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Drought events and their effects on vegetation productivity in China

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Abstract. Many parts of the world have experienced frequent and severe droughts during the last few decades. Most previous studies examined the effects of specific drought events on vegetation productivity. In this study, we characterized the drought events in China from 1982 to 2012 and assessed their effects on vegetation productivity inferred from satellite data. We first assessed the occurrence, spatial extent, frequency, and severity of drought using the Palmer Drought Severity Index (PDSI). We then examined the impacts of droughts on China's terrestrial ecosystems using the Normalized Difference Vegetation Index (NDVI). During the period 1982–2012, China's land area (%) experiencing drought showed an insignificant trend. However, the drought conditions had been more severe over most regions in northern parts of China since the end of the 1990s, indicating that droughts hit these regions more frequently due to the drier climate. The severe droughts substantially reduced annual and seasonal NDVI. The magnitude and direction of the detrended NDVI under drought stress varied with season and vegetation type. The inconsistency between the regional means of PDSI and detrended NDVI could be attributed to different responses of vegetation to drought and the timing, duration, severity, and lag effects of droughts. The negative effects of droughts on vegetation productivity were partly offset by the enhancement of plant growth resulting from factors such as lower cloudiness, warming climate, and human activities (e.g., afforestation, improved agricultural management practices).

Key words: China; drought; drought effects; Normalized Difference Vegetation Index; Palmer Drought Severity Index; vegetation productivity.

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Introduction

The drought-affected global land area has been significantly increasing during the last five decades. Globally, the percentage of areas under drought had increased by about 1.74% per decade from 1950 to 2008 (Dai 2011). Frequent and severe droughts had hit different parts of the world (Zhao and Running 2010), such as North America (Chen et al. 2012), South America (Phillips et al. 2009), Africa (Shanahan et al. 2009), Europe (Ciais et al. 2005), Asia (Saigusa et al. 2010), and Australia (Nicholls 2004). Frequent drought events during recent decades had a close connection with global climate change (Dai 2013). Increases in drought were mainly driven by higher temperatures, higher evaporation, and lower precipitation (Dai 2013). Droughts can reduce vegetation greenness and productivity through their impact on photosynthetic activity. Severe droughts can affect terrestrial ecosystems at regional to global scales. The global-scale study by Zhao and Running (2010) indicated that droughts reduced global net primary production (NPP) by 0.55 Pg C during the period 2000–2009. At regional scales, severe and extended droughts reduced vegetation productivity and carbon uptake in regions such as United States (Xiao et al. 2010, Zhang et al. 2010), Arctic (Welp et al. 2007), East Asia (Saigusa et al. 2010), China (Zhang et al. 2012), and Europe (Ciais et al. 2005).

The intensity and duration of drought partly determined the effects of drought on plant productivity. The timing of drought also affects ecosystem responses to drought (Scott et al. 2009, Pei et al. 2013). Previous studies mainly focused on summer droughts (Ciais et al. 2005, Xiao et al. 2010, Zhao and Running 2010). Drought seasonality also influenced plant productivity. For example, grass growth in a cold desert ecosystem was more sensitive to winter drought than to summer drought (Schwinning et al. 2005). A spring drought led to significant decline in vegetation greenness in Southwest China (Zhang et al. 2012). Spring drought can regulate the availability of soil moisture during the summer season and therefore constrain the annual carbon uptake (Kwon et al. 2008).

The majority of the global land area experienced a warming climate during the last three to four decades (IPCC 2014). The warming trend, especially for summer temperature, is particularly apparent in China (Hansen et al. 2012). The weakened East Asian summer monsoon in the late 1970s led to the changes in precipitation in China and resulted in the so-called southern flood and northern drought pattern (Wang et al. 2012*a*). The severity of droughts in China has been investigated extensively. North China experienced severe and prolonged dry periods, and a significant increase in drought area since the late 1990s was observed (Zou et al. 2005). The frequency of droughts had increased during recent years in China, especially in southern China (Wang et al. 2012*b*). The average area affected by drought reached 21.56 million hectares from 1950 to 2010 causing large annual average grain loss of 16.12 billion kg (or by 4.53%; Liu 2012). The drought-affected area had increased nearly 12-fold from 1950 to 2009 (Wang et al. 2012*b*). The frequency of extreme droughts in China is also projected to increase during the remainder of the 21st century (Wang et al. 2012*a*).

Although the satellite-derived Normalized Difference Vegetation Index (NDVI) showed an overall increasing trend in China (Liu and Gong 2012), the increasing rate of vegetation greenness decreased during the period 2000–2010 compared to the previous two decades (1982–1999; Peng et al. 2011). The decrease in the increasing rate of NDVI may be partly caused by frequent drought events (Xiao et al. 2009, Sun et al. 2013). With the rapidly changing climate and increasing world population, food security has received growing attention (Funk et al. 2008). Droughts may aggravate the problem of food insecurity in China, the most populous country in the world. Assessing the consequences of the increasing drought occurrence on vegetation productivity is essential for better understanding the vulnerability of terrestrial ecosystems and food security to climate change.

Different remotely sensed vegetation indices have been used to approximate vegetation productivity and to examine the effects of drought on terrestrial ecosystems (Kogan 1997, Ji and Peters 2003, Shahabfar et al. 2012). NDVI is perhaps the most widely used vegetation index. NDVI has been used to examine climate impacts on vegetation greenness in China (Peng et al. 2011, Wang et al. 2015). Despite these studies, the sensitivity of NDVI to drought and its capability for indicating drought conditions have been less investigated at the national scale and at decadal timescales. The impacts of droughts on vegetation productivity in China have also been examined using ecosystem models (Xiao et al. 2009, Potter 2013, Liu et al. 2014). Compared to modeling, NDVI provides an independent and alternative approach for assessing vegetation productivity. The Global Inventory Monitoring and Modeling Studies (GIMMS) Group's NDVI3g product (Pinzon and Tucker 2014) consists of biweekly NDVI data for a 31-year period from 1982 to 2012 and provides the longest NDVI record for regional- to global-scale studies. The recent availability of this product allows us to assess vegetation productivity in response to drought over the last three decades.

In this study, we characterized the drought events in China over the period 1982–2012 and examined the impacts of droughts on vegetation productivity. We first assessed the occurrence, spatial extent, frequency, and severity of drought using the Palmer Drought Severity Index (PDSI). We then assessed the effects of droughts on vegetation productivity using the GIMMS NDVI3g product. The ecosystem responses to drought were analyzed for different seasons and different vegetation types.

Data and Methods

Drought index

In this study, we used the PDSI (Palmer 1965) to characterize the drought events in China over the period 1982–2012. PDSI is perhaps the most widely used drought index (Mishra and Singh 2010). It incorporates the antecedent precipitation, moisture supply, and moisture demand and therefore can capture dry and wet spells (Palmer 1965). PDSI has been proven to be a good proxy for surface moisture condition in measuring environmental water stress (Dai et al. 2004) and has been routinely used for drought monitoring in the United States (Heim 2002).

Although PDSI is a widely used drought index, it may have limitations in capturing the dry and wet conditions and representing the complexity of drought. The Thornthwaite method is commonly used for estimating potential evapotranspiration (PET) in the calculation of PDSI because the input data for this method, mean monthly temperatures, are readily available (van der Schrier et al. 2011). The use of this empirical approach has been questioned (Zhao and Running 2010). The previously reported increase in the frequency and severity of drought based on PDSI might have been overestimated because of the use of the simplified PET model that responds only to changes in temperature and thus may respond incorrectly to global warming in recent decades (Sheffield et al. 2012). However, van der Schrier et al. (2011) assessed the differences in global PDSI maps using two estimates of PET, one based on the Thornthwaite method and one based on the Penman-Monteith approach. The PDSI values based on the two PET estimates were very similar in terms of correlation, regional averages, trends, and identified extremely dry or wet months (van der Schrier et al. 2011).

We used the global PDSI dataset at 0.5° spatial resolution and monthly time step from the Numerical Terra dynamic Simulation Group, University of Montana (http://www.ntsg.umt.edu/) (Zhao and Running 2010), to characterize drought in China during 1982–2012. The drought severity was classified into three categories: mild ($-1.0 <$ PDSI < -2.0), moderate ($-2.0 <$ PDSI < -3.0), and severe to extreme (PDSI < -3.0). The average PDSI and percentage drought-affected area (%) were calculated for each category at both seasonal and annual scales for characterizing the occurrence, severity, and frequency of drought. The spatial PDSI data can provide information on spatial extent and intensity of droughts.

