Driving force and changing trends of vegetation phenology in the Loess Plateau of China from 2000 to 2010

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Abstract: Changes in vegetation phenology are key indicators of the response of ecosystems to climate change. Therefore, knowledge of growing seasons is essential to predict ecosystem changes, especially for regions with a fragile ecosystem such as the Loess Plateau. In this study, based on the normalized difference vegetation index (NDVI) data, we estimated and analyzed the vegetation phenology in the Loess Plateau from 2000 to 2010 for the beginning, length, and end of the growing season, measuring changes in trends and their relationship to climatic factors. The results show that for 54.84% of the vegetation, the trend was an advancement of the beginning of the growing season (BGS), while for 67.64% the trend was a delay in the end of the growing season (EGS). The length of the growing season (LGS) was extended for 66.28% of the vegetation in the plateau. While the temperature is important for the vegetation to begin the growing season in this region, warmer climate may lead to drought and can become a limiting factor for vegetation growth. We found that increased

precipitation benefits the advancement of the BGS in this area. Areas with a delayed EGS indicated that the appropriate temperature and rainfall in autumn or winter enhanced photosynthesis and extended the growth process. A positive correlation with precipitation was found for 76.53% of the areas with an extended LGS, indicating that precipitation is one of the key factors in changes in the vegetation phenology in this water-limited region. Precipitation plays an important role in determining the phenological activities of the vegetation in arid and semiarid areas, such as the Loess Plateau. The extended growing season will significantly influence both the vegetation productivity and the carbon fixation capacity in this region.

Keywords: The Loess Plateau; Trend analysis; Phenology; NDVI; Vegetation green-up date

Introduction

A key part of the terrestrial ecosystem, vegetation plays an irreplaceable role in regulating

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the global carbon balance, reducing greenhouse gases and stabilizing the global climate (Piao et al. 2003; Wang et al. 2011). Vegetation adjusts according to the global climate change, showing significant regional characteristics over different time scales (Fang and Yu 2002). Many studies have shown that the phenomenon of global warming is becoming more and more observable. The fifth assessment report issued by the Intergovernmental Panel on Climate Change (IPCC) points out that the average global temperature has risen by 0.85°C over the past 130 years (1880–2012), with a warming rate of 0.12°C/10a in the last 60 years, and 30 of the warmest years since 1850 all occurring between 1983 and 2012 (IPCC 2013). Such climate change has had a significant effect on vegetation phenology. To adapt to the warming trend in the spring and autumn, there has been a change in the growth behavior of vegetation. This change is not only a sensitive and easily observed indicator of how the biosphere is responding to climate warming, it also has profound effects on other factors, including the carbon balance of the biosphere (Niemand et al. 2005). Therefore, studies on the changes in vegetation phenology will be key factors in monitoring the relationship between vegetation growth behavior and climate change.

Previous phenology research has mostly focused on ground based-observed data (observed data for short hereafter). Limited by the number of samples, the data can not accurately reflect the influence of the climate on phenology. With the development of satellites, however, remote data can now provide continuous coverage and monitor regional or global vegetation trend changes. Remote data (e.g. the normalized difference vegetation index (NDVI)) are thus now widely used in vegetation phenology monitoring (White et al. 2005; Zhang et al. 2003).

Researchers have successfully used four methods to estimate the growing season of vegetation based on NDVI data, the NDVI threshold (Justice et al. 1985; Fischer 1994; Markonet al. 1995), the smoothed moving average (Reed et al. 1994; Li et al. 2003), the seasonal midpoint NDVI methodology (Schwartz et al. 2002), and the greatest NDVI change slope (Yu et al. 2003).

Eleonora (2001) found a strong connection between vegetation phenology and the NDVI.

When the NDVI value is below 0.10, it is impossible for vegetation to begin growing. Based on the NDVI data, Reed (1994) successfully estimated the beginning of the growing season (BGS) of vegetation in the USA using the delayed moving average method. Li (2003) found that 0.1 was the best NDVI threshold value for estimating the BGS of the grassland in Inner Mongolia. Chen (2000, 2001), based on both the NDVI data and observed data, determined the NDVI threshold value for the BGS and estimated the length of the growing season (LGS) of area without observed data.

