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Decreasing control of precipitation on grassland spring phenology in temperate China

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Abstract

Aim: Vegetation phenology is highly sensitive to climate change. The timing of spring phenology in temperate grasslands is primarily regulated by temperature and precipitation. This study aims to determine whether the primary factor regulating vegetation phenology changed under ongoing climate change and its underlying mechanisms.

Location: Temperate semidry grasslands in China

Time period: 1982-2015

Major taxa studied: Temperate grassland

Method: We extracted start-of-season (SOS) dates using five standard methods from satellite-derived normalized difference vegetation index (NDVI) data and determined the primary regulating factor for spring phenology using partial correlation analysis.

Results: The SOS date did not change significantly during the entire 1982-2015 study period in these semidry grasslands, but interannual variability increased significantly from the first subperiod (1982-1998, Std: 8.8±1.1 day) to the second subperiod (1999-2015, Std: 10.3±1.1 day). Interestingly, we found that the primary regulating factor of SOS shifted from precipitation during 1982-1998 to temperature during 1999-2015. Specifically, we found that during the first period, the SOS in 67.5% of the study area was determined by precipitation (mean partial correlation coefficient r= 0.58±0.16), but during the second period, the main regulating factor in 75.0% of the study area was temperature (r= 0.61±0.14).

Main conclusion: The shift in the primary drivers of spring phenology was mainly attributed to significant increases in preseason precipitation. Our study highlights that the response of spring phenology to climatic factors may change under ongoing climate change. This shift should be addressed in phenology models to better simulate grassland phenology and its impact on carbon and water cycles under future climate conditions.

Keywords: climate warming, precipitation, grassland, spring phenology, start of season

1. Introduction

Grassland phenology is strongly sensitive to climatic changes (Henebry, 2013; Ge *et al.*, 2015). Previous studies have reported shifted spring phenology in temperate grasslands that subsequently affected plant productivity, species distribution and feedbacks to climate systems (Chuine *et al.*, 2000; Peñuelas *et al*, 2009; Fridley *et al.*, 2016; Piao *et al.*, 2019). Changes in grassland phenology have been associated with the climate warming observed over the last four decades (Jeong *et al.*, 2011; Hu *et al.*, 2015). Temperature and precipitation are considered to be the main regulating factors of spring phenology (which we consider equivalent to start-of-season, SOS) in grassland ecosystems (Shen *et al*., 2016), but their interactive effects on SOS remain unclear. Specifically, to our knowledge, it has not yet been investigated whether the primary factor regulating the start-of-season (SOS) has changed over time in temperate grasslands. Identifying such potential shifts will improve the understanding and predictions of grassland responses to ongoing and future climate change.

While climate change has substantially altered the timing of spring phenological events in temperate grasslands, differences have been reported in both the magnitude of the changes and the factors regulating the timing (Shen *et al.*, 2015; Wu *et al*., 2015). 2015). Climate change implies not only rising temperatures but also shifting precipitation temporal and spatial patterns. Climate warming has advanced spring flushing in cold grasslands, for example, in Tibet and in geographical locations at high latitudes (Cong *et al.*, 2012; Zhang *et al.*, 2013), whereas in seasonally dry grasslands, less advancement and even delays in spring flushing have been observed (Ren *et al.*, 2017; Wang *et al.*, 2019). This scenario is mainly because spring phenology is primarily regulated by temperature in cold grasslands but by water availability in dry grasslands (Ma *et al.*, 2007; Vico *et al.*, 2015). In temperate grasslands in China, the driver of SOS varies greatly among locations. Ren *et al.* (2020) found that rainfall has strong control over the SOS in the northeast, air temperature in the south, and snowfall in the northwest. Temperature and precipitation have been found to have negative effects on SOS in temperate grasslands (Piao *et al.*, 2006; Ren *et al.*, 2018; Shen *et al*., 2015). It has been suggested that precipitation may be the dominant factor of SOS timing in Inner Mongolia, especially in desert steppes (Miao *et al*., 2014). For meadow and typical steppe, in some studies, no significant causal connectivity of climate factors with the SOS has been detected, with the exception of spring precipitation (Zhu & Meng, 2015). However, to our knowledge, how the main drivers of SOS change over time has not yet been investigated in temperate dry and semidry grasslands in China. As a result of climate warming and shifted precipitation regimes, the primary factor regulating grassland spring phenology might change, yet to our knowledge, this also has not been investigated.

Ground-based observations are commonly used to investigate vegetation phenology (Cleland *et al.*, 2007). However, due to small spatial coverage and limited species numbers, species-specific observations are difficult to apply in large-scale grassland phenology studies. Satellite-based remote sensing observations have therefore been widely used to investigate grassland phenology at a large scale (Zhang *et al.*, 2003; Shen *et al.*, 2011). Different methods have been developed to extract dates of spring phenological events from remote sensing data, but there are large uncertainties in the methods (White *et al.*, 2009; Cong *et al.*, 2012). For example, in the temperate grasslands of China, Zhou found a one-month difference in the date of spring phenological events depending on the method used (Zhou *et al.*, 2020). Because of the methodological differences in eliminating noise from the normalized difference vegetation index (NDVI) time series and differences in defining phenological stages, remote-based phenology dates have substantial uncertainty. To reduce this uncertainty, the use of several methods was recommended for extracting the SOS date from NDVI data (Cong *et al.*, 2012; Zhou *et al.*, 2020).