Normalized Difference Vegetation Index

As an effective indicator of plant growth, the NDVI has been widely used to examine the spatial and temporal patterns of vegetation greenness and productivity and their responses to climate change (Xiao and Moody 2004, 2005, Beck and Goetz 2011, de Jong et al. 2012, Zhang et al. 2014*b*). In our study, we used the GIMMS NDVI3g dataset product (http://ecocast.arc.nasa.gov/data/pub/gimms/; Pinzon and Tucker 2014) to examine vegetation productivity from 1982 to 2012. The GIMMS NDVI3g dataset provides global NDVI maps with 15-day intervals and 1/12-degree spatial resolution for the period from 1981 to 2012, which is currently considered to be the best dataset available for long-term NDVI analysis (Fensholt and Proud 2012, Zeng et al. 2013). To minimize the effects of sensor changes among the NOAA satellites and orbital decay on the quality of the AVHRR data, calibration was performed using Bayesian methods with high-quality, well-calibrated NDVI data from Sea-Viewing Wide Field-of-view Sensor (SeaWiFS) for deriving AVHRR NDVI calibration parameters. The GIMMS NDVI3g dataset has better quality and longer record than its predecessor, the GIMMS NDVI dataset (1981–2006).

We aggregated the biweekly NDVI data into monthly intervals for the entire study area from 1982 to 2012 using the maximum value composite method (Holben 1986), which further reduced the effects of cloud and other noise. For each pixel, we calculated the annually and seasonally averaged NDVI for each year to approximate annual and seasonal vegetation productivity. The seasonal NDVI was calculated as the mean NDVI for winter (December–February), spring (March–May), summer (June–August), and autumn (September–November), respectively.

Net primary productivity data

We used annual net primary productivity (NPP; g $C \cdot m^{-2} \cdot yr^{-1}$) data to assess the effects of drought on agricultural productivity. Annual crop NPP was estimated from crop yield statistics data using the harvest index method (Prince et al. 2001, Huang et al. 2007). The crop yield statistic data were downloaded from the National Bureau of Statistics of China (http://data.stats.gov.cn/). We obtained the harvested area and yield per unit harvested area of cereals (including rice, wheat, corn, millet, and sorghum), beans, and potatoes over the period 1982–2012 for each province (or autonomous region, municipality).

The annual NPP including the aboveground and belowground components was calculated for each crop type and for each province from harvested yield data using the crop-specific harvest index value from Huang et al. (2007). The aboveground residue was calculated from crop yield using the ratio of aboveground residue production to the economic yield. The belowground mass was estimated as a function of aboveground mass (sum of aboveground residue and crop yield for cereals and beans, only aboveground residue for potatoes) based on root-to-shoot biomass ratio (Huang et al. 2007). Finally, the total dry mass (aboveground and belowground) was converted to carbon mass (NPP). The final crop NPP was calculated as the sum of NPP for rice, wheat, corn, millet, sorghum, beans, and potatoes divided by the harvested area.

Data analysis

We used annual and seasonal PDSI data to characterize the spatial extent, severity, and duration of droughts across China during the period from 1982 to 2012. The percentage area experiencing each category of drought (mild, moderate, or severe to extreme) was calculated by dividing the drought-affected area by the total vegetated area of the region. We also calculated the spatially averaged annual and seasonal NDVI by averaging the NDVI values of each pixel across China and then detrended both time series following Xiao et al. (2015). For annual and seasonal NDVI, we determined the best linear fit between NDVI and time (yr; Eq. 1) and then removed the best linear fit from the NDVI time series (Eq. 2):

$$\hat{y} = a + bx + \varepsilon \tag{1}$$

$$y_{\mathrm{detrend}} = y - \hat{y} \tag{2}$$

where $\hat{y}$ is the dependent variable representing the best linear fit of annual or seasonal NDVI, x is the independent variable year, and ε is the stochastic error term. y_{detrend} represents detrended NDVI. The detrended NDVI time series is essentially the residuals from the linear fit. Here, we define vegetation stress as negative detrended NDVI. The detrended NDVI is a better indicator for identifying vegetation stress than the anomaly of NDVI relative to the long-term mean because the detrended NDVI removed the long-term trend in NDVI induced by climate change or human activities (Zhou et al. 2001, Wang and You 2004).

We then used both PDSI and detrended NDVI data to assess the impacts of drought on vegetation productivity. Partial correlation was used to assess the drought impact of a certain season on vegetation productivity after excluding the drought effect of other seasons (i.e., the partial correlation between spring PDSI and summer detrended NDVI represents the drought impact of spring drought on summer vegetation productivity by excluding the effects of summer drought).

To analyze the changes of NDVI and PDSI and their relationships in different regions, we divided the entire China into nine geographic regions: the Northeast, Inner Mongolia, the Northwest, North China, Qinghai–Tibetan Plateau, East China, Central China, the Southwest, and South China (Fig. 1). China covers a large territory with a wide variety of vegetation types including evergreen forests, deciduous forests, mixed forests, shrublands, savannas, grasslands, and croplands. According to the 2005 MODIS land cover map (MCD12Q1, collection 5.1, IGBP classification) obtained from NASA's Earth

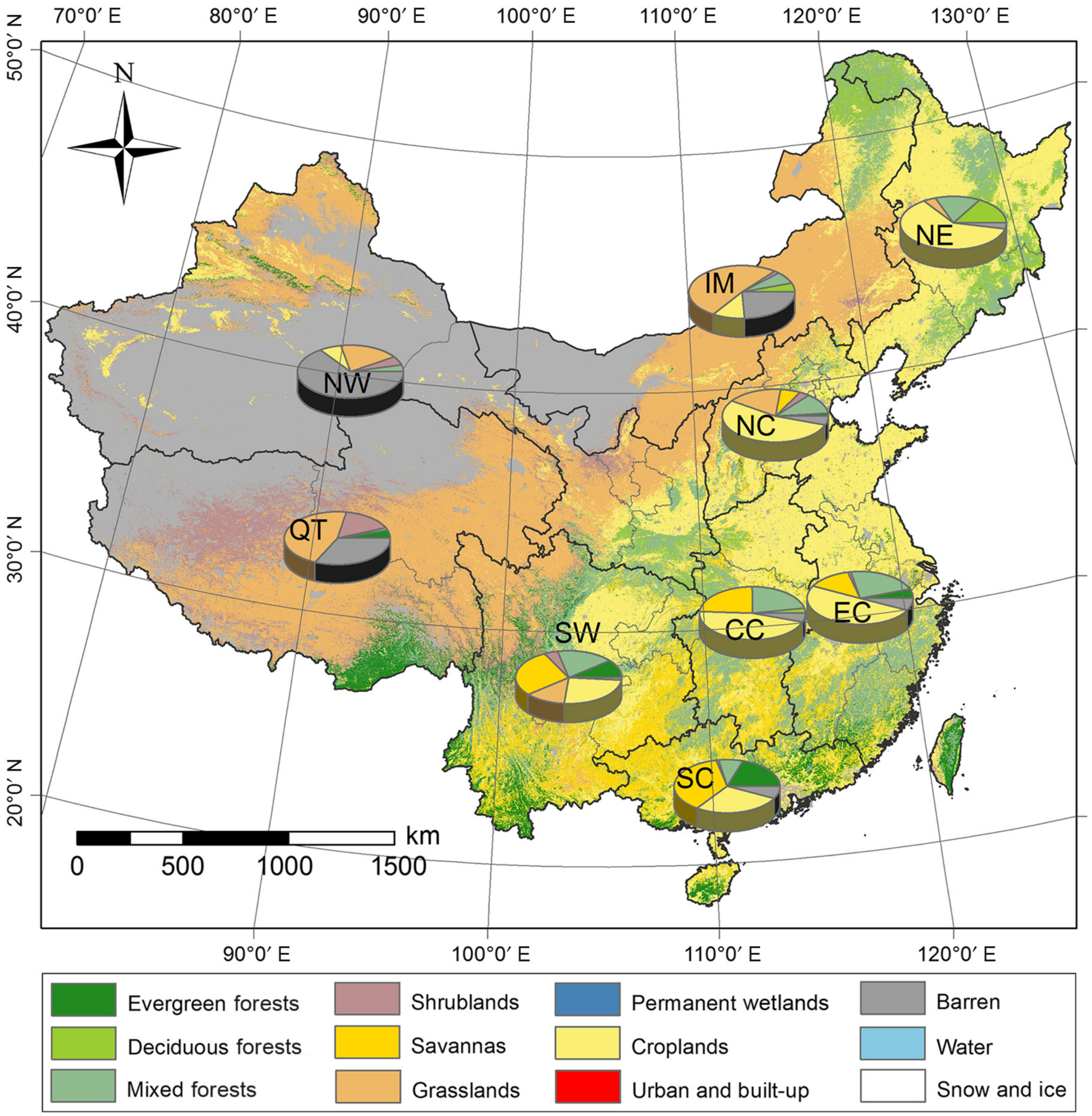

Fig. 1. Distribution of land cover types in China and the nine geographic regions. The land cover map is reclassified from the 500-m MODIS land cover map (MCD12Q1, collection 5.1, IGBP classification) in year 2005. The nine regions include the Northeast (NE); Inner Mongolia (IM); the Northwest (NW); North China (NC); Qinghai–Tibetan Plateau (QT); East China (EC); Central China (CC); the Southwest (SW); and South China (SC). The pie chart in each region illustrates the percentage of land area (%) for each vegetation type.

