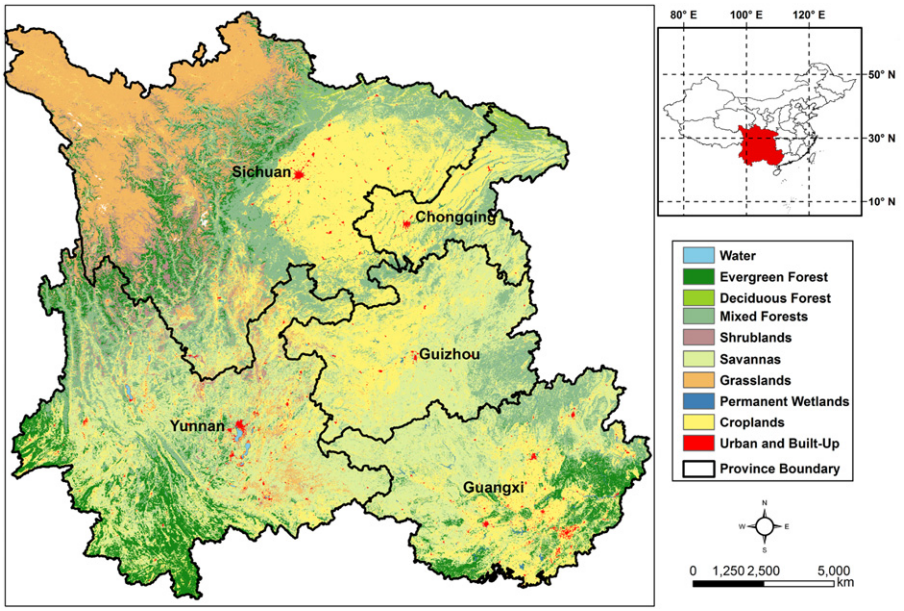

Figure 1. Location of our study region within southwestern China. The land cover map is reclassified from the 500 m MODIS land cover map.

at a variety of spatial scales (e.g. Kawabata *et al* 2001, Slayback *et al* 2003, Xiao and Moody 2005, de Jong *et al* 2012). Compared to the NDVI, the EVI remains sensitive to vegetation variations even in areas with high biomass and high coverage area (Gao *et al* 2000, Huete *et al* 2002). In our study, we used the MODIS EVI product (MOD13A2; collection 5) obtained from the Earth Observing System (EOS) Data Gateway. This product provides EVI with 16 day intervals and 1 km spatial resolution for the period from March 2000 to December 2010.

GPP is the amount of carbon absorbed by ecosystems through photosynthesis and is an important component in land–atmosphere CO_2 exchange. NPP is the difference between GPP and the respiratory loss by the plants (autotrophic respiration) and quantifies the net production of organic matter by plants. We obtained 1 km MODIS GPP (MOD17A2; collection 5) and NPP (MOD17A3; collection 5) from the Numerical Terradynamic Simulation Group (www.ntsg.umt.edu) for the period from March 2000 to December 2010 (Zhao *et al* 2005, Zhao and Running 2010).

The MOD17A2 product provides GPP estimates with an 8 day interval and is intended for monitoring seasonal dynamics of photosynthetic activity. The MOD17A3 NPP product provides annual NPP for evaluating spatial–temporal variations in productivity and terrestrial behavior at the annual scale. These products have been recently improved by temporally filling missing or cloud-contaminated FPAR/LAI, spatially interpolating coarse resolution meteorological data to the 1 km MODIS pixel level, and modifying the representation of autotrophic respiration in the algorithm (Zhao *et al* 2005, Zhao and Running 2010).

2.3. Climate data

We used gridded climate data from the global Modern Era Retrospective-Analysis for Research and Applications (MERRA) reanalysis data set. The MERRA reanalysis data set is developed by NASA's Global Modeling and Assimilation Office (GMAO). It provides meteorological data with a spatial resolution of $0.5° \times 0.667°$, spanning the period from 1979 to the present. MERRA makes use of observations from NASA's Earth Observing System satellites and reduces the uncertainty in precipitation and interannual variability by improving the representation of the water cycle in reanalyses (Rienecker *et al* 2011). We used monthly precipitation and temperature data from MERRA for the period 2000–2010 in this study.