In this study, we extracted SOS dates using five methods from the Advanced Very High Resolution Radiometer (AVHRR) data from 1982 to 2015 in grasslands of temperate China and determined the variability in the SOS dates and their primary environmental factors for a slow warming period (1982-1998) and a rapid warming period (1999-2015). We hypothesize that the primary factor regulating grassland spring phenology might change as the climate warms and precipitation regimes shift. The main aims of this study were 1) to determine the primary climatic factors regulating grassland spring phenology, 2) to explore whether these primary regulating factors changed with climate change, and 3) to address the possible mechanisms of the changes.

2. Materials and methods

2.1 Study area

Our study focuses on temperate grasslands in China (Figure 1, http://www.resdc.cn). Three grassland vegetation types are dominant in this region: meadow steppe, typical steppe, and desert steppe. This area is characterized by a temperate continental monsoon climate, with cold-dry winters and hot-moist summers. The mean annual temperature is 4 °C, and the mean annual precipitation is 338 mm.

2.2 NDVI and meteorological datasets used

We used satellite normalized difference vegetation index (NDVI) records from NASA's GIMMS group from 1982-2015. This NDVI dataset has been produced at a spatial resolution of 8 km and a time resolution of 15 days (Tucker *et al.*, 2004). The dataset has been corrected through multiple methods, including calibration, removal of atmospheric interferences, and other effects not related to vegetation changes (Tucker *et al.*, 2005; Pinzon & Tucker, 2014). To verify the accuracy of the results, we also extracted the phenology dates using the MODIS vegetation index EVI. The EVI product was released by the Vegetation Index and Phenology Laboratory at the University of Arizona (https://vip.arizona.edu/viplab_data_explorer.php), and we resized it to match the resolution of the NDVI data. The SOS dates that were extracted from the EVI were similar to the dates extracted from the NDVI (Figure S1); therefore, we estimated the climatic drivers of SOS using the NDVI-based dataset. The meteorological data used were acquired from the Cold and Arid Regions Science Data Center in Lanzhou (He & Yang, 2011) (http://card.westgis.ac.cn/), including daily mean air temperature and daily precipitation from 1982-2015 at a spatial resolution of 0.1° × 0.1°.

2.3 Estimation of spring phenology

The NDVI is a vegetation parameter that permits vegetation growth and activity to be examined (Huete *et al.*, 2002). However, NDVI data might involve artifacts caused by bare soil and snow (Grippa *et al.*, 2005). To remove the artifacts, we defined no spring phenological events as occurring before the air temperature surpassed 0 °C for 5 consecutive days (Cong *et al.*, 2012). In addition, we excluded pixels where the mean annual NDVI value was below 0.1. Croplands were removed from the data to avoid anthropogenic influences in the data. We used in the Vegetation Map of the People's Republic of China at the same resolution as was used in the NDVI images and then removed the pixels marked as croplands. Extracting dates of phenological spring events was conducted in two steps.

First, we used one of five filter functions to smooth the NDVI series since in those series, there are always some abnormal values due to atmospheric interference. Then, we used linear interpolation for the daily values between the biweekly observations because a biweekly resolution is too coarse to estimate dates of spring phenological events. The threshold values for different methods are shown in Table 1. Finally, we defined a threshold value of the NDVI for identifying the date of spring phenological events. To illustrate the methods used in extracting the SOS dates, we chose one pixel in a meadow steppe and used three filter methods as an example (Figure S2). Five methods, each characterized by its filter function and the corresponding threshold, were used for extracting the dates of the start of season at each pixel from the NDVI: Gaussian, Spline, Polyfit, HANTS, and Timesat-SG (for details, see Table 1). After we obtained the SOS from each method, we used the mean value of the five different methods to represent the SOS date at each pixel.

2.4 Data analyses

Linear regression was used to analyze the trend in the SOS during the entire 1982-2015 study period. We took the slope of the linear regression as the trend value of the SOS during the entire period. The variability in the SOS during the two subperiods 1982-1998 and 1999-2015 was evaluated as its standard deviation (Std), similar to the approach in Menzel *et al.* (2006) and Forkel *et al.* (2015). The differences in the SOS and Std between the two periods were tested using paired t-tests. Linear regression was also used to investigate the changes in the climate factors from December to the mean date of the SOS during the entire 1982-2015 study period. To examine the effects of temperature on the timing of the SOS, we determined the most temperature-relevant periods (preseason) for the SOS using partial correlation analysis (Fu *et al.*, 2019). To determine the primary climatic factor, either precipitation or temperature, affecting SOS timing during the whole period of 1982-2015 and the two subperiods (1982-1998 and

1999-2015), we used partial correlation to remove the compound effect (Fu *et al.*, 2015) and defined the main regulating factor of SOS date as the maximum of the absolute value of the partial correlation coefficient for each pixel. The percentages of the study area that were dominated by the primary climatic factor were determined over both the entire period and the two subperiods separately.

3. Results

3.1 Spatial differences in spring phenology

Consistent with the results of previous studies (White *et al*., 2009; Cong *et al*., 2012), a large variation in SOS dates was found among the five methods we used (Figure S3). Across the whole study area and over the entire study period of 1982-2015, the mean date of the start of the season (SOS) was day of year (DOY) 116. The SOS date displayed notable spatial variability (Figure 2a), with a generally decreasing trend from the northeast to the southwest. In the southwestern corner of the study area and at high latitudes, the main vegetation type is meadow steppe, and the SOS date was latest (DOY 123 on average). In the desert steppe, which is mostly located in the southwestern part of the study area, the mean SOS date was DOY 108. Our results are consistent with those in a previous study in which ground-based observations were combined with remote sensing results (Ren *et al*., 2017).