Observing System Data and Information System (EOSDIS; http://reverb.echo.nasa.gov), grasslands and croplands occupy 23.6% and 22.2% of China's land area, respectively. Grasslands are mainly distributed in Inner Mongolia and Qinghai–Tibetan Plateau, while croplands are mainly distributed in the Northeast, North China, East China, Central China, and South China. Forests account for 15.4% of China's land area with evergreen forests mainly distributed in South China, deciduous forests in the Northeast, and mixed forests in East China, Central China, and the

Southwest. Savannas and shrublands are mainly distributed in South China and Qinghai–Tibetan Plateau. We analyzed the responses of NDVI to drought in different regions and different vegetation types.

We also used the relative risk (or risk ratio) of vegetation stress occurrence to examine whether vegetation stress was more likely to occur in drought years than in non-drought years following Xiao and Zhuang (2007). Relative risk is the ratio of the probability of an event occurring in an exposed group to the probability of the event occurring in a comparison, non-exposed group (Agresti 2002). In this study, the estimate of the relative risk of vegetation stress occurrence is the ratio of the proportion of vegetation stress occurrence in drought years to the proportion of vegetation stress occurrence in non-drought years. A relative risk of 1.0 corresponds to independence; a relative risk greater than 1 indicates that vegetation stress is more likely to occur in drought years than in non-drought years; a relative risk less than 1 indicates that vegetation stress is less likely to occur in drought years than in non-drought years.

Results

China's droughts during the period from 1982 to 2012

Based on annual mean PDSI, we calculated the frequency and percentage area of droughts occurred in China (Fig. 2). Many parts of China experienced frequent droughts during the period from 1982 to 2012. The frequency of drought varied over space with generally higher frequency in the northern half of the country and lower frequency in the southern counterpart. The highest drought frequency was observed in the eastern half of Inner Mongolia, the western part of the Northwest, the eastern half of North China, and small parts of the Northeast and the

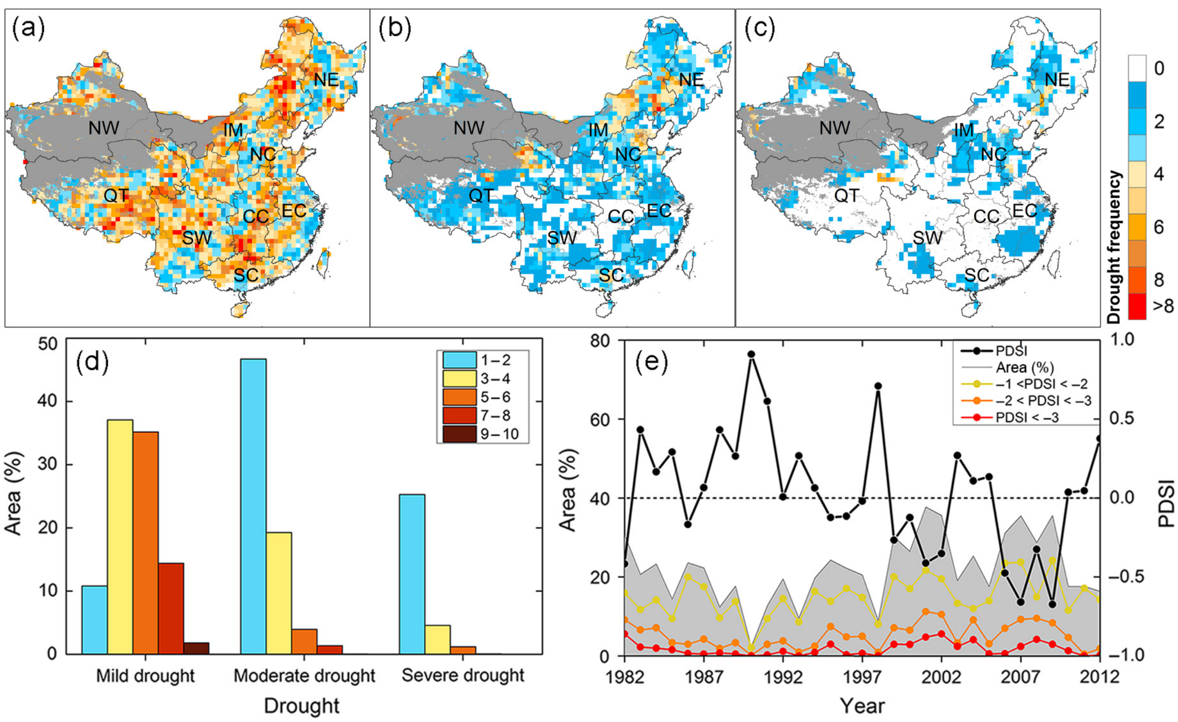

Fig. 2. Drought frequency and percentage area of droughts occurred in China during the period 1982–2012: (a)–(c) drought frequency of mild drought (−2.0 < PDSI < −1.0), moderate drought (−3.0 < PDSI < −2.0), and severe drought (PDSI < −3.0); (d) drought frequency and the percentage area affected by different categories of drought; and (e) time series of PDSI and the percentage area affected by droughts. PDSI, Palmer Drought Severity Index.

Qinghai–Tibet Plateau. The frequency and affected area (%) varied with the severity of drought. Mild droughts occurred more frequently and impacted larger land areas than moderate or severe droughts (Fig. 2a–c). During the study period, mild drought with occurrence of 3–4 times and 5–6 times hit 37.1% and 35.2% of China's vegetated area, respectively, and mild drought with occurrence of 7–8 times and 1–2 times affected additional 14.4% and 10.8% of China, respectively (Fig. 2d). The PDSI averaged across China exhibited a significant decreasing (drying) trend over the study period (−0.015/yr, $P < 0.05$; Fig. 2e). Overall, the percentage area experiencing drought showed an upward trend that was statistically insignificant (0.28%/yr, $P = 0.11$). The percentage area affected by mild drought exhibited a significant increasing trend (0.20%/yr; $P < 0.05$), while the percentage areas affected by moderate ($P = 0.36$) and severe ($P = 0.64$) droughts showed insignificant trends. The drought conditions had been more severe in China since the end of the 1990s with lower PDSI and higher percentage area affected by droughts (Fig. 2e).

The droughts affected over 25% of China's land area are illustrated in Fig. 3. Drought had increased in both occurrence and drought-affected area for most of the regions except for the Qinghai–Tibetan Plateau. The droughts in 2000–2002, 2004, and 2006–2009 affected large areas (>25%) in China, especially in northern parts of China, such as Inner Mongolia, the Northeast, the Northwest, and North China. The droughts in 2001, 2002, 2007, and 2009 were most extensive in terms of the drought-affected regions. For southern parts of China, the recent droughts had extensive impacts over South

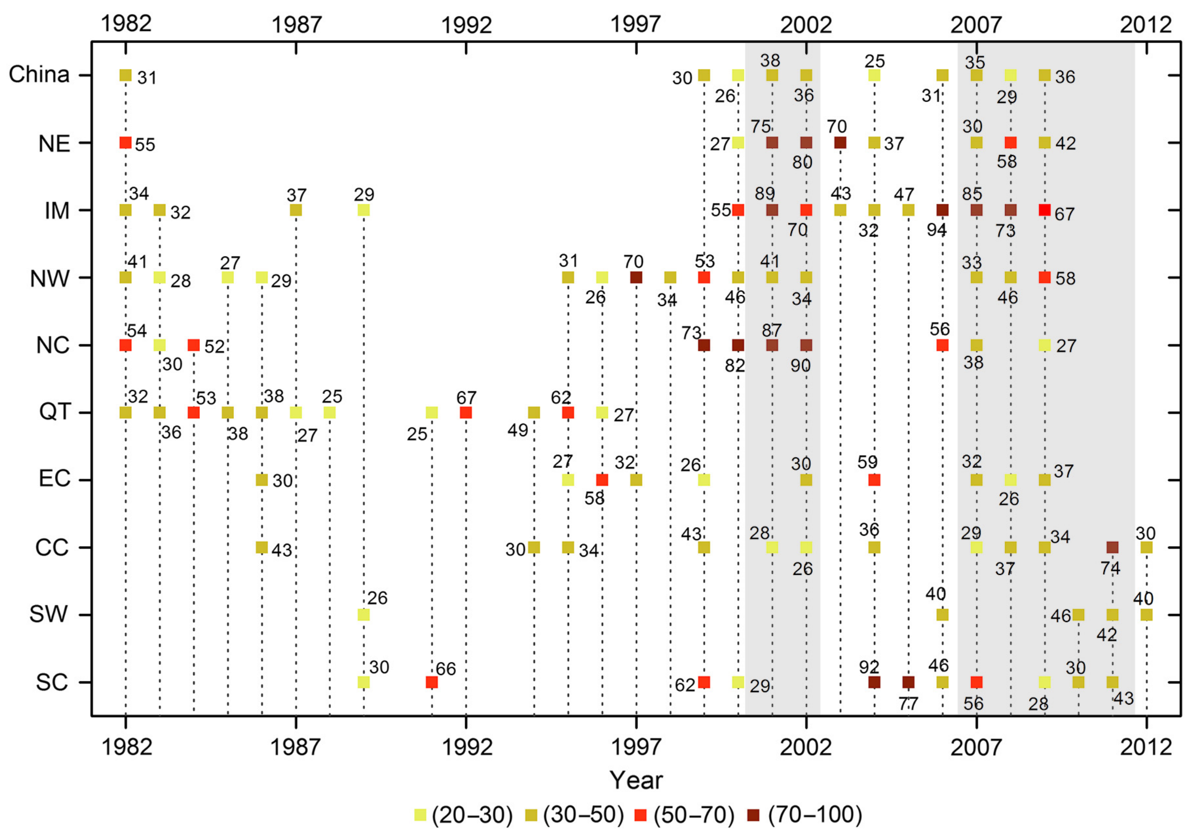

Fig. 3. Drought years with drought-affected area exceeding 25% in China over the period 1982–2012. The percentage number (unit: %) indicates the drought-affected area. The years highlighted with light gray are further examined in Fig. 8. NE, Northeast; IM, Inner Mongolia; NW, Northwest; NC, North China; QT, Qinghai–Tibetan Plateau; EC, East China; CC, Central China; SW, Southwest; SC, South China.