We also used the Palmer drought severity index (PDSI; Palmer 1965). The PDSI is a measure of the cumulative departure in the surface water balance, and has been proven to be a good proxy for surface moisture conditions in measuring environmental water stress. The PDSI uses monthly precipitation and temperature as inputs to assess drought and is perhaps the most widely used index of meteorological drought (Dai *et al* 2004). The PDSI incorporates the antecedent precipitation, moisture supply and moisture demand, and captures dry and wet spells, thereby reflecting how much soil moisture is currently available compared to that for normal or average conditions (Palmer 1965). It has been routinely used for monitoring droughts in the United States. We used the global PDSI data at $2.5° \times 2.5°$ spatial resolution from the National Center for Atmospheric Research (Dai *et al* 2004). The PDSI varies roughly between -10.0 (dry) and $+10.0$ (wet). PDSI values between -0.5 and 0.5 are considered near normal. Values of -1.0 to -1.9 stand for mild drought, -2.0 to -2.9 for moderate drought and values below -3.0 for severe to extreme drought.

2.4. Data analysis

We used PDSI data to characterize the spatial extent, severity and duration of the 2010 spring drought across southwestern

China. For each grid cell, we also used mean monthly PDSI data during the drought period to characterize the surface drought conditions. The percentage area experiencing drought over the study region was calculated by dividing the drought-affected area by the total land area of the region.

We also used climate data from MERRA to examine the precipitation and temperature conditions for the drought period relative to the long-term climatological means. The standard definition of climate is based on mean conditions over a 30 year period. We thus calculated the mean monthly precipitation and temperature for the period 1980–2009 and used these as the long-term means. We also calculated the anomalies of precipitation and temperature for each month in 2010 relative to the means over the 10 year period 2000–2009 to illustrate the climate conditions in the drought relative to the period during which we have access to MODIS EVI, GPP and NPP data.

We used MODIS EVI, GPP and NPP data to assess the impacts of the 2010 spring drought on vegetation greenness and productivity. First, we calculated the spatial means of monthly EVI and GPP by averaging the values of each variable across the study region. We then calculated monthly EVI and GPP anomalies for each month in 2010 relative to the means for the period 2000–2009. For each grid cell, we also calculated monthly anomalies for EVI and GPP and annual anomalies for EVI, GPP and NPP in 2010 relative to the means for the 10 year period (2000–2009).

3. Results

3.1. Characterization of the 2010 spring drought

Figure 2 illustrates the monthly average temperature and monthly total precipitation for southwestern China for the period 2009–2010, the averages for 1980–2009, and the averages for 2000–2009 from MERRA data. These results showed that southwestern China experienced large precipitation deficits during spring 2010. This spring drought can be traced back to the fall and winter of 2009. From September 2009 to May 2010, precipitation decreased by 11.6% and 10.7% relative to the 1980–2009 and 2000–2009 means, respectively (figure 2(a)). Precipitation from January to May, 2010 declined by 8.3% and 10.9% in 2010 relative to the means for 1980–2009 and 2000–2009, respectively. Precipitation in February, in particular, decreased by 51.4% (26 mm) and 49.5% (24 mm), respectively.

During this drought, large water deficits were concurrent with higher air temperatures (figure 2(b)). From January to May 2010, mean air temperature increased by 7.5% relative to the mean for the 30 year period 1980–2009, with an increase of 1.6 °C and 1.3 °C in January and February, respectively. Relative to the means for the period 2000–2009, mean air temperature increased by 5.2% from January to May 2010, with an increase of 1.4 °C and 0.8 °C in January and February, respectively.