We detected temporal phenology trends in the study area for 1982-2015, with substantial spatial variability in the trends (Figure 2b, Figure S4). An advancing trend in the SOS date was found for 37.8% of the study area and was mainly due to responses in the meadow steppe, where the average trend was -0.07 days/year. In the desert steppe and typical steppe, trends were not significant. On average, the trend over the whole study area was a slight delay in SOS (+0.02 days/year), with this trend being significant for 29.8% of the area.

The standard deviation (Std) of the SOS date quantified the SOS date fluctuation over the entire study period of 1982-2015 (Figure 2c). The fluctuation displayed a significant increasing trend from the northeast to the southwest, which was likely due to differences among the vegetation types, with the meadow steppe displaying the lowest SOS date fluctuation (mean Std value 3.6 days) versus 4.2 days for the typical steppe and 7.6 days for the desert steppe.

3.2 Differences in spring phenology between 1982 and 1998 and 1999 and 2015

Based on the rate of climatic warming, we divided the entire study period into two subperiods: 1982-1998 (slow warming) and 1999-2015 (fast warming). However, we did not find significant changes in the SOS, although the average SOS dates slightly advanced by approximately two days from the first subperiod (DOY 119.6±18.4) to the second subperiod (DOY 117.5±13.3). Interestingly, however, the interannual variability in the SOS dates between these two periods did differ significantly, with fewer SOS date fluctuations during the first subperiod (mean Std = 8.8 ± 1.1 days) than during the second subperiod (mean Std = 10.3 ± 1.1 days) (Figure 3b). For the different grassland types, the SOS in the desert steppe advanced by approximately three days from the first subperiod (DOY 109.2±8.6) to the second subperiod (DOY 106.1±10.5). In contrast, the other two types of grasslands showed little difference between the two time periods. Among these three vegetation types, the desert steppe showed the largest differences between the two time periods.

3.3 Temporal changes in the climatic factors over the study area

Mean temperature and precipitation during winter and spring (between December in the last year to May in the next year) increased over the entire study period of 1982-2015 at rates of 0.09 °C/year and 0.36 mm/year, respectively (Figure 4a, 4b, 4c). The rate of increase in the mean temperature grew from 0.01 °C/year during 1982-1998 to 0.17 °C/year during 1999-2015. The rate of precipitation changes significantly increased from 0.04 mm/year during the first to 0.27 mm/year during the second subperiod. To test the robustness of the results, during the study period, we also examined the temporal trends in the climatic factors prevailing during the preseason and found very similar results (Figure 4d, e and f) as was examined for the fixed winter-spring period (Figure 4a,b,c). The rate of mean temperature increase during preseason increased from 0.03°C/year during the first subperiod 1982-1998 to 0.13°C/year during the second subperiod 1999-2015, whereas the rate of precipitation increase significantly increased from 0.14 mm/year during the first subperiod to 0.63 mm/year during the second subperiod. For the southwestern part of the study area, where the vegetation type is mainly desert steppe, the precipitation showed decreasing trends.

3.4 Changes in climate controls on spring phenology

Over the entire study period of 1982-2015, the main factor governing spring phenology was temperature in 70.6% of the study area (Figure 5). However, we found that the main regulating factor changed from the first subperiod to the second subperiod (Figure 6). Precipitation was the main regulating factor during the 1982-1999 period in 67.5% of the study area, with a mean partial correlation coefficient of 0.58±0.16. This scenario was apparent especially in the northern part of the study area, where the meadow steppe and typical steppe dominated (Figure 6a). In contrast, during the second subperiod, the main regulating factor changed to temperature in 75% of the study area, with a mean partial correlation coefficient of 0.61±0.14 (Figure 6c). In general, the area where spring phenology was previously regulated by precipitation became regulated by temperature. Statistically, 53% of the pixels were converted from precipitation regulation to temperature regulation, 10.5% of the pixels were converted from temperature regulation to precipitation regulation, 22% of the pixels were still regulated by temperature, and the remaining 14.5% of the pixels were still regulated by precipitation (Figure 6b). To test the robustness of these results, we also checked the temporal changes in the climatic controls over three time periods, i.e., 1982-1992, 1993-2004 and 2005-2015, and very similar results were found (Figure S5).

4. Discussion

4.1 Changes in SOS trends and interannual variability

Based on the five methods to extract SOS data from the NDVI series in temperate semidry grasslands in China, the start of the growing season did not change significantly over the 1982-2015 period for the whole study area, although there was spatial variability in the temporal trends. This result is consistent with those of previous studies based on ground-based observations and remote sensing (Hou *et al.*, 2014; Wang *et al.*, 2019). We found that the date of SOS displayed an advancing trend in the northern part of the study area, where the main vegetation type is meadow steppe. This scenario was likely caused by rising temperatures and increasing precipitation in the preseason, which are both thought to affect spring phenology (cf. Richardson *et al.*, 2013; Chen *et al.*, 2014). The delayed SOS trend in the southern region, where mainly desert steppe occurs, may be the result of drought during preseason being dominant in that part of the study area. Weaker vegetation growth was found to be highly correlated with drought in the southern area (Li *et al.*, 2018).