The Loess Plateau is located in the upper and middle reaches of the Yellow River in northern China. It is a transition zone from a sub-humid climate to an arid and semiarid climate. With a very fragile ecological environment, the vegetation there is sensitive to climate change (Lu et al. 2012; Gong et al. 2005; Wang et al. 2005). Earlier studies have shown that temperatures in the Loess Plateau have been rising since 1985, a trend consistent with the temperatures across China (Fu et al. 2002). This kind of climate change has an important effect on the ecological conditions and vegetation activities in this area. However, previous research in the Loess Plateau has only focused on the relationship between climatic variables and vegetation coverage (Liu et al. 2006; Xu et al. 2012). Researchers have paid little attention to the influence of climate change on the vegetation phenology in this area.

Therefore, we used NDVI remote data on the Loess Plateau area in China to determine how vegetation activities responded to changes in climatic conditions from 2000 to 2010. The objectives were to (1) quantify the changes in plant phenology in the Loess Plateau over the decade, to identify the spatio-temporal patterns of vegetation phenology, (2) investigate the relationship between the phenology data and climatic factors, and (3) determine the specific climatic factors responsible for the changes in vegetation phenology.

1 Data and Methods

1.1 Study area

The Loess Plateau is located in the upper and middle reaches of the Yellow River in northern

China ($33^{\circ}43'7''\text{N}$ - $41^{\circ}16'7''\text{N}$, $100^{\circ}54'7''\text{E}$ - $114^{\circ}33'7''\text{E}$) (Figure 1). As the world's largest loess area, it includes seven provinces and is almost 630,000 km² (Liu et al. 2011). From southeast to northwest, the climate types are, respectively, a warm temperate zone, a sub-humid climate, a semiarid climate, and an arid climate. The range of the annual average temperature in this area is from 6 to 14°C. The average annual precipitation decreases from southeast to northwest, ranging from about 200-700 mm. The vegetation in the Loess Plateau varies with evident zonal characteristics, including forest-steppe, steppe, and desert-steppe from south to north (Su et al. 2013).

The Loess Plateau is fragile in its ecological system and its ability to resist natural disasters. An arid climate, concentrated precipitation, sparse vegetation, and unstable natural conditions result in frequent and severe disasters, including earthquakes, floods, droughts, meteorological disasters, and soil erosion (Yi et al. 2014; Liu et al. 2013). Moreover, nearly 8.5% of the Chinese population lives in this area, with the population

density reaching 168 people per square kilometer, posing another threat to the ecological system (Fu et al. 2011). Due to the excessive exploitation and utilization of natural resources, including estrepement and excessive grazing, natural disasters hit this area more frequently, seriously affecting the Loess Plateau's social and economic development (Zhou et al. 2012; Chen et al. 2007).

1.2 Dataset

This study uses the climatic data from the China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn/>) on precipitation and temperature from 2000 to 2010. We used the Kriging method to produce the interpolation maps in the ArcGIS 9.3 software, with climate data from 85 stations within and around the Loess Plateau (Figure 1). The spatial resolution of the maps is 250 m.

The NDVI data from 2000 to 2010 used in this research came from the International Scientific and Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences

Figure 1 The sketch map of the Loess Plateau area in China. (a) Topographical view of the Loess Plateau, based on a digital elevation model map. (b) Vegetation types of the Loess Plateau. Spatial patterns of the 85 stations and the average climate conditions in the Loess Plateau from 2000 to 2010. (c) Temperature, (d) Precipitation.

(<http://www.gscloud.cn>). The data name is MODNDQT. It was made based on the MODIS MOD09GQ data set provided by the Chinese Academy of Sciences. Its spatial resolution is 250 m and the temporal resolution is 10 days. To reduce the effect of bare soils and sparsely vegetated grids on the NDVI trends, grid cells with an annual mean NDVI smaller than 0.1 during the 11 years were excluded from the analysis, as in Zhou et al. (2001, 2003). Many studies have validated these kinds of data for vegetation growing conditions, biomass estimation, environment monitoring, and global change (Li et al. 2011; Jeganathan et al. 2014; de Jong et al. 2013; Chen et al. 2006; Fang et al. 2007; Xiao et al. 2002).