The drought affected almost the entire study region except the northwest portion (figure 3). Approximately 56.3% of the region suffered from severe drought; an additional

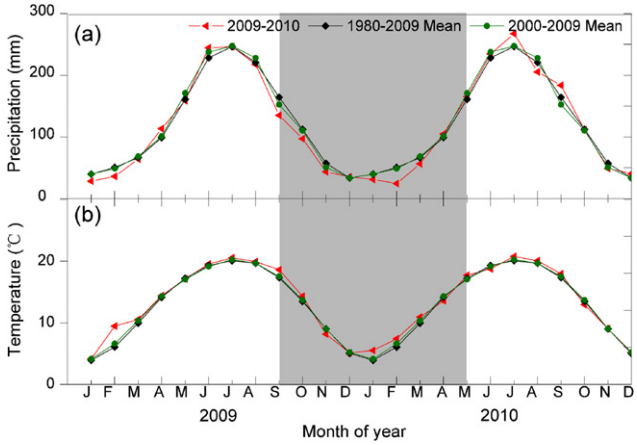

Figure 2. Monthly air temperature and precipitation averaged over southwestern China: (a) monthly total precipitation (mm), (b) monthly mean temperature (°C). The 2010 spring drought can be tracked back to September 2009. The shaded area indicates the entire dry period from September 2009 to May 2010 including the 2010 spring drought event.

10.5% and 7.0% of the study region was affected by moderate and mild drought, respectively. The severity of the drought varied over space. The central and south of the study area were most severely affected. During the drought period, precipitation was significantly lower than the long-term mean, particularly in Yunnan, the west of Guangxi and Guizhou, and southern Sichuan (figure 3). Yunnan was the most severely impacted province, exhibiting the largest precipitation deficits among the five provinces. In Yunnan, precipitation in the spring decreased by 12.8% and 22.6% relative to the means for the periods 1980–2009 and 2000–2009, respectively, and the mean air temperature increased by 3.9 °C and 3.8 °C, respectively.

3.2. Impacts of the spring drought on vegetation greenness and productivity

Figure 4 illustrates the influence of the 2010 spring drought on vegetation greenness and primary productivity averaged over the study region. The 2010 spring drought substantially reduced spring EVI and GPP relative to the mean over the period 2000–2009. For instance, EVI and GPP declined by 9% and 14% in April, respectively. Both EVI and GPP also substantially declined in the summer relative to the means over the period 2000–2009, and did not fully recover from the drought stress until August. EVI decreased by 12.5% and 6.4% in June and July, respectively, and GPP decreased by 14.0% and 12.8%, respectively. After August, precipitation substantially increased and exceeded the 30 year (1980–2009) mean for the same period (figure 2(a)), and both EVI and GPP were also higher than the 10 year means in August and September.

The impacts of the spring drought on primary productivity varied with vegetation type (figure 5). Grasslands and shrublands were the least affected vegetation types. These two vegetation types are mainly distributed in northwest of the study region, which were least affected by this spring