We found that in comparing the fast warming period 1999-2016 to the slow warming period 1982-1998, the variability in the SOS dates increased significantly with climate warming. Different climatic drivers of phenology in different areas may have driven this increased interannual variability. We propose three prime reasons for this trend. First, climate warming has been widely recognized as the main regulating factor causing advances in SOS dates (Park *et al.*, 2016; Richardson *et al.*, 2018). Ma and colleagues (2019) found that since the 1990s, both temperature and the variability therein increased rapidly in Inner Mongolia. The increased temperature differences between years likely contributed to the larger variability in the SOS. Second, precipitation increased until the mid-1990s for the whole study area (Lee & Sohn, 2011), which was likely related to the significant preseason increase in precipitation across the whole study area over the study period, reducing growth sensitivity to water availability in these arid and semiarid regions (Shen *et al*., 2015; Felton *et al*., 2019; Li *et al.*, 2019). As a result, phenology dynamics may have become more related to temperature and variability therein. Third, more extreme high temperature events and drought events have been observed over the study regions (Shen *et al*., 2015; Mohammat *et al.*, 2013), and such extremes might cause large variability in SOS. Considering that more extreme events are expected to occur under future climate change conditions (Stott *et al.*, 2016; Zscheischler *et al.*, 2018), increased variability in phenology is likely, although increased information on phenological triggers is needed to improve models and predictions.

4.2 Changes in the factors regulating SOS date

Temperature and water availability are widely accepted as the dominant factors controlling the processes determining SOS dates in temperate dry and semidry grasslands (Forkel *et al.*, 2015). However, the interactive effects of precipitation and temperature on SOS processes are still largely unknown (Garonna *et al.*, 2018). Our results provide evidence for the dynamic nature of climatic constraints on SOS dates, with the relative importance of the two main climatic factors of SOS dates shifting from precipitation to temperature regulation on Inner-Mongolian grasslands. In the absence of a clear water limitation, temperature may then become the primary limiting factor. Despite ongoing warming, we only found a slightly advance in the SOS during the rapid warming period of 1999-2015. This may indicate that precipitation requirements for initiating SOS were not always met, even though precipitation significantly increased (Ogle & Reynolds, 2004); at the same time, the heat requirement for spring phenology, i.e., growing degree days, significantly increased due to climate warming (Fu *et al*, 2015). With continuously increasing precipitation and warming, we may expect an advanced trend in spring phenology because the precipitation threshold might be reached earlier. Overall, and consistent with previous studies (Liu *et al.*, 2014), we found that both precipitation and air temperature determine the spring phenology of temperate grasslands. The novelty of our study lies in the observation that the primary regulating factor changed with changing climate conditions. Under climate change, both precipitation and temperature show an increasing trend in arid and semiarid regions (Dai, 2012; Stocker, 2014). Our results thus suggest that an advanced trend in the spring phenology of temperate grasslands in China is likely if precipitation thresholds are reached earlier.

In addition to temperature and precipitation, spring phenology can also be influenced by photoperiod and snowmelt in grasslands. Julitta et al. (2014) found that advanced snowmelt strongly correlated with advancing spring phenology in subalpine grasslands. As snowmelt depends on meteorological factors such as precipitation, temperature and radiation during previous months, it may then present an indirect effect of climatic factors on spring phenology dates. However, the snow layer of temperate grasslands in China is shallow because of very low precipitation during winter (Chen *et al.*, 2015) and is thus not a major regulating factor of phenology in our study region (Peng *et al.*, 2013). However, the advanced SOS date may increase summer water stress due to higher water loss through evapotranspiration (Lian *et al*, 2020), which in turn may reduce vegetation growth (Zhou *et al.*, 2020) and subsequently affect autumn sentence (Fu *et al.*, 2014; 2019) and the following year's spring phenology dates (Fu *et al*, 2014; Signarbieux *et al.*, 2017). In addition, as changes in land use may also influence spring phenology, we estimated the land use change over the study area by using the GLASS-GLC dataset, which is the first record of 34-year annual dynamics of global land cover spanning 1982 to 2015 at a 5 km resolution (Chen *et al.*, 2019). We found that only 0.52% of the area was changed. This result indicates that the land use changes likely did not significantly impact our results. Furthermore, species composition may change over time and then impact the drivers of vegetation spring phenology due to species-specific phenology responses to climate change. Experimental studies with various species are thus needed to confirm our results. Given the complex potential interactions affecting spring phenology under climate change, further research is clearly required, for example, through experimental control of environmental drivers to improve process understanding (De Boeck *et al.*, 2015). In addition, compared to tree and forest phenology, grassland phenology is addressed only in a few modeling studies, and the models are generally less developed than those developed for trees (Xin *et al*., 2015). Our study may provide an avenue to improve model performance by considering the shifting dominant factor under changing climatic conditions. The shift may not be restricted only to spring phenology. Rather, such shifts may also occur during other phenological events, such as autumn senescence, and affect the regulation of the length of the growing season. This impact remains to be investigated in forthcoming studies. The dynamic controls of temperature and precipitation on grassland spring phenology could thus be coupled to phenological models to better understand the carbon and water cycles in grassland ecosystems.

Conflict of interest

The authors declare that they have no conflicts of interest.

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Data Accessibility

The spring phenology dates were uploaded from the online dataset Dryad: https://doi.org/10.5061/dryad.mkkwh70xn. All other data used in this study were from published resources as described in the Materials and Methods section.

Table

Table 1. Five methods used for extracting start-of-season (SOS) dates from the NDVI dataset. The functions used for data filtering and the threshold criteria for SOS determination are indicated.