China. On the contrary, the droughts in the Qinghai–Tibetan Plateau occurred frequently before 1997 but occurred less frequently since the end of the 1990s.

We then examined the trend of PDSI over the period 1982–2012 on a per-pixel basis (Fig. 4a). Drying trends (i.e., decreasing PDSI) were observed for many areas including northeastern Inner Mongolia, western part of the Northeast, southern half of the Southwest, central part of Central China, and small parts of other regions. Wetting trends were mainly observed in the northern part of East China and many areas of the Qinghai–Tibet Plateau. The remaining areas exhibited no significant trends in PDSI.

We also assessed the trends of mean PDSI and drought-affected area (%) for each region (Fig. 4b). A significant decreasing trend in PDSI (drying trend) and a significant increasing trend in drought-affected area were observed for the Southwest, Inner Mongolia, and Central China. The drought conditions in these regions had persisted for several years since 1999, which suggests that the droughts hit these regions more frequently during the period 2000–2012. Among these regions, Inner Mongolia had the fastest drying rate over the period 1982–2012 with −0.05/yr for PDSI and 1.3%/yr for drought-affected area, respectively. Although the Qinghai–Tibetan Plateau is adjacent to the Southwest, they exhibited different drying trends pre- and post-2000s. In the Southwest, the PDSI continued to decrease (−0.14/yr, $P < 0.05$) and the drought-affected areas continued to increase (2.7%/yr, $P < 0.05$) since 2000. Different from the Southwest, the Qinghai–Tibetan Plateau experienced frequent droughts in the 1980s and the 1990s, but nearly no severe droughts in the 2000s.

Drought effects on vegetation productivity at seasonal and annual timescales

The relationship between PDSI and detrended NDVI varied by region and by season (Appendix S1: Figs. S1, S5, S6). For example, at the regional scale, summer PDSI was significantly correlated with summer detrended NDVI ($P < 0.05$) for Inner Mongolia, North China, and the Northwest (Fig. 5). Significant correlation between summer PDSI and summer detrended NDVI was observed for 45.4% ($r_{max} = 0.88$), 21.4% ($r_{max} = 0.81$), and 26.8% ($r_{max} = 0.78$) of the vegetated pixels for Inner Mongolia, North China, and the Northwest, respectively (Fig. 6). The autumn PDSI and autumn NDVI had the strongest correlation for North China and Inner Mongolia (Fig. 5); autumn vegetation stress was mainly controlled by autumn PDSI for 13.4% ($r_{max} = 0.78$) and 6.3% ($r_{max} = 0.83$) of the vegetated pixels for North China and Inner Mongolia, respectively (Fig. 6). We also assessed the lag effects of drought on vegetation productivity. At the regional scale, spring PDSI and summer detrended NDVI had the strongest correlation for the Northeast, the Southwest, and South China (Fig. 5); spring droughts reduced summer NDVI for 22.0% ($r_{max} = 0.77$), 8.5% ($r_{max} = 0.67$), and 6.8% ($r_{max} = 0.62$) of the vegetated pixels for the Northeast, the Southwest, and South China, respectively (Fig. 6).

We selected the six regions with significant partial correlations between seasonal PDSI and seasonal NDVI in Fig. 5 to further assess the impacts of drought on vegetation productivity. Fig. 7 illustrates the time series of seasonal detrended NDVI and PDSI over the six regions. Among these regions and seasons, synchronous effects of drought on vegetation productivity were observed for five droughts: the summer droughts for Inner Mongolia, the Northwest, and North China and the autumn droughts for Inner Mongolia and North China. Lag effects of drought on vegetation productivity were observed for the spring droughts, and these droughts reduced summer vegetation productivity for the Northeast, the Southwest, and South China.

In the northern half of China except the Northeast, droughts usually had synchronous effects on vegetation productivity. For example, in Inner Mongolia and North China, the summer and autumn droughts had synchronous effects on vegetation productivity (Fig. 7). The summer droughts reduced summer vegetation productivity in Inner Mongolia in 2000, 2001, 2006, 2007, and 2009, in North China in 1982, 1999, 2000, 2001, and 2002, and in Northwest in 1982, 1995, 1997, 2000, 2001, and 2008. The autumn droughts caused the decline in autumn vegetation productivity in Inner Mongolia in 1982, 2000, 2001, 2002, 2005, 2008, and 2009 and in North China in 1984, 1999, 2000, 2002, and 2006. By contrast, droughts usually had lag effects on vegetation productivity in the Northeast and the southern

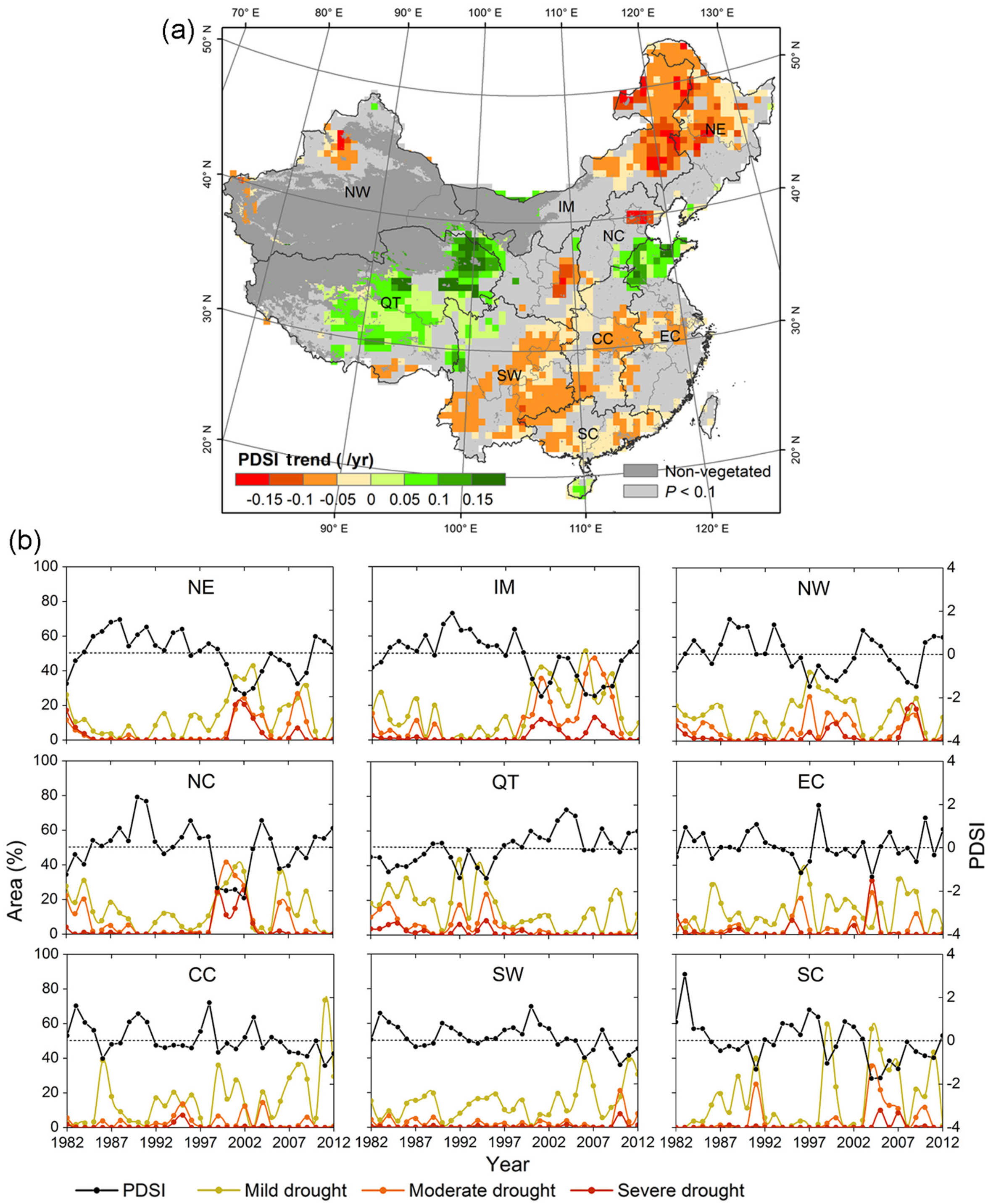

Fig. 4. Trends of PDSI and drought-affected area in China over the period 1982–2012: (a) trend of PDSI on a per-pixel basis; (b) time series of the percentage of drought-affected area over the nine regions. PDSI, Palmer Drought Severity Index; NE, Northeast; IM, Inner Mongolia; NW, Northwest; NC, North China; QT, Qinghai–Tibetan Plateau; EC, East China; CC, Central China; SW, Southwest; SC, South China.