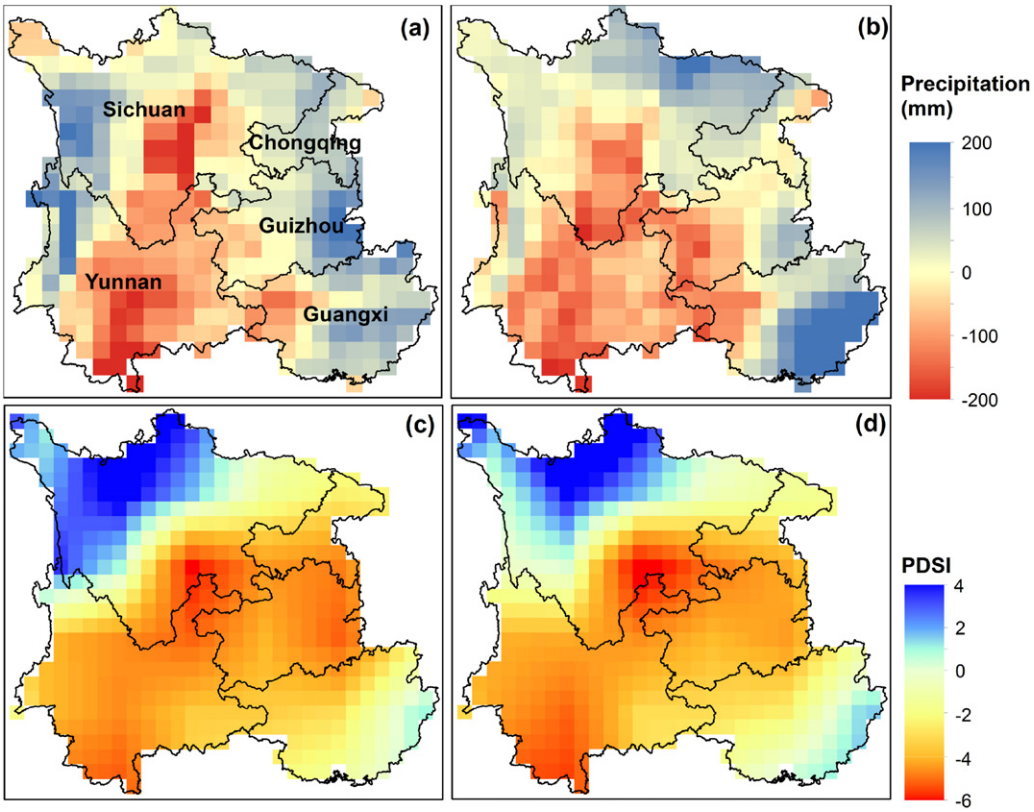

Figure 3. Spatial extent and severity of the 2010 spring drought in southwestern China. (a) Precipitation anomalies for spring (March–May) 2010 relative to the mean over the period 1980–2009, (b) precipitation anomalies for September 2009–May 2010 relative to the mean over the period 1980–2009, (c) mean monthly PDSI for spring (March–May) 2010, (d) mean monthly PDSI for September 2009–May 2010.

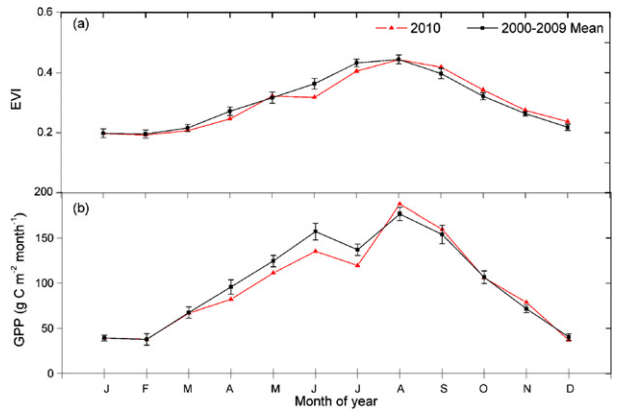

Figure 4. Intra-annual variations of (a) EVI and (b) GPP for 2010 together with the means for 2000–2009. For the 2000–2009 mean, the error bars denote mean ± standard error.

drought (figures 1 and 3). Deciduous and mixed forests were more severely affected than evergreen forests. For evergreen forests, GPP during the drought period did not substantially decline because a significant fraction of this vegetation type is distributed in the northwest and southeast of the study region and was not severely affected by the drought. The drought had the greatest impact on croplands and substantially reduced cropland GPP during spring and summer (from early March to late July). For example, the cropland GPP decreased by 16.0% and 13.9% in March and May, respectively. Following the spring, the spring drought continued to suppress the growth of crops. In June and July, the GPP of croplands was 19.0% and 15.5% lower than the means over the period 2000–2009, respectively.

Spatially, our results show widespread vegetation stress during the drought period. Both EVI and GPP exhibited strong negative anomalies in the drought-affected areas during the spring (March–May) (figure 6). On average, spring EVI and GPP decreased by 5.6% and 9.6%, respectively. For badly damaged croplands, spring EVI and GPP showed a decline of 16.6% and 8.1%, respectively. The largest anomalies occurred in Guizhou and Yunnan, and these two provinces are dominated by croplands and savannas.