Method	Data filter function	Threshold criterion
Gaussian	$\text{NDVI(t)} = a+b\times e^{-((t-c)/d)^2}$	NDVI ratio > 0.5
Spline	$\text{NDVI(t)} = a_t t^3 + b_t t^2 + c_t t + d_t$	NDVI ratio > 0.5
Polyfit	$\text{NDVI(t)} = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + \cdots a_n t^n$	Maximum variation
HANTS	$\text{NDVI(t)} = a_0 + \sum_{i=1}^{n} a_i \cos(w_i t - \varphi_i)$	Maximum variation
Timesat	$\text{NDVI(t)} = \frac{\sum_{i=-m}^{i=m} C_i NDVI_{j+i}}{N}$	20% of NDVI amplitude

Figure legend

Fig 1. Study region and the geographical distribution of the three grassland types in China.

Fig 2. (a) Spatial distribution of the mean SOS date and temporal trends in (b) SOS dates and (c) the standard deviation of the SOS dates during the entire study period of 1982-2015.

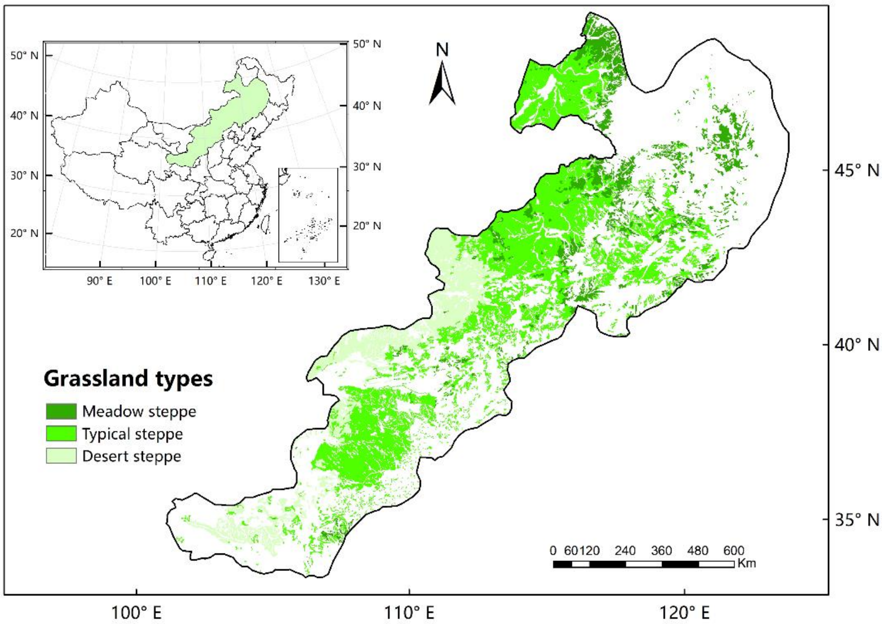
Fig 3. (a) Frequency distributions over the two subperiods 1982-1998 (blue) and 1999-2015 (red) of the mean SOS date over the whole study area and (b) its standard deviation. The symbol * indicates a significant difference between 1982 and 1998 and 1999 and 2015.

Fig 4. (a) Temporal trends in (a) temperature and (b) precipitation in winter and spring during the entire study period of 1982-2015 and (c) the average temperature and precipitation sum in winter and spring in the two subperiods 1982-1998 (blue) and 1999-2015 (yellow); (d) temporal trends in temperature and (e) precipitation in the preseason during the entire study period of 1982-2015 and (f) the average temperature and precipitation in the preseason in the two subperiods.

Fig 5. Spatial distribution of the partial correlation coefficients between the SOS date and the meteorological factors temperature (red) and precipitation (blue) over the whole study period of 1982-2015.

Fig 6. Spatial distribution of the absolute values of the partial correlation coefficients between the SOS date and the meteorological factors temperature (red) and precipitation (blue) in the (a) first subperiod of 1982-1998 and (c) the second subperiod of 1999-2015; (b) changes in the area from the first to the second subperiod regarding main factor, either temperature (red) or precipitation (blue), regulating the SOS date. The size of each of the colored areas indicates the proportion of the pixels for the corresponding change.

603 Figure 1.



50° N
40° N
30° N
20° N
90° E
100° E
110° E
120° E
130° E
N
Grassland types
Meadow steppe
Typical steppe
Desert steppe
0 60120 240 360 480 600
Km
45° N
40° N
35° N
100° E
110° E
120° E