1.3 Methods

1.3.1 Determination of vegetation green-up date

Different land types have different effects on phenological behavior, especially for farmlands dominated by anthropogenic activities, when compared to grasslands and forests. Due to the semi-arid climatic conditions, people in the agricultural region of the Loess Plateau can only adopt one cropping pattern for cultivation. Furthermore, the phenological activities of the crops in the Loess Plateau are roughly consistent with those of the nearby natural vegetation. In addition, the Chinese government implemented a series of ecological projects to help to restore vegetation. For example, the area of farmland in the Loess Plateau has decreased by 10.8% (Lu et al. 2012), due to the Grain to Green Program initiated in 1999. As the croplands in the Loess Plateau have a similar phenological behavior to the natural vegetation, and considering that the cropland has continued to decrease in recent decades, the authors believe that human activity, such as farming, has a limited influence on the results of this study.

We used the Polyfit-Maximum method to estimate the phenology of the vegetation in the Loess Plateau, a method first used by Piao et al. (2006). Its basic purpose is to identify the period of the greatest changes in the NDVI at the beginning or the end of the growing season (Figure 2). First we calculated the average seasonal NDVI curves at

10-day intervals for the entire 2000-2010 dataset. Then we used the following formula to determine the rates of the change in the average seasonal NDVI curves:

Figure 2 Flowchart of the procedures used to determine the onset dates of phenological events from the NDVI time series. t is time, $NDVI(t)$ is the NDVI in period t , $NDVI_{ratio}(t)$ is the ratio of the NDVI change between period t and period $t+1$, $NDVI(\text{green up})$ is the NDVI threshold of the onset of green up, and $NDVI(\text{dormancy})$ is the NDVI threshold of the onset of vegetation dormancy.

$$NDVI_{ratio}(t) = \frac{[NDVI(t+1) - NDVI(t)]}{[NDVI(t)]} \quad (1)$$

where, t is time. The timing of the greatest NDVI change, namely the maximum and minimum values of the $NDVI_{ratio}$, was then used to determine the average onset dates of vegetation green up and dormancy. We used the value of t with the maximum $NDVI_{ratio}$ as the threshold for the onset date of green-up. After finding t with the minimum $NDVI_{ratio}$, the value in time $t+1$ was used as the NDVI threshold for the onset date of vegetation dormancy. To interpolate the original 10-day resolution NDVI data into the daily data, we performed a least square regression analysis between the NDVI data and its corresponding day of the year (Julian day) for each year. At last, the green-up onset dates was calculated via the reconstructed daily series, based on the local threshold for each pixel (Piao et al. 2006; Kafaki et al. 2009).

1.3.2 Spatial distribution and trend detection

In this study, temperature and precipitation were considered as two elements of climatic data. The annual data were calculated using the monthly

data. The temporal and spatial distributions of the annual data were calculated using the ArcGIS software (version 9.3) to reveal the relationship between the climatic elements and the vegetation phenology data.

The formula for the correlation coefficient was used to estimate the correlation between the vegetation phenology data and the annual climate variables.

$$r = \frac{n \sum_{i=1}^n x_i y_i - \sum_{i=1}^n x_i \cdot \sum_{i=1}^n y_i}{\sqrt{n \sum_{i=1}^n x_i^2 - \left(\sum_{i=1}^n x_i \right)^2} \cdot \sqrt{n \sum_{i=1}^n y_i^2 - \left(\sum_{i=1}^n y_i \right)^2}} \quad (2)$$

where, r is the Pearson correlation coefficient, i is the order of the year from 1 to n , n is the number of years, x_i encompasses the vegetation phenology data when the time is i , and y_i refers to the climate variables when the time is i (Zhao and Running 2010).