The annual EVI, GPP and NPP exhibited large negative anomalies in most drought-affected areas (figure 7). For many areas, annual EVI in 2010 decreased by 0.05–0.1 relative to the 10 year mean; annual GPP decreased by 200–400 g C m^{-2} yr^{-1}; annual NPP decreased by 100–200 g C m^{-2} yr^{-1}. On average, nearly 63% of the region showed declines in annual NPP. We found that the largest NPP reduction occurred in Yunnan, Guizhou and Guangxi. On average, annual NPP decreased by 9.8% in Guizhou, and a large agricultural area in the province was affected by the drought. In Yunnan, where there are extensive savannas, NPP decreased by 5.7%. In Guangxi, which has extensive croplands and savannas, NPP decreased by 4.8%.

Spatially-averaged annual NPP in 2010 (641 g C m^{-2} yr^{-1}) was 4.9% lower than the mean over

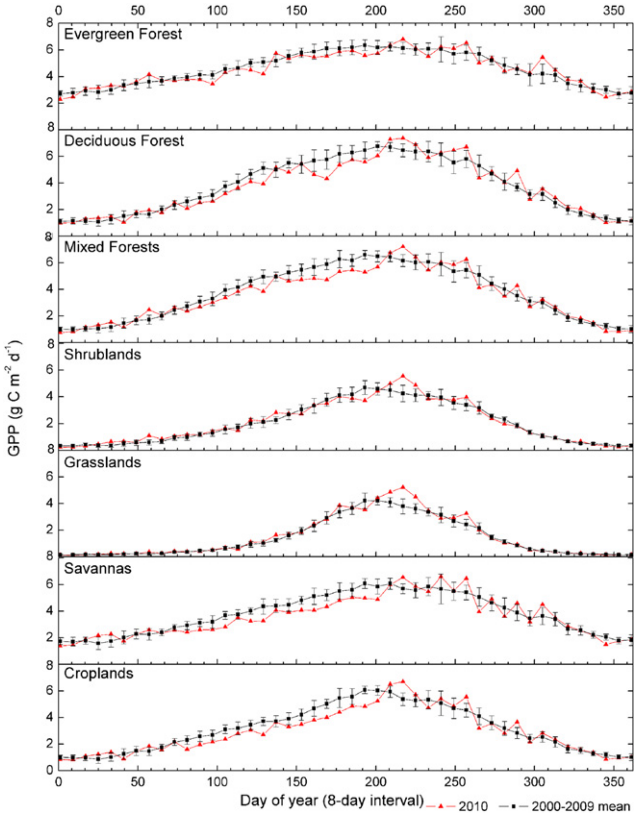

Figure 5. Intra-annual variations of GPP for 2010 and 2000–2009 average for different vegetation types. For the 2000–2009 mean, the error bars denote mean ± standard error.

the period 2000–2009 (674 g C m^{-2} yr^{-1}) and was 6.0% lower than annual NPP in 2009 (682 g C m^{-2} yr^{-1}). The reduction of annual NPP was mainly caused by the reduction of annual GPP. Spatially-averaged GPP decreased by 4.0% (47.8 g C m^{-2} yr^{-1}) relative to the mean over the period 2000–2009 (918 g C m^{-2} yr^{-1}). Overall, the drought reduced regional annual GPP and NPP by 65 and 46 Tg C yr^{-1}. The effects of this spring drought on GPP and NPP were amplified by high spring temperature. The spring and annual carbon fluxes (GPP and NPP) in 2010 were among the lowest during the 10 year period 2000–2009 and were as low as those of 2000, one of the driest years of the last five decades. The southwest of China is a typical Chinese agricultural region and winter wheat is the major crop. The annual wheat production declined by 24.0% relative to the mean production from 2000 to 2009 (China Statistical Yearbook from National Bureau of Statistics, www.stats.gov.cn/), which is generally consistent with our results.

We also compared the responses of primary productivity to this spring drought for different vegetation types (figure 8). The cumulative spring EVI and GPP decreased in 2010 relative to the means over the period 2000–2009 for all vegetation types except grasslands (figure 8(a)). Croplands, savannas and deciduous forests were the most impacted ecosystem types, with reductions of 8.1%, 6.3% and 11.6%, respectively for spring EVI and 16.6%, 15.5% and 11.5%, respectively for spring GPP. Both EVI and GPP showed larger relative changes (declines) during the spring season than for the year as a whole.