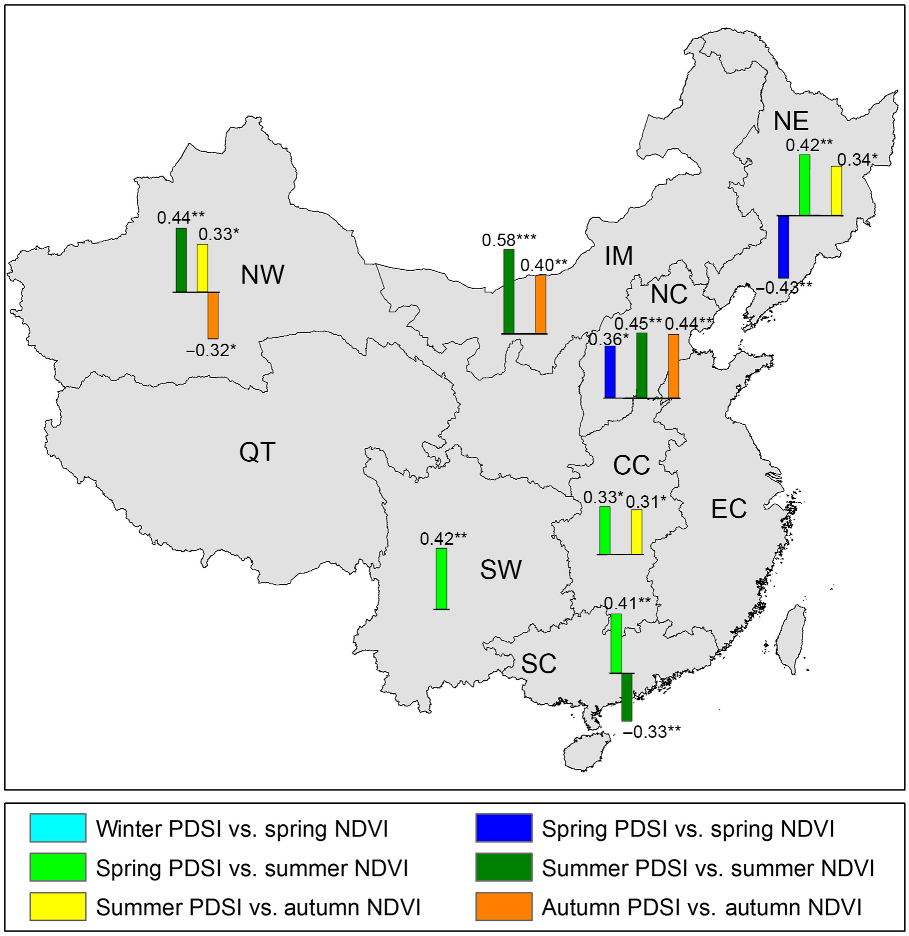

Fig. 5. Partial correlations between seasonal PDSI and seasonal detrended NDVI in the nine regions of China. The numbers stand for correlation coefficients (***$P < 0.001$, **$P < 0.05$, *$P < 0.1$). The insignificant partial correlations ($P > 0.1$) are provided in Appendix S1: Fig. S1. PDSI, Palmer Drought Severity Index; NDVI, Normalized Difference Vegetation Index; NE, Northeast; IM, Inner Mongolia; NW, Northwest; NC, North China; QT, Qinghai–Tibetan Plateau; EC, East China; CC, Central China; SW, Southwest; SC, South China.

half of China (Fig. 7). Drought also had lag effects on vegetation productivity. In the Northeast, the spring droughts had lag effects on summer productivity, and the spring droughts in 2002, 2003, and 2009 reduced summer NDVI. In the southern parts of China, the spring droughts reduced summer NDVI in Southwest in 2010 and in South China in 1991, 1999, 2005, 2006, 2007, 2008, and 2010.

We compared the spatial patterns of seasonal PDSI and NDVI to assess the effects of extensive droughts since 2000 on vegetation productivity over space (Fig. 8). PDSI and detrended NDVI generally matched well over space. For example, the widespread spring and summer droughts suppressed summer NDVI in the Northeast in 2002, Inner Mongolia in 2002 and 2009, East China in 2008, Central China in 2008, and the Southwest in 2010; spring drought reduced summer NDVI in the Northeast (2009) and South China (2008); summer droughts suppressed summer NDVI in Inner Mongolia (2001 and 2007) and North China (2001 and 2002). However, PDSI and NDVI did not match well in some regions or seasons. For example, the negative detrended NDVI was more extensive than spring and summer droughts in Qinghai–Tibetan Plateau (2008) and East China (2010); little or less

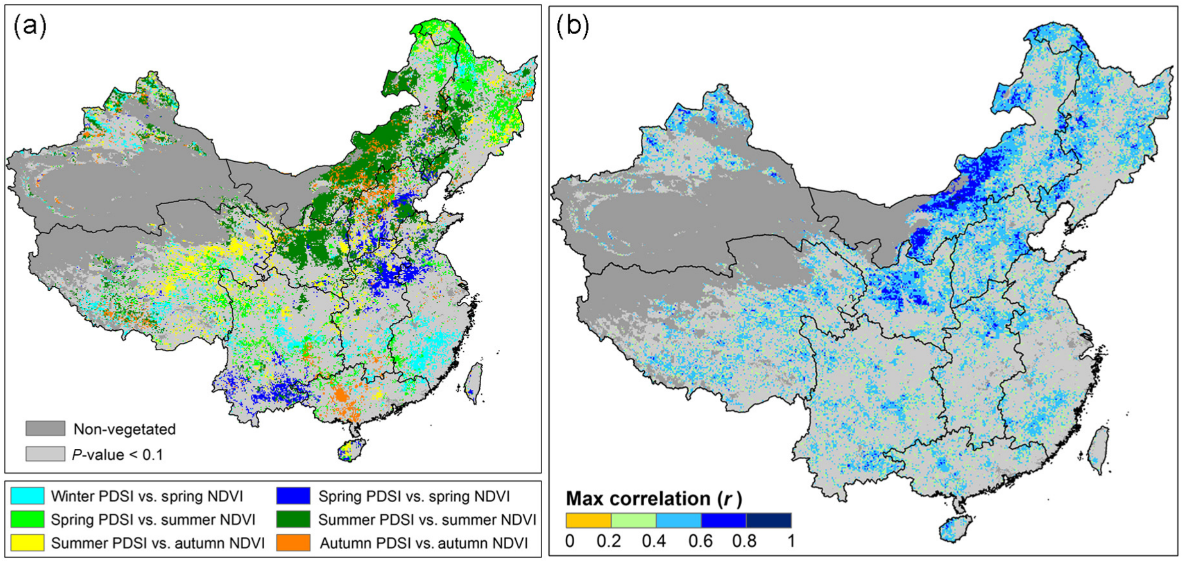

Fig. 6. Relationship between seasonal PDSI and seasonal detrended NDVI in China over the period 1982–2012: (a) the type of correlation with the maximum correlation; (b) the maximum correlation coefficient between seasonal PDSI and seasonal detrended NDVI. PDSI, Palmer Drought Severity Index; NDVI, Normalized Difference Vegetation Index.

NDVI decline was observed for the spring and summer droughts in the Northeast in 2008, Inner Mongolia in 2008, and East China in 2009, and southern parts of China in 2011.

To further demonstrate the relationship between vegetation stress and droughts, we examined the spatial relationships between vegetation stress and drought. During the period 1982–2012, the relative risk for 62.2% of the vegetated areas for entire China was greater than 1, and these pixels were mainly located in the northern parts of China (Fig. 9), indicating that vegetation stress was more likely to occur in drier northern areas than in wetter southern areas. The Wilcoxon rank sum test of the data showed that the probability of vegetation stress occurrence in drought years was significantly greater than that in non-drought years ($P < 0.001$), demonstrating that drought significantly declined vegetation activity in China over the period 1982–2012.

Responses of vegetation productivity to droughts by vegetation type

The magnitude and direction of the detrended NDVI in drought seasons also differed with vegetation type (Fig. 10). We selected the regions where spring and summer droughts had significant impacts on summer NDVI (Fig. 5), and examined the vegetation types that occupy over 10.0% of the land area in these regions.