2 Results

2.1 Spatial pattern of green-up date

Figure 3 shows the vegetation growing seasons from 2000 to 2010 in the Loess Plateau. The average distribution diagram of the BGS indicates an obvious space difference. From north to south, the BGS showed a gradually advanced trend. More accurately, 54.55% of the vegetation began to grow in May or later and was mostly concentrated in the northern part of the plateau, 16.09% began to grow in April, with most localized in the middle of the Loess Plateau, and 29.36% began to grow in March, predominantly localized in the south. Although the end of the growing season (EGS) had no evident spatial difference, a gradual delay trend was still observed from the north to the south. In the northern part of the Loess Plateau, which takes up 40.07% of the area, the vegetation growing season ended in September or earlier, while in the southern part which accounts for 59.93% of the area, the EGS took place in October or later. The space distribution of the average LGS is similar to the distribution pattern of the BGS. From the north to the south, the LGS became longer. For 21.25% of the vegetation it was within 100 days, for 39.55% it was between 100 to 200 days, and for 39.2% it was more than 200 days.

Figure 3 Average time of the beginning of the growing season (BGS), the end of the growing season (EGS) and the length of the growing season (LGS) from 2000 to 2010. The blank area in the figure is an area of no vegetation, such as a desert, an urban area, etc.

2.2 Change in green-up date

From 2000 to 2010, the BGS in the Loess Plateau occurred earlier each year. The spatial distribution in Figure 4 shows that, 54.84% of the vegetation began its growing season in advance, with most of this localized in the southern Loess Plateau (areas in blue in the figure indicate a negative correlation between the BGS and the year). The BGS of 45.16% of the vegetation in the area was postponed, with most of this localized in the northwest (areas in red in the figure indicate a positive correlation between the BGS and the year). A significant advancement in the BGS was observed for 4.39% of the vegetation, mostly

Figure 4 Spatial patterns of the beginning of the growing season (BGS), the end of the growing season (EGS) and the length of the growing season (LGS) from 2000 to 2010.

localized near Lvliang Mountain. For 2.97% of the vegetation a significant delay in the BGS occurred, mostly near the Mu Us Sandland area (Figure 4, Table 1).

For the last 11 years, the timing of the EGS in the Loess Plateau has been obviously delayed. The EGS of the vegetation in 67.64% of the area was postponed (areas in red in the figure indicate a

Table 1 Spatial statistics in the BGS, EGS, and LGS (beginning/end/length of the growing season) change trends (Unit: %)

Variables	PC	NC	Sig. PC	Sig. NC
BGS	45.16	54.84	2.97	4.39
EGS	67.64	32.36	4.36	1.22
LGS	66.28	33.72	11.85	1.05

Notes: Positive/negative correlation (PC/NC) is the changed areas (percentages) showing the positive/negative linear trends between BGS/EGS/LGS and the year. The significant positive/negative correlation (Sig. PC/ Sig. NC) is the changed areas (percentages) showing a significantly ($p < 0.05$) change trends.

positive correlation between the EGS and the year). Most of this was concentrated in the northwest of the plateau. An advanced EGS was observed for the vegetation in 32.36% of the area (areas in blue in Figure 4 indicate a negative correlation between EGS and the year), with most of this in the southeast. In general, 4.36% of the vegetation had a significant delay in the EGS, especially in the east Hetao region. Finally, areas with a significantly advanced EGS were sparse and scattered near Liupan Mountain, accounting for merely 1.22% of the area of the entire region (Figure 4, Table 1).

The changes in the BGS and EGS contribute to the variation in the LGS. From 2000 to 2010, vegetation in the Loess Plateau had an extended LGS. In general, the LGS for 66.28% of the vegetation in the plateau increased (areas in red in Figure 4 indicate a positive correlation between the LGS and the year), while for 33.72% it became shorter (areas in blue in Figure 4 indicate a negative correlation between LGS and the year). It is worth noting that the LGS of 11.85% of the vegetation, located in the Hetao and Lvliang Mountain areas, was significantly extended. In contrast, 1.05% of the vegetation at Liupan Mountain showed a significant reduction (Figure 4, Table 1).