The drought effects on annual GPP and NPP also varied with vegetation type (figure 8(b)). Croplands and savannas exhibited the greatest relative changes (declines) in annual NPP relative to the means over the period 2000–2009, with reductions of 7.3% and 7.2%, respectively. For croplands, the regional annual NPP decreased by 6.0% in 2010 compared to 2009. For shrublands, annual GPP decreased by 3.1% and annual NPP increased by 3.6%. For deciduous forest, annual GPP increased by 6.7% and annual NPP decreased by 2.0%. For both shrublands and deciduous forest, the changes in annual GPP and NPP were in different directions. The different responses of annual GPP and NPP to the drought for shrublands and deciduous forest are likely due to the different response of respiration to the drought. The spring drought did not reduce the annual NPP of grasslands and shrublands. Grasslands and shrublands are mainly distributed in the northwest of this region and were least affected by the drought.

4. Discussion

The 2010 spring drought in southwestern China was the most severe spring drought of the last five decades

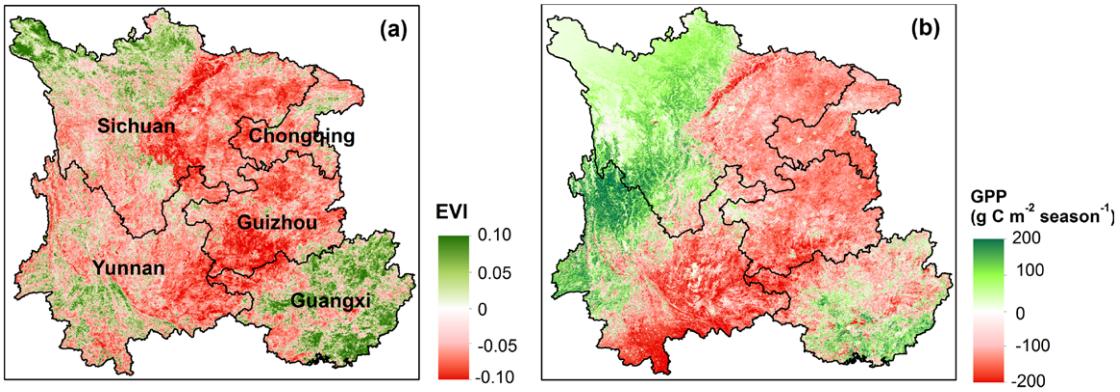

Figure 6. Regional anomalies of (a) EVI and (b) GPP during spring (March–May) 2010 relative to the means over the period 2000–2009.

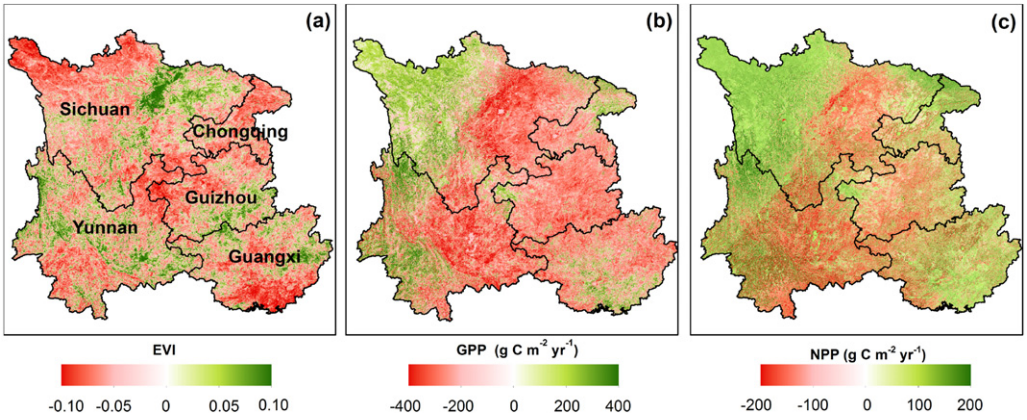

Figure 7. Regional anomalies of annual (a) EVI, (b) GPP and (c) NPP in 2010 relative to the means over the period 2000–2009.