604 Figure 2.

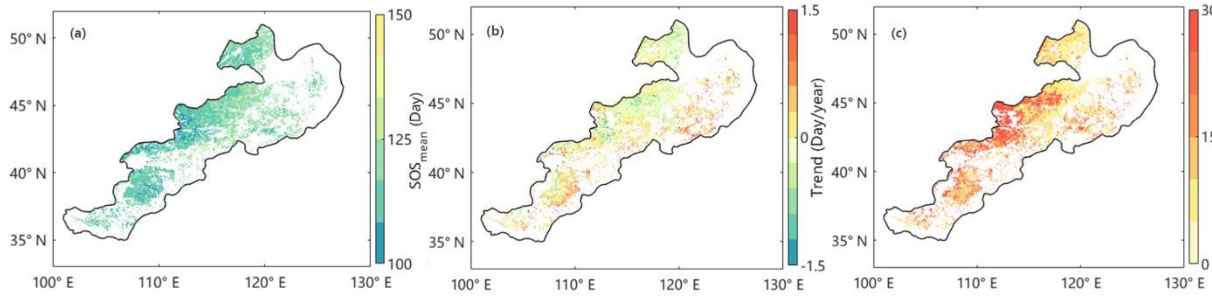
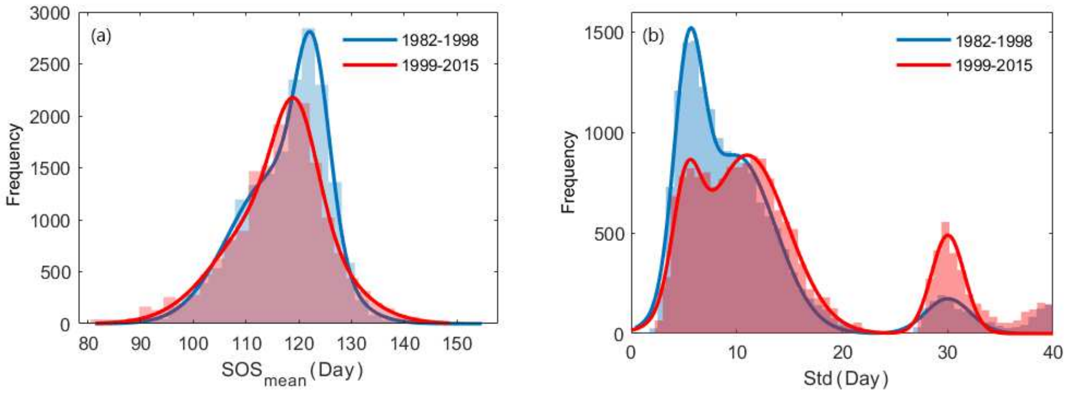
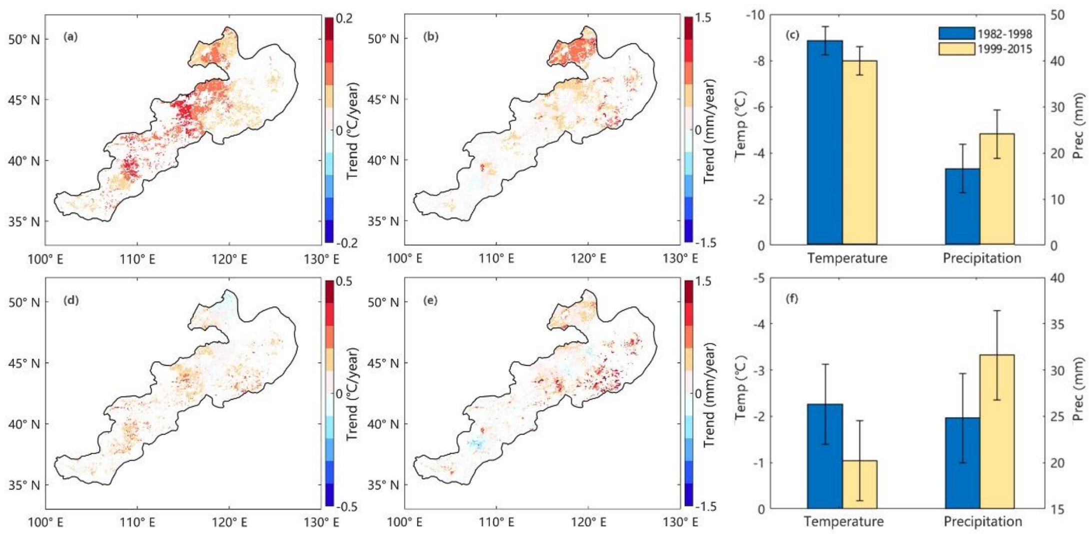

(a)
(b)
(c)
50° N
45° N
40° N
35° N
100° E
110° E
120° E
130° E
150
125
100
SOS_mean (Day)
1.5
0
-1.5
Trend (Day/year)
30
15
0
STD (Day)

Figure 3.

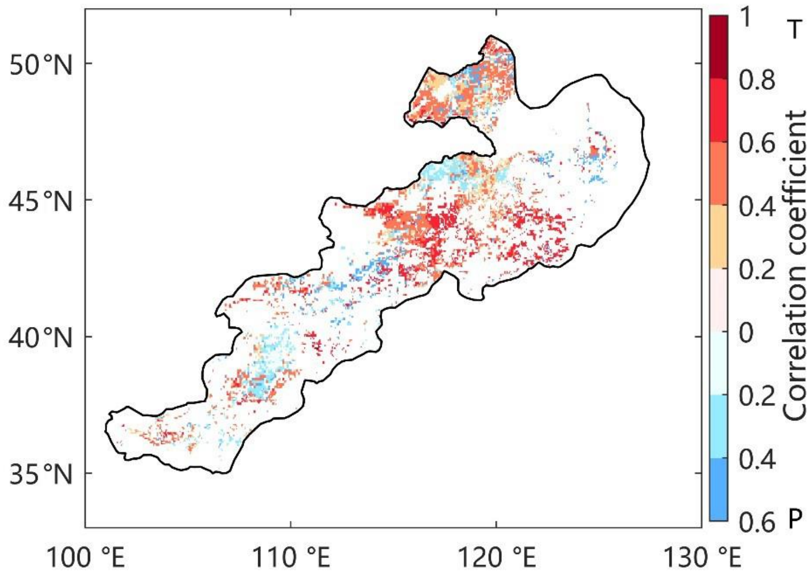

(a)
1982-1998
1999-2015
Frequency
3000
2500
2000
1500
1000
500
0
80
90
100
110
120
130
140
150
SOS mean (Day)
(b)
1982-1998
1999-2015
Frequency
1500
1000
500
0
0
10
20
30
40
Std (Day)