2.3 Correlations between green-up date and climate variables

Correlations between the climate variables (temperature and precipitation) and the BGS in the areas with an advanced BGS are shown in Figure 5a and Figure 5b. A positive correlation was found with temperature for 61.02% of these areas, with areas of high correlation mainly located in the

Figure 5 Spatial patterns of the correlations between the beginning of the growing season (BGS) and the climate variables. (a) temperature, (b) precipitation, in areas with advanced BGS. (c) temperature, (d) precipitation, in areas with postponed BGS.

northern part of the Qinling Mountain Range and at Lvliang Mountain. The percentage of areas negatively correlated with temperature was 38.98%, mainly located in Wushao Mountain. A positive correlation with precipitation was seen for 47.55% of the areas with an advanced BGS, in the eastern Qinling Mountain Range. Areas near Lvliang Mountain, Liupan Mountain, and Ziwu Mountain to the north of Qinling, which account for 52.45% of the advanced BGS areas, showed a negative correlation with precipitation.

For the areas with a postponed BGS, the correlation analysis results are shown in Figure 5c and Figure 5d. There was a positive correlation with temperature for 61.29% of the areas, with areas of highest correlation mainly concentrated in the southern Kubuqi Desert and the northern Mu Us Desert. On the other hand, 38.71% of the area negatively correlated with temperature. Of the areas with a delayed BGS, 70.73% positively correlated with precipitation and were mainly located in North Shaanxi, the Helan Mountain area, and at Yinshan Mountain. A negative correlation with precipitation was found for 29.27% of the

areas with a postponed BGS and these were loosely distributed (Figure 5, Table 2).

Table 2 Spatial statistics for the correlation analysis between climate and green-up date

Variables	Positive correlation	Negative correlation
For Figure 5		
TMP – BGS (a)	61.02%	38.98%
PRE – BGS (b)	47.55%	52.45%
TMP – BGS (c)	61.29%	38.71%
PRE – BGS (d)	70.73%	29.27%
For Figure 6		
TMP – EGS (a)	61.72%	38.28%
PRE – EGS (b)	79.31%	20.69%
TMP – EGS (c)	58.75%	41.25%
PRE – EGS (d)	46.27%	53.73%
For Figure 7		
TMP – LGS (a)	58.9%	41.1%
PRE – LGS (b)	76.53%	23.47%
TMP – LGS (c)	60.8%	39.2%
PRE – LGS (d)	46.66%	53.34%

Notes: TMP/PRE – BGS/EGS/LGS is the correlation between the temperature (TMP)/precipitation (PRE) and the beginning/end/length of the growing season (BGS/EGS/LGS).

Correlations between the climate variables (temperature and precipitation) and the EGS in the areas with postponed EGS are shown in Figure 6a and Figure 6b. Of these areas, 61.72% positively correlated with temperature, and these were mainly located in the southern Kubuqi Desert, the northern Mu Us Desert, and the Lvliang Mountain area. A negative correlation with temperature was noted for 38.28% of the areas concentrated in the Hetao area and Wushao Mountain. Of the areas with a postponed EGS, the 79.31% showing a positive correlation with precipitation were mainly located in the southern part of the Mu Us Desert.

Areas near the western part of Taihang Mountain, which accounts for 20.69% of the postponed EGS areas, showed a negative correlation with precipitation. In areas with an advanced EGS, the correlation analysis results are shown in Figure 6c and Figure 6d. Of these, 58.75% positively correlated with temperature, with areas of the highest correlation mainly concentrated in the northwest of the Qinling Mountains. A negative correlation with temperature was noted for 41.25%

of areas and these were loosely distributed. For precipitation, 46.27% of the advanced EGS areas positively correlated and these were mainly in the east of the Qinling Mountains. Meanwhile, 53.73% of the advanced EGS areas showed a negative correlation with precipitation. Most of these were located in the Ziwu Mountain and northwest of the Qinling Mountains (Figure 6, Table 2).

The correlations between the climate variables (temperature and precipitation) and the LGS in the areas with an extended LGS are shown in Figure 7a and Figure 7b. Of such areas, 58.9% positively correlated with temperature, with areas of high correlation mainly in the southern part of the Kubuqi Desert or north of the Mu Us Desert. The percentage of areas that negatively correlated with temperature was 41.1%, and these were located in the Lvliang Mountain area and the western Taihang Mountain. A positive correlation with precipitation was observed for 76.53% of areas with an extended LGS, and these were mainly located in the southern part of the Mu Us Desert.