(Yang *et al* 2012). The PDSI data clearly delineated the spatial extent, intensity and duration of the drought (figure 3). This drought affected the majority of the study region. It can be traced back to September 2009 and was most severe from February to April 2010. The severe drought was mainly caused by regional atmospheric anomalies (Lu *et al* 2011), and was characterized by large precipitation deficits and high temperatures. Higher air temperatures increased evaporation and further exacerbated water deficits. For instance, the average evaporation for Yunnan during July and December 2009 was 822.5 mm, which is 12% higher than the long-term average (733.6 mm) (Liu *et al* 2011). The drought also led to declines in stream flows, lower reservoir levels, frequent forest fires and widespread tree mortality. The unique Karst landform in large areas of southwestern China may also have exacerbated the surface water conditions. The water dissolution effect of the Karst landform led to strong infiltration of surface water and severe surface water shortages, which further exacerbated the drought (Zhou *et al* 2012).

The 2010 spring drought substantially reduced vegetation greenness and primary productivity in the spring in most drought-affected areas. The negative effects of water deficits outweighed the positive effects of higher temperatures and solar radiation (Xiao *et al* 2009). The concurrence of low precipitation and high temperatures led to low moisture conditions, and thereby substantially reduced GPP and NPP in large parts of the drought-affected regions. Plant growth did not fully recover from the drought stress until August 2010. The particularly wet conditions starting from August led to positive anomalies in GPP in August and September despite the spring drought. The high crop production during the latter part of the year can also be attributed to improved farming practices. As a result of a drought mitigation strategy, the farmers in the area planted different crops together in the same field, rather than as a monoculture, which boosted yields by up to 30% (Qiu 2010).

The spring drought led to significant declines in annual EVI, GPP and NPP in 2010. The annual GPP and NPP in 2010 were the lowest over the period from 2000 to 2010. For the entire region, the drought resulted in a reduction of 46 Tg C yr^{-1} in annual NPP in 2010. For croplands,

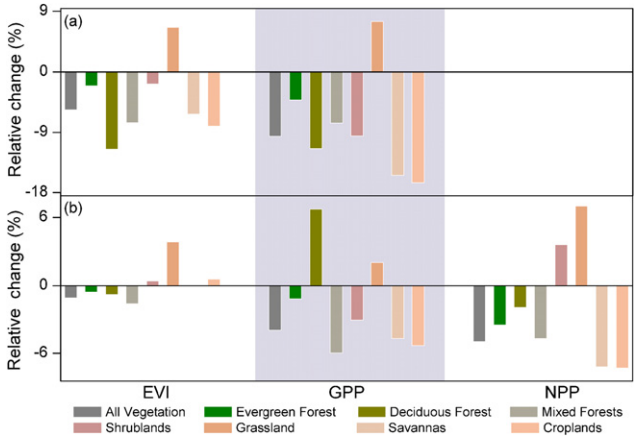

Figure 8. Relative changes (%) in (a) spring (March–May) and (b) annual EVI, GPP and NPP in 2010 relative to the means over the period 2000–2009 for different vegetation types.

the decline in annual NPP was presumably caused by the reduced yield of winter wheat due to the spring drought. According to the China Statistical Yearbook from the National Bureau of Statistics (www.stats.gov.cn), the winter wheat yield in southwestern China in 2010 decreased by 10.8% relative to 2009. Winter wheat is the major food product in southwestern China and winter wheat is in its jointing and heading stages and requires a lot of water during spring. In addition to winter wheat, the yield of other crops such as rapeseed and sugarcane was also significantly reduced by the drought (Li *et al* 2010). The negative impacts of the drought on annual primary productivity were partly offset by the high productivity in August and September due to the exceptionally wet conditions in late summer and early fall and the farming practices adopted to mitigate drought effects.