606 Figure 4.

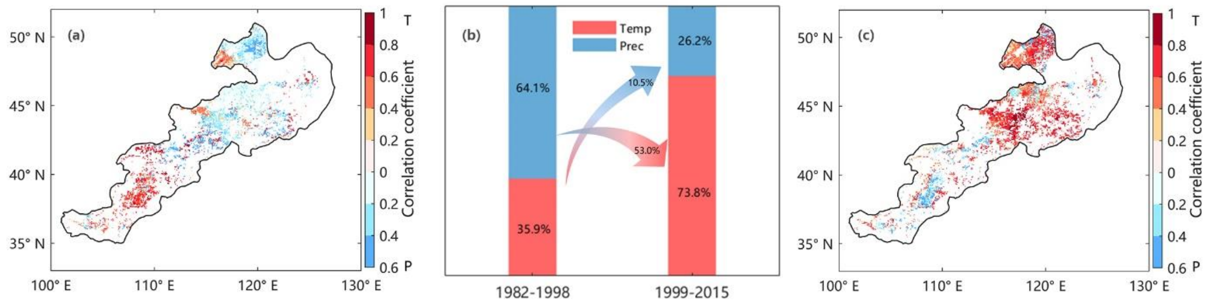


(a)
(b)
(c)
(d)
(e)
(f)
Trend (℃/year)
Trend (mm/year)
Temp (℃)
Prec (mm)
1982-1998
1999-2015
Temperature
Precipitation
100° E
110° E
120° E
130° E
35° N
40° N
45° N
50° N

607 Figure 5.


50°N
45°N
40°N
35°N
100 °E
110 °E
120 °E
130 °E
1
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
T
P
Correlation coefficient

608 Figure 6.



(a)
50° N
45° N
40° N
35° N
100° E
110° E
120° E
130° E
1
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
T
P
Correlation coefficient
(b)
Temp
Prec
64.1%
35.9%
26.2%
73.8%
10.5%
53.0%
1982-1998
1999-2015
(c)

Appendix

Figure S1 Spatial distribution of the mean SOS date (a), its temporal trends (b), and the standard deviation of the SOS dates (c). The phenological dates were extracted from the EVI dataset.

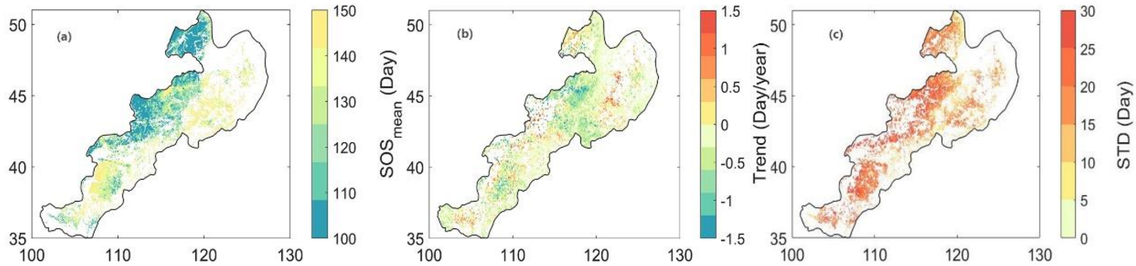


Figure S2. Smoothed time-series of the NDVI (gray points) and curves fitted to the data. The curves were fitted using the GS, SP and SG methods at one pixel in a meadow steppe to obtain the start-of- season (SOS) date. The red, green and blue points indicate the SOS dates determined by the GS, SP, and GS methods, respectively. The details of each method can be found in Table 1.

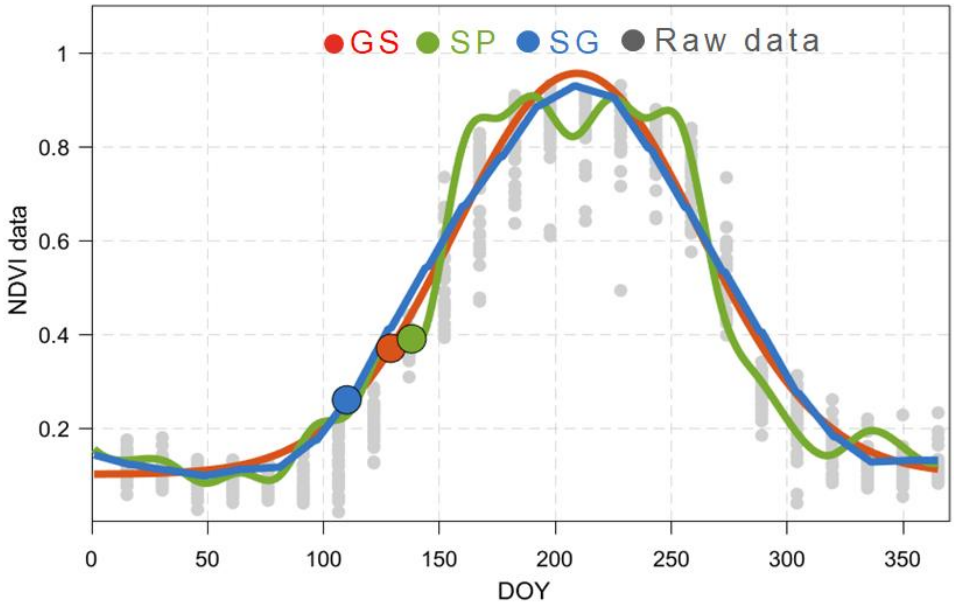


Figure S3 Spatial distribution of the mean SOS date extracted by five different methods.