Areas near the western Taihang Mountain,

Figure 6 Spatial patterns of the correlations between the end of the growing season (EGS) and the climate variables. (a) temperature (TMP), (b) precipitation (PRE), in areas with postponed EGS. (c) temperature (TMP), (d) precipitation (PRE), in areas with advanced EGS.

Figure 7 Spatial patterns of the correlations between the length of the growing season (LGS) and the climate variables. (a) temperature (TMP), (b) precipitation (PRE), in areas with extended LGS. (c) temperature (TMP), (d) precipitation (PRE), in areas with reduced LGS.

which accounts for 23.47% of the extended LGS areas, showed a negative correlation with precipitation. In areas with a reduced LGS, the correlation analysis result is shown in Figure 7c and Figure 7d. Of such areas, 60.8% positively correlated with temperature and areas of the highest correlation were mainly concentrated in the northwest area of the Qinling Mountains. A negative correlation with temperature was noted for 39.2% loosely distributed areas. For advanced LGS areas, 46.66% positively correlated with precipitation and were mainly located in the east of the Qinling Mountains. Of the reduced LGS areas, 53.34% showed a negative correlation with precipitation. Most of these were located in the Ziwu Mountain and northwest of the Qinling Mountains (Figure 7, Table 2).

3 Discussion

Many studies have shown that global climate change has caused vegetation phenology to change

around the world. Stockli and Vidale (2004) found that the trends in the phenological phases reveal a general shift to be prolonged (0.96 d/a) in Europe. Zhou (2001) showed that the green-up date in North America was arriving earlier, at a rate of 0.4 d/a. Wu (2009) and Yu (2010) also pointed out that the advancement of the BGS and the extension of the LGS were now common phenomena in China. In this study, we found that the vegetation phenology is also changing in the Loess Plateau. More specifically, 54.84% of the vegetation entered its growing season in advance, 67.64% of the vegetation had a delayed EGS, and 66.28% of the vegetation exhibited an extended LGS. The growing season of vegetation in the Loess Plateau is occurring earlier and lasting longer.

The results of the correlations between the BGS and the climate variables show that the warming trend is a limiting factor for the BGS, and precipitation is playing an important role in the vegetation growth process. Previous studies suggested that temperature is the key factor influencing the BGS of the vegetation, with the

increased temperature accelerating growth. Consequently, there should be a negative correlation between temperature and the BGS (Jeong et al. 2011; Menzel et al. 2006; Parmesan 2006; Root et al. 2003). However, in our study, 61.02% of areas with an advanced BGS in the Loess Plateau show a positive correlation between temperature and the BGS, implying that increased temperatures have postponed the BGS in these areas. This finding is similar to that of Yu (2003), who found that the BGS of the vegetation in water-limited areas was delayed by the warming trend in eastern central Asia.

We believe that, in arid or water-limited areas, the increased temperature accelerates evapotranspiration and reduces soil moisture. Under these conditions, if rainfall is unable to supplement the loss of water, the growth of vegetation is inhibited. While few studies have focused on the relationship between precipitation and vegetation phenology (Kramer et al. 2011), we found that 52.45% of the advanced BGS areas in the Loess Plateau showed a negative correlation between the BGS and precipitation, suggesting that the increase in precipitation accelerates vegetation growth. Adequate rainfall improves the soil moisture and helps vegetation to survive during spring droughts in arid and semiarid areas. In addition, clouds decrease evapotranspiration and help vegetation to begin growing (Piao et al. 2006; Nan et al. 2012).

In areas with a postponed BGS, 70.73% positively correlated with precipitation and most were located in the northwest of the Loess Plateau. Water in these areas is limited and 61.29% of these regions had a positive correlation between the BGS and temperature. In the water-limited regions, the increased temperature evidently accelerates the evapotranspiration rate (Mabutt et al. 1989). As a result, if the rainfall fails to offset the loss of water, due to the increased evapotranspiration caused by the warming climate, the beginning of phenological activities will be delayed.