The influence of the drought on vegetation greenness and primary productivity varied with vegetation type. Croplands exhibited the largest decline in productivity and were most sensitive to the drought. This extreme drought lowered the water levels of rivers, reservoirs and lakes, and even dried up some water bodies (Li *et al* 2010), which limited water for irrigation. The drought-affected spring plowing and also led to a substantial decline in summer-harvested crops (Yun *et al* 2012). Forests are generally more resilient to

drought because trees have deeper roots and have access to ground water. However, this extreme drought resulted in tree damage and mortality (Xiong *et al* 2011) and also triggered widespread forest fires (Department of Forestry of Guizhou Province 2012). Grasslands and shrublands were the least affected as these vegetation types are mainly distributed in the northwest portion of the region and were not significantly affected by the drought.

A number of studies have examined the influence of drought on plant productivity and the terrestrial carbon cycle (e.g., Ciais *et al* 2005, Phillips *et al* 2009, Xiao *et al* 2009, 2010, 2011, Zhao and Running 2010, Potter *et al* 2011, Lewis *et al* 2011, Zhang *et al* 2011). The majority of these studies, however, focused on summer drought, and spring drought has received much less attention (Kwon *et al* 2008, Noormets *et al* 2008, Scott *et al* 2009). Our results show that similar to summer droughts, spring droughts can also have significant impacts on vegetation productivity and terrestrial carbon cycling. Drought in summer limits transpiration and directly reduces photosynthesis. Water stress in spring can also directly reduce photosynthesis. Moreover, spring drought can suppress canopy development and peak leaf area, leading to a decline in annual net carbon uptake (Noormets *et al* 2008). Spring drought can also shorten the length of the growing season, particularly for crops. Spring drought can reduce spring carbon uptake and also enhance summer respiration, thus leading to reduced annual carbon uptake or even net annual carbon loss (Scott *et al* 2009). In a desert grassland ecosystem, Schwinning *et al* (2005) concluded that the grass growth is far more sensitive to spring drought than summer drought. Spring drought can constrain annual carbon uptake by regulating the availability of soil moisture during the summer season (Kwon *et al* 2008, Noormets *et al* 2008, Scott *et al* 2009). Our results showed that the 2010 spring drought led to significant declines in vegetation greenness and primary productivity for both the spring and the year as a whole in southwestern China.

5. Conclusions

The 2010 spring drought that occurred in southwestern China was the most severe spring drought over the last five decades. We first assessed the spatial extent, duration and severity of the drought using precipitation and PDSI data. The drought affected almost the entire study region except the northwest portion. Approximately 56.3% of the study region suffered from severe drought; an additional 10.5% and 7.0% of the region was affected by moderate and mild drought, respectively.

We then examined the impacts of this drought on vegetation greenness and primary productivity using MODIS EVI, GPP and NPP data products. Our results show that the terrestrial ecosystems in southwestern China were significantly influenced by the 2010 spring drought. Nearly 63% of the region showed declines in vegetation productivity. The drought substantially reduced spring EVI and GPP. Both EVI and GPP also substantially declined in the summer relative to the means over the period 2000–2009 and did not fully recover from the drought stress until August. The drought reduced regional annual GPP and NPP in 2010 by 4.0% and 5.0%, respectively, relative to the means over the period 2000–2009. The impacts of the spring drought on annual GPP and NPP were partly offset by the remarkably high productivity in August and September due to the exceptionally wet conditions and improved farming practices. The spring and annual primary productivity (GPP and NPP) in 2010 were the lowest over the 11 year period 2000–2010. Our results show that severe and extended spring droughts can have significant impacts on vegetation productivity in both spring and early summer, leading to declines in annual GPP and NPP.

Droughts are projected to become more frequent and more severe during the remainder of the 21st century (Meehl and Tebaldi 2004, IPCC 2007, Funk *et al* 2008). Our results indicate that future droughts will likely have larger impacts on plant growth and the terrestrial carbon cycle. More frequent and more severe droughts will partly offset the enhancement effects of rising atmospheric CO_2 concentrations, elevated air temperatures, and nitrogen deposition on plant growth and ecosystem carbon sequestration (Xiao *et al* 2009). The negative effects of spring and summer droughts on terrestrial ecosystems may constitute a positive feedback to the climate system (Xiao *et al* 2009).

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