Of the nine regions, grasslands are mainly distributed in Inner Mongolia, the Northwest, North China, and the Southwest. In the northern parts of China, the summer droughts mainly reduced the NDVI of grasslands. For examples, the summer droughts reduced the grassland NDVI in Inner Mongolia ($r = 0.72$, $P < 0.001$) in 1983, 2000, 2001, 2005, 2006, 2007, and 2009 (Fig. 10); in the Northwest ($r = 0.47$, $P = 0.008$) in 1982, 1997, 2000, 2001, 2008; and in North China ($r = 0.46$, $P = 0.011$) in 1999, 2000, 2001, 2002, 2006, and 2007. However, in the southern parts of China, it was mainly the spring drought that reduced the grassland NDVI. For example, the spring droughts reduced the summer detrended NDVI of grasslands by −0.024, −0.026, and −0.025 in 1982, 1987, and 1993, respectively, for the Southwest ($r = 0.53$, $P = 0.002$). Among the major vegetation types (Fig. 10), grasslands were most sensitive to droughts, particularly in North China, Inner Mongolia, the Northwest, and the Southwest.

Croplands are mainly distributed in the Northeast, North China, South China, the Southwest,

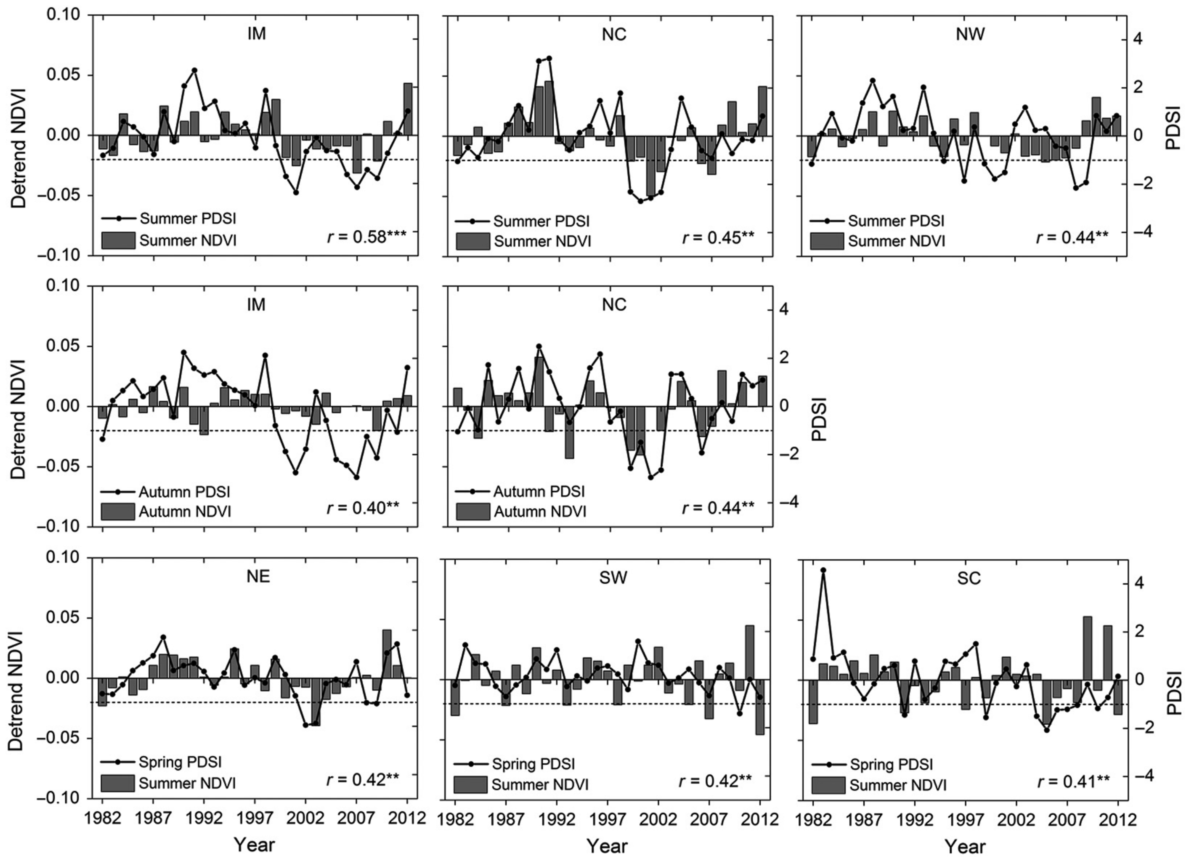

Fig. 7. Time series of seasonal detrended NDVI and seasonal PDSI during the period 1982–2012 over the regions with significant partial correlation in Fig. 5. $^{***}P < 0.001$, $^{**}P < 0.05$, $^{*}P < 0.1$. PDSI, Palmer Drought Severity Index; NDVI, Normalized Difference Vegetation Index; NE, Northeast; IM, Inner Mongolia; NW, Northwest; NC, North China; QT, Qinghai–Tibetan Plateau; EC, East China; CC, Central China; SW, Southwest; SC, South China.

and Inner Mongolia. In North China, summer PDSI had significant correlation with cropland summer detrended NDVI ($r = 0.49$, $P = 0.006$) and the summer droughts in 1982, 1999, 2000, 2001, 2002, and 2003 reduced the cropland summer NDVI (Fig. 10). In Inner Mongolia, the summer droughts in some years reduced the cropland summer NDVI, although the correlation between the summer PDSI and the summer detrended NDVI was insignificant ($r = 0.19$, $P = 0.314$). In the Northeast, the Southwest, and South China, the spring droughts reduced the cropland summer NDVI, although the relationships between spring PDSI and summer NDVI were insignificant.

Evergreen and deciduous forests account for 18.3% and 13.9% of the land area of South China and the Northeast, respectively, and mixed forests are mainly distributed in the Northeast, North China, the Southwest, and South China. For forests, it was mainly the spring PDSI that had significant correlation with summer detrended NDVI. The spring droughts reduced the summer NDVI for mixed forests ($r = 0.49$, $P = 0.006$) in 2003 and 2012, for deciduous forests ($r = 0.57$, $P = 0.001$) in the Northeast in 1983 and 2012, for mixed forests in the Southwest in 2010 and 2012 ($r = 0.37$, $P = 0.046$), for evergreen forests in 1991, 1999, 2005, and 2008 ($r = 0.41$, $P = 0.025$), and for mixed forests ($r = 0.43$, $P = 0.019$) in South China in 1991, 1999, 2005, 2006, and 2010 (Fig. 10). Among the forests, mixed forests were most sensitive to droughts, particularly in the Northeast, the Southwest, and

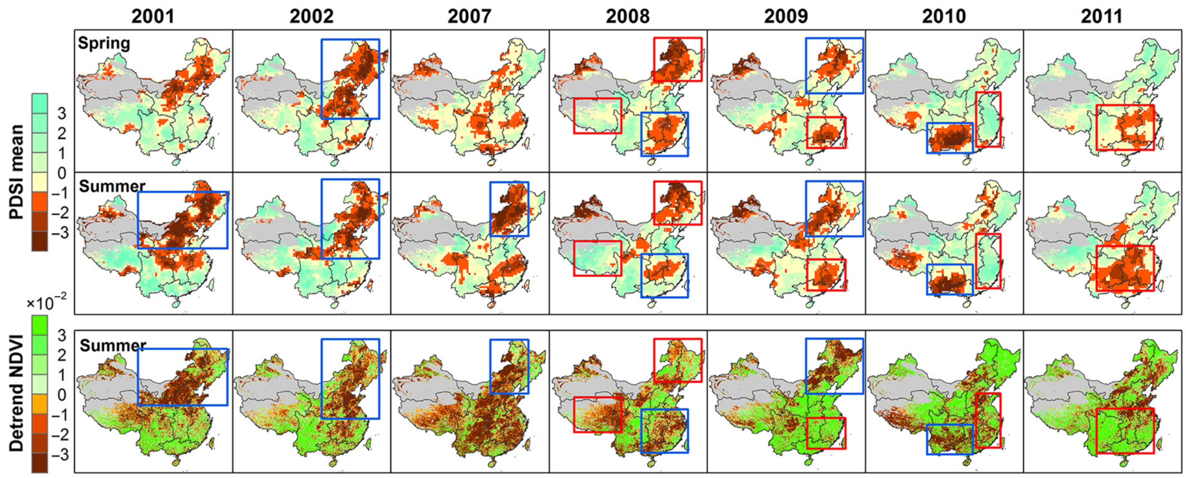

Fig. 8. Spatial distributions of seasonal PDSI and summer detrended NDVI in 2001, 2002, 2007, 2008, 2009, 2010, and 2011. Blue box indicates regions that summer detrended NDVI matches well with seasonal droughts, and red box indicates regions that summer detrended NDVI is inconsistent with seasonal droughts. PDSI, Palmer Drought Severity Index; NDVI, Normalized Difference Vegetation Index.