Areas with a postponed EGS are mostly concentrated in the northern part of the Loess Plateau. Of these areas, 61.72% positively correlated with temperature and 79.31% positively correlated with precipitation. Yang et al. (2014) suggested that the effect of temperature on plant growth will increase if the soil moisture constraints

are released, especially in the semiarid areas. This demonstrates that maintaining the appropriate temperature and rainfall in autumn or winter can enhance the photosynthesis of vegetation, extending the growth process (Ciais et al. 2005; Griffin et al. 2004). Meanwhile, in the southern part of the Loess Plateau, the EGS in most areas occurred earlier, with 58.75% of such areas positively correlating with temperature and 53.73% negatively correlating with precipitation. The low temperature and high rainfall causes a rise in the occurrence probabilities of negative climatic events, such as frosts and cold waves, which would certainly suppress the vegetation growth (Augspurger 2009; Eccel et al. 2009).

The distribution of the vegetation phenology in the Loess Plateau showed a clear spatial heterogeneity. Areas with an advanced BGS were mostly in the southeast of the region. Areas with a delayed EGS were mostly in the northwest. The spatial pattern of the LGS resulted from the combined actions of the BGS and EGS. Areas with an extended LGS were mainly in the northwest of the Loess Plateau, as for the EGS. The results demonstrate that changes in the EGS play an effective role in altering the LGS. According to Jeong et al. (2011), this may be due to the asymmetric seasonal warming patterns, between periods during which climate change occurs due to the BGS variation, and those during which climate change occurs due to the EGS variation. Further studies of the Loess Plateau should thus pay more attention to the effects of seasonal climate changes on the vegetation phenology. Of the areas with an extended LGS, 76.53% showed a positive correlation with precipitation, but only 58.9% positively correlated with temperature. This result confirms again that precipitation is one of the key factors in changing the vegetation phenology in water-limited environments (Yu, 2003; Fensholt et al. 2012).

The shifts in the vegetation phenology will significantly affect the carbon budget in the Loess Plateau. Piao et al. (2007) reported that changes in the growing season closely relate to the changes in both gross and net primary productivity. Previous studies have identified that spring phenology is a potential indicator of the annual carbon uptake (Black et al. 2000). The main reason for such enhancement of carbon sequestration was found to

be the prolonged growing season (Chen et al. 2000). But now, more studies have focused on the shift in autumn phenology (Yang et al. 2015). Wu et al. (2013) found that a significant amount of the interannual variability in the annual net ecosystem productivity can be explained by the changes in the autumn phenology. Piao et al. (2008) and Xia et al. (2014) both pointed out that the increase in respiration is much greater than the increase in photosynthesis during autumn warming, resulting in a net carbon loss, despite the delayed EGS.

In this study, we found that both the spring and the autumn phenology were prolonged in the Loess Plateau and that changes in the EGS play an effective role in altering the LGS. Thus, the carbon budget changes in the Loess Plateau, as led by changes in the BGS or EGS, would be worthwhile investigating in future studies. Furthermore, although the annual net carbon exchange might not change, changes in the timing of the start and the end of the growing season can change the atmospheric CO₂ amplitude (Jeong et al. 2011). We strongly suggest that further studies investigate the link between changes in vegetation phenology and the net carbon balance in the Loess Plateau.

4 Conclusion

In this study, we analyzed NDVI data and the concurrent climate information for the Loess Plateau area in China from 2000 to 2010, and successfully built the correlations between

vegetation phenology and climatic variables. The results confirm the lengthening of the growing season due to global warming. The BGS in the Loess Plateau shows an advancing trend, while the EGS is delayed, and the LGS is significantly extended. In addition, we found that the vegetation phenology in this region is sensitive to variations in precipitation. Thus, temperature is not the only factor influencing vegetation phenology in water-limited areas such as the Loess Plateau. Precipitation also plays an important role in the vegetation growth process.

Studies on the influence of climate variables on vegetation phenology will help scientists to understand the relationship between vegetation growth and climate variables, and should therefore be a key focus for the global scientific community. The findings of this study underline the importance of precipitation in vegetation phenology in arid, semiarid, and water-limited areas. We thus suggest that the effects of precipitation on vegetation phenology should be included in future phenological models. In addition, as the growing season becomes extended in the Loess Plateau, the vegetation productivity and the carbon fixation capacity in this area will significantly change.

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