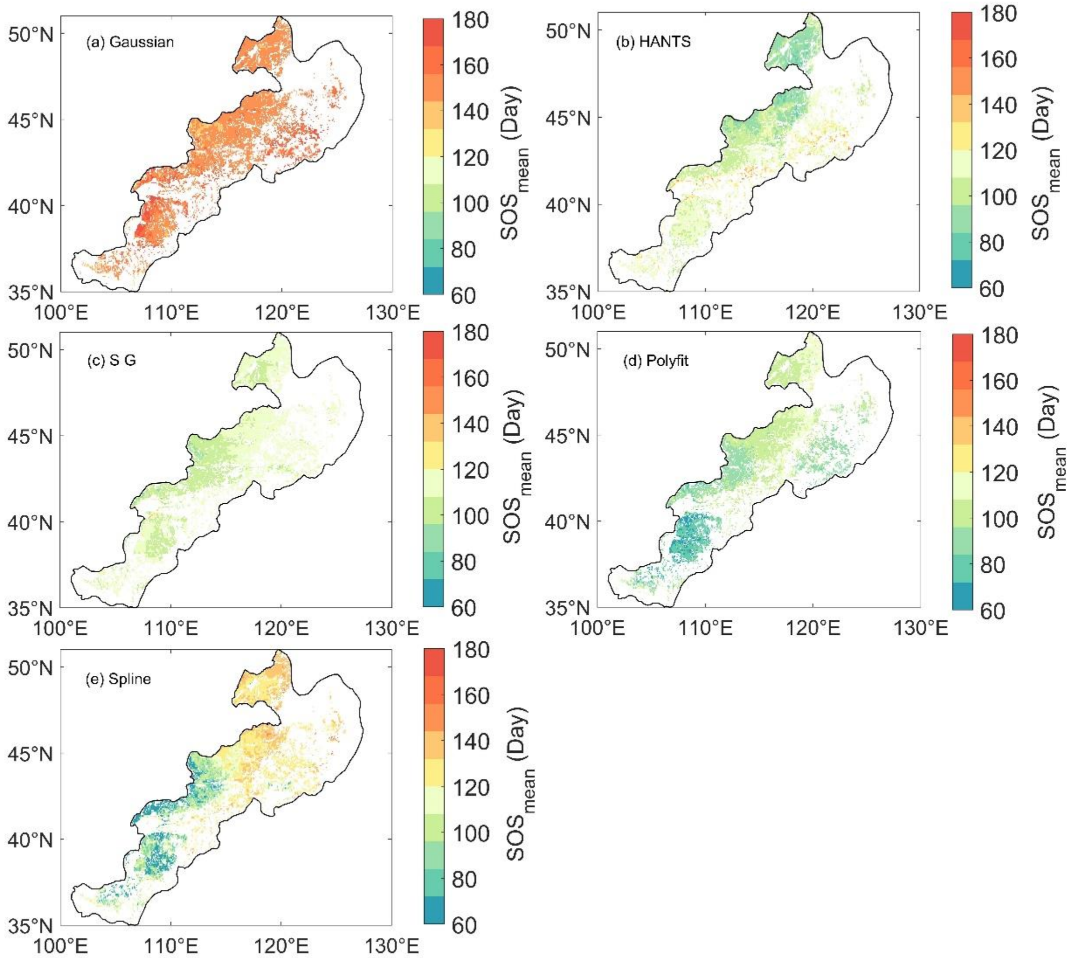


Figure S4 Spatial distribution of the SOS trends for the five methods, i.e., (a) Gaussian, (b) Hants, (c) Polyfit, (d) SG and (e) Spline during the entire study period of 1982-2015.

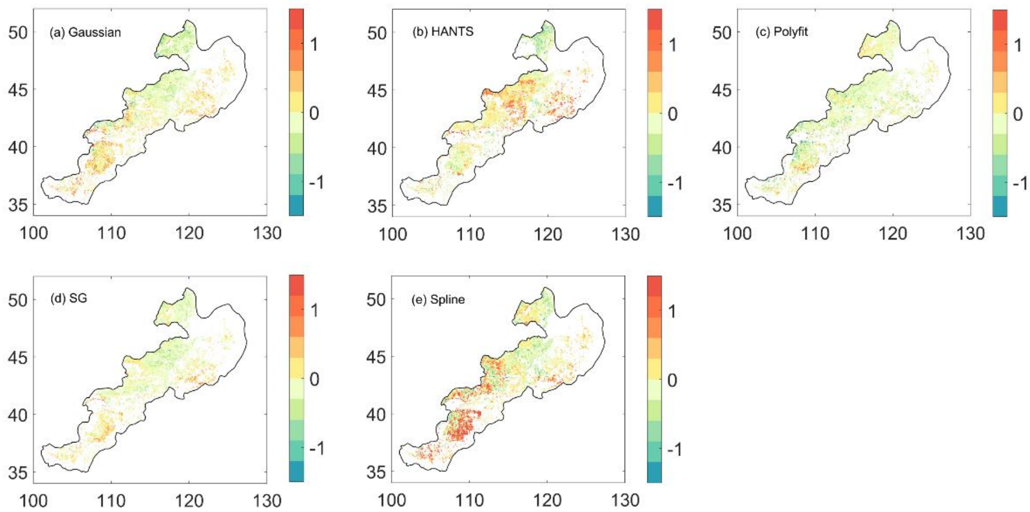


Figure S5. Changes in area over the three time periods, i.e., 1982-1992, 1993-2004 and 2005-2015, regulating the SOS date by either temperature (red) or precipitation (blue) as the main factor. The size of each of the colored areas indicates the proportion of the pixels for the corresponding change.