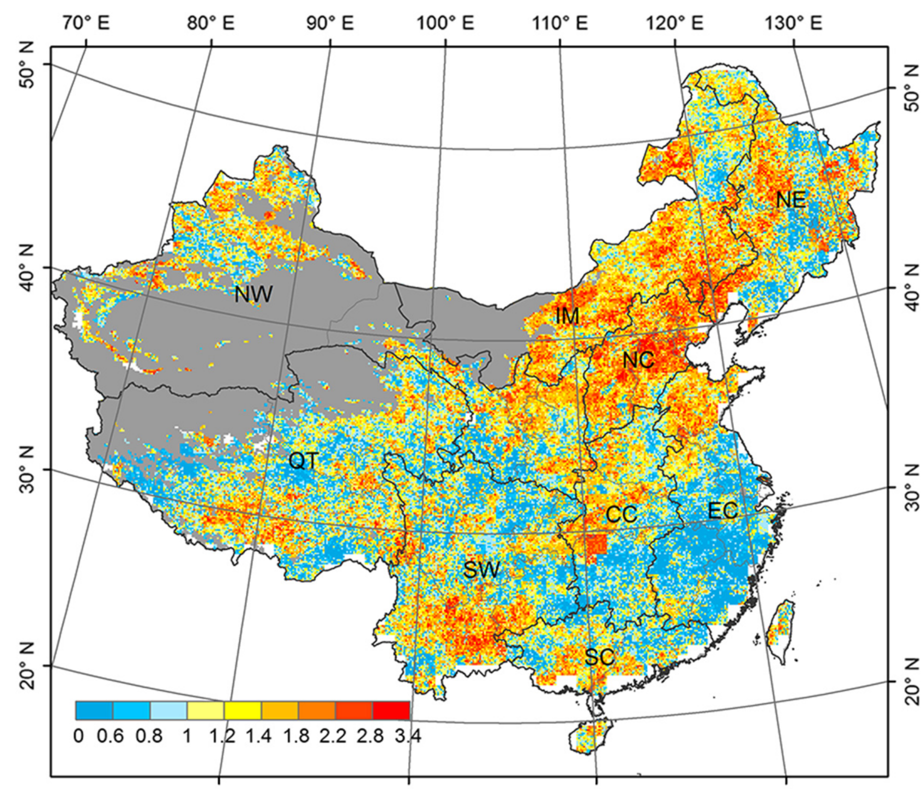

Fig. 9. Relative risk of vegetation stress in drought years across China during the period 1982–2012. NE, Northeast; IM, Inner Mongolia; NW, Northwest; NC, North China; QT, Qinghai–Tibetan Plateau; EC, East China; CC, Central China; SW, Southwest; SC, South China.

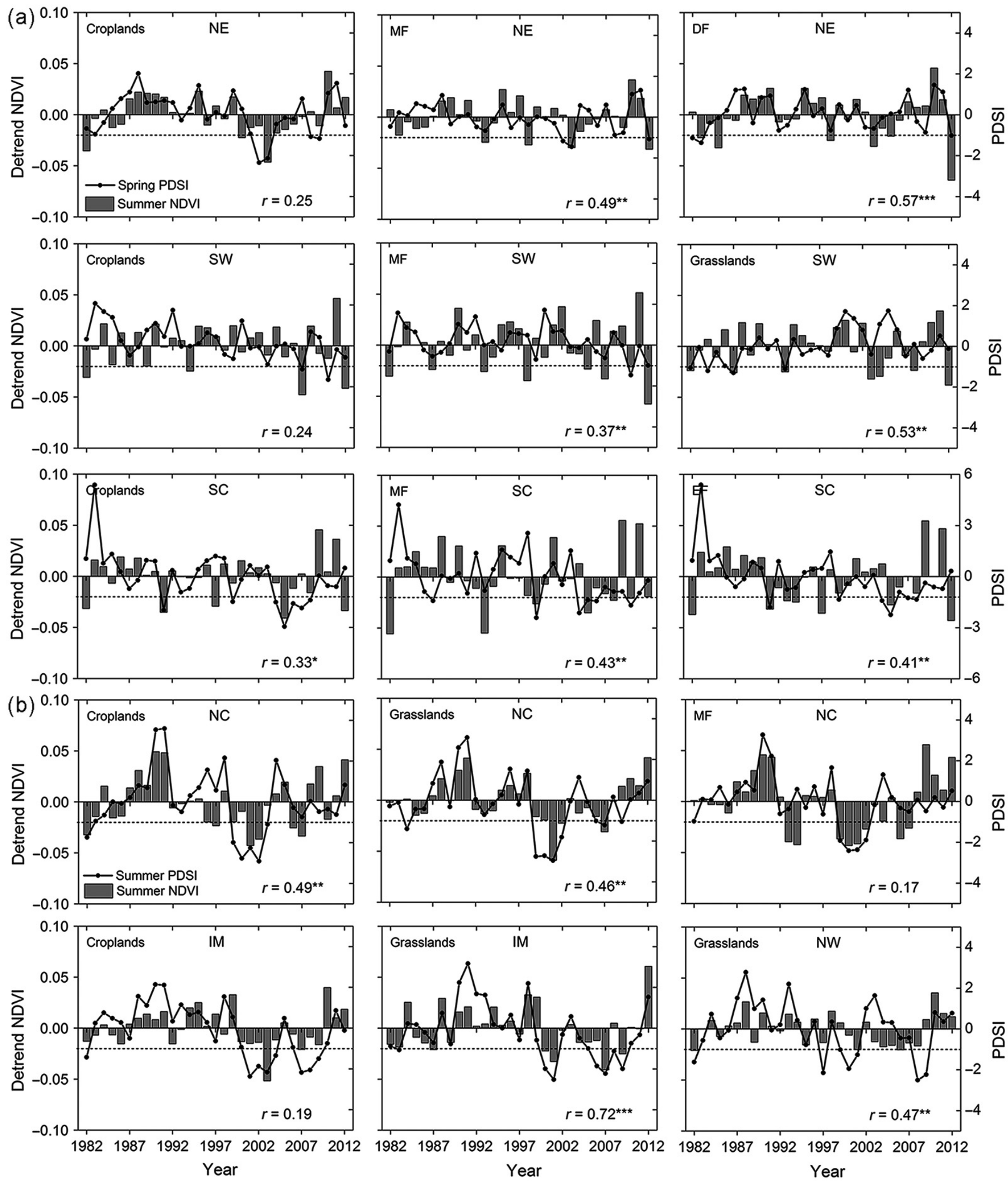

Fig. 10. Time series of seasonal detrended NDVI and seasonal PDSI during the period 1982–2012 for different vegetation types in the nine regions: (a) spring PDSI vs. summer detrended NDVI and (b) summer PDSI vs. summer detrended NDVI. $^{***}P < 0.001$, $^{**}P < 0.05$, $^{*}P < 0.1$. EF, evergreen forests; DF, deciduous forests; MF, mixed forests; PDSI, Palmer Drought Severity Index; NDVI, Normalized Difference Vegetation Index; NE, Northeast; IM, Inner Mongolia; NW, Northwest; NC, North China; QT, Qinghai–Tibetan Plateau; EC, East China; CC, Central China; SW, Southwest; SC, South China.

South China that were mainly affected by spring droughts.

Besides the satellite-derived NDVI dataset, we also used crop NPP estimated from statistic data to examine the impacts of drought on agricultural productivity. The annual NPP is likely able to better reflect agricultural productivity than NDVI. We first examined the relationship between growing-season (spring–summer–autumn) mean NDVI and annual NPP (Appendix S1: Fig. S2). The annual NDVI well captured the variations of NPP for eight of the nine regions ($P < 0.05$; Appendix S1: Fig. S2). We then examined the relationship between growing-season (spring–summer–autumn) PDSI and annual NPP (Fig. 11) for regions that had significant partial correlation between seasonal PDSI and seasonal detrended NDVI as in Fig. 5.

Drought had significant ($P < 0.1$) impacts on crop productivity (measured by NPP) in the Northeast, Inner Mongolia, North China, the Northwest, and the Southwest (Fig. 11). These results demonstrated that NDVI is a good proxy for vegetation productivity, and drought significantly reduced agricultural productivity.

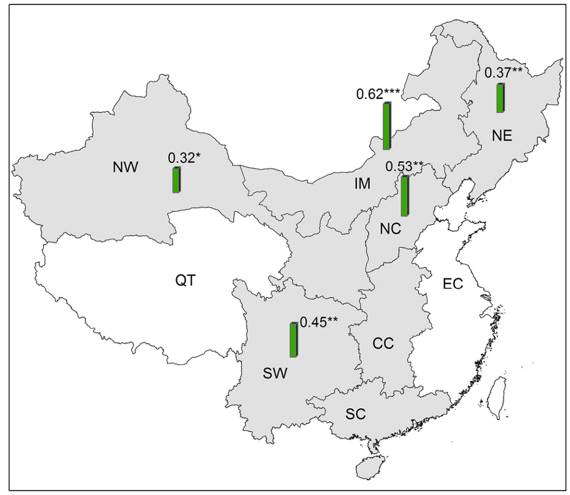

Fig. 11. Spearman's correlations between growing-season (spring–summer–autumn) mean PDSI and detrended annual crop NPP over the regions with significant partial correlation in Fig. 5 (gray shaded areas). The numbers stand for correlation coefficients ($^{***}P < 0.001$, $^{**}P < 0.05$, $^{*}P < 0.1$). PDSI, Palmer Drought Severity Index; NE, Northeast; IM, Inner Mongolia; NW, Northwest; NC, North China; QT, Qinghai–Tibetan Plateau; EC, East China; CC, Central China; SW, Southwest; SC, South China.

Discussion

Rising air temperatures induced the increased drying trend since the 1970s (Dai et al. 2004). During the past three decades, air temperature has been increasing across China, while the changes of precipitation depend on regions (e.g., increases in the west part of the Southwest and decreases in the northern parts of China; Zhai and Zou 2005). Simulations of soil moisture indicated that China had become drier (Wang et al. 2011). A previous study showed that there was no significant drying trend for China over the period 1951–2003 (Zou et al. 2005). Our results showed that, overall, China exhibited no increasing trend in the percentage area experiencing drought from 1982 to 2012. Despite the insignificant trend in drought-affected area at the national scale, frequent droughts and drying trends were observed in northern China because of decreasing precipitation and increasing temperature (Ma and Ren 2007, Wang et al. 2012*a*). Large regions of northern China are characterized as arid and semi-arid regions where water is limited. During the past half century, decreasing trends were observed for the number of rainy days and the longest durations of consecutive rainfall (Zhai et al. 1999). The reduced precipitation and warmer climate further enhanced evapotranspiration, aggravating water stress in these arid and semi-arid areas.

Both temperature and precipitation had increased in southern parts of China (Peng et al. 2011), and the wetting trends in the 1990s and the drying trends in the 1980s and 2000s were observed. Although drought frequency was relatively low in southern parts of China compared to the northern counterpart, increasing drought frequency was observed in 2006 and 2010–2012 for the Southwest and 2004–2007 and 2009–2011 in South China. The 2006 and 2010 droughts in the Southwest were the most severe droughts during the last 100 years in the region (Hao et al. 2007). Air temperature in the Southwest switched from a decreasing trend to an increasing trend since the 1980s (Ma and Ren 2007), which could likely increase the frequency of the extreme drought event.

Our results showed that drought had significant effects on vegetation productivity, particularly in northern parts of China. The decrease in the NDVI increase rate during the period 2000–2010 compared to the period 1982–1999 (Peng et al. 2011) could be partly attributed to the frequent droughts in the recent decade. The decrease in vegetation growth over the Northeast and Inner Mongolia was related to the increase in extreme drought events in the 2000s. The effects of drought on vegetation productivity also varied with drought severity. Severe and extreme droughts had larger impacts on vegetation growth than mild droughts. Mild droughts may not have substantial effects on vegetation (Pei et al. 2013, Zhang et al. 2014*a*).

The timing of the drought is a key factor in influencing vegetation productivity. The ecosystem responses to droughts varied with season (Zhao and Running 2010, Peng et al. 2011). Spring and summer droughts had larger impacts on vegetation productivity. The droughts affected spring plowing and also led to a substantial decline in the yield of summer-harvested crops (Yun et al. 2012). Spring droughts can not only reduce photosynthesis and suppress canopy development and peak leaf area but also enhance summer respiration, thus reducing annual net carbon uptake (Noormets et al. 2008, Scott et al. 2009). Spring droughts can also constrain annual carbon uptake by regulating the availability of soil moisture during the summer (Kwon et al. 2008, Noormets et al. 2008, Scott et al. 2009) and shortening the length of the growing season, particularly for crops. Some ecosystems like desert grasslands are more sensitive to spring droughts than to summer droughts (Schwinning et al. 2005). The 2010 spring drought in Southwest China showed that spring droughts led to significant declines in vegetation productivity for both the spring and the annual scales (Zhang et al. 2012). The negative effects of summer droughts on plant growth were particularly significant over arid and semi-arid regions such as Inner Mongolia, the Northwest, and North China. Drought in summer limits transpiration and directly reduces photosynthesis. Zhou et al. (2013) showed that severe drought during canopy development (summer) induced a lasting reduction in vegetation productivity, while the severe autumn droughts at the end of the growing season did not significantly reduce vegetation productivity.

The effects of drought on vegetation productivity also varied with vegetation type. The summer droughts mainly reduced summer grassland NDVI in Inner Mongolia, the Northwest, and North China. The frequent droughts caused large economic and societal losses and posed a threat to the ecological environment in these arid and semi-arid regions. The spring droughts in the Northeast, the Southwest (2010, 2012), and South China reduced NDVI for forests, although forests have deeper roots and access to ground water and are generally more resilient to drought stress than other vegetation types. Cropland NDVI in summer exhibited large decline in the Northeast, Inner Mongolia, North China, and the Southwest, although irrigation may partially relieve the drought stress. Drought in the eastern half of China poses a serious threat to food security in China as most agricultural lands are distributed in these regions. For example, the summer drought during 1999–2000 in North China induced by the persistent anomalous circulation over the Eurasia reduced the crop yield by 20–30% (Wei et al. 2004). Drought in 2000 damaged more than 40 million hectares of crops in northern China (Song et al. 2005). Frequent droughts in central Inner Mongolia, especially over the period 1999–2001, seriously affected local agricultural and grazing activities and resulted in heavy economic loss (Liu and Wang 2012), although agricultural management can regulate the responses of crops to drought to some extent (Barriopedro et al. 2012).

Although drought generally reduced vegetation productivity, drought sometimes did not lead to a decline in NDVI. The vegetation productivity inferred from NDVI sometimes could be slightly higher in drought years than in wet years. For example, annual NDVI increased with low PDSI in parts of the Northeast (2008), Inner Mongolia (2008), East China (2009) and southern parts of China (2011). This inconsistence can be attributed to the differences in drought intensity, extent, duration, and the cumulative and lag responses of vegetation to precipitation deficits (Hoover and Rogers 2016). Plant growth in humid regions may increase during mild droughts because the lower cloudiness and higher temperatures could increase the incoming PAR and enhance plant growth (Xiao et al. 2009, Xu et al. 2012). Despite the frequent droughts during the late 1990s and 2000s, significant increasing trends in NDVI were observed in northern parts of China (i.e., the Northwest and North China) during the period 2000–2012 that generally agreed with the results based on an ecosystem model (Potter 2013). This is mainly because rising air temperature, increasing atmospheric CO_2 concentrations, improved agricultural management practices, and afforestation enhanced vegetation productivity (Xiao et al. 2015).

To separate the possible effects of land cover change on vegetation productivity from the effects of drought, we calculated the difference between the 2012 MODIS land cover map and the AVHRR land cover map (Appendix S1: Fig. S3) on a per-pixel basis to identify pixels that experienced land cover changes from the early 1990s to 2012. The 1-km resolution AVHRR land cover map was obtained from the Global Land Cover Characterization (GLCC; https://lta.cr.usgs.gov/GLCC). The GLCC land cover map was based on unsupervised classification of 1-km AVHRR 10-day NDVI composites from April 1992 through March 1993 (Belward 1996). The MODIS land cover data (MCD12Q1) were produced using an ensemble decision tree supervised classification algorithm. It should be noticed that these maps were based on different sources of data, resolution, and classification schemes and both maps had significant uncertainty in land cover classification, indicating that the differences in these two maps should not be totally interpreted as changes in land cover (pink color in Appendix S1: Fig. S3). We masked out the pixels with changes in land cover from Fig. 8, and the resulting figure (Appendix S1: Fig. S4) contrasted the spatial distribution of seasonal PDSI and summer detrended NDVI for those pixels that had not experienced changes in land cover. As in Fig. 8, Appendix S1: Fig. S4 shows that droughts generally reduced vegetation productivity, indicating that the use of a static land cover map in our analysis does not undermine our findings.

Conclusions

In this study, we first assessed the occurrence, spatial extent, severity, and frequency of droughts in China from 1982 to 2012 using PDSI data. Although the percentage area experiencing drought at the national scale showed an insignificant trend during this period, most regions in the northern parts of China showed drying trends and experienced frequent extreme drought events during the recent decade. We then examined the impacts of the droughts on vegetation productivity as approximated by NDVI. The terrestrial ecosystems in northern parts of China were significantly influenced by droughts. The drought impacts on vegetation productivity varied with region, season, and vegetation type. Spring and summer droughts had larger impacts on vegetation productivity than autumn droughts. The extensive droughts in 1999–2002, 2004, and 2006–2009 impacted large areas (>25%) and substantially reduced annual NDVI. Other factors such as higher temperatures, lower cloudiness, improved agricultural practices, and afforestation may counterbalance the negative effects of drought on vegetation productivity.

Acknowledgments

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Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.1591/full