Diverse effects of climate at different times on grassland phenology in mid-latitude of the Northern Hemisphere

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Introduction

Plant growth in grasslands is sensitive to both air temperature and water availability. Many studies based on ground records and satellite observations have revealed that over the past several decades, preseason temperature increases have prompted significant advances in spring phenological events in grassland vegetation (such as greenup date and growing season start date). However, when water supply is short in a location, increasing temperature may have no significant effects on grassland spring phenology. This means that water supply also plays a critical role in regulating phenological changes for herbaceous plants and enough water supply usually facilitates plants to grow earlier under suitable heat conditions, especially in arid and semi-arid places. Meanwhile, several studies reported that increasing precipitation had no significant effect on flowering dates in two temperate grasslands of North America, while reducing water supply resulted in an earlier greenup and flowering date of herbaceous species in some field experiments. In alpine, high-latitude, and temperate regions covered by snowfall in non-growing season, spring phenology of non-woody plants has also been linked with the snow melting date, the snow cover duration, and the amount of snow. The effects of snowfall on grassland spring phenology was also detected to be vegetation type and location dependent in a Tibetan Plateau. Therefore, the response of spring phenology of grassland vegetation to climatic variables is complex and still controversial. It's urgent to elucidate the responses of grassland spring phenology to climate change and their possible spatiotemporal differences at continental scale.

Compared with spring phenology, autumn phenology has been relatively less well investigated in phenology-climate interaction studies. But autumn phenological events are of great importance in determining the growing season length and controlling carbon and energy exchange. As reported, increasing temperature in preseason has led to an extensive delay of autumn phenological activities for woody plants. Besides temperature, autumn phenology of grassland vegetation could be also significantly influenced by previous precipitation, as shallow-rooted herbaceous plants are susceptive to the timing of rainfall in autumn. But the roles of previous temperature and precipitation in controlling autumn phenology of grassland vegetation differ among diverse species and grassland types in varied spatial scales. Based on the correlation between satellite-derived growing season end dates and air temperature and precipitation at 56 meteorological stations of the Inner Mongolia grassland, Ren et al. (2017) found precipitation was a more important factor in regulating autumn phenology of grassland vegetation than air temperature. But their further work at the region scale revealed an overall dominance by control of air temperature on the dynamics of growing season end date of grassland vegetation, though a decisive effect of precipitation was detected in desert steppe. The decisive role of temperature in determining autumn phenology of grassland vegetation was also reported by other studies in frozen ground regions of Mongolia and temperate grassland over China. The above studies suggest a vital role of grassland autumn phenology in vegetation-air interactions but complex responses to climate change. However, our knowledge of the controls regulating autumn phenology of grassland ecosystems at global scale is still limited.

In this study, we investigated temporal patterns of spring and autumn phenological events of plants and their climatic controls across mid-latitude (30° N~55° N) grasslands of the Northern Hemisphere. The specific questions addressed are as follows: (i) How have the SOS and EOS of grassland vegetation changed from 1981 to 2014? (ii) How do the SOS and EOS of grassland vegetation respond to changes in temperature and precipitation? (iii) Is there a spatial pattern in the response of SOS and EOS to climatic factors among global grasslands?

Data and methods

Remote sensing data and processing

A NDVI data product (1981-2014), that combined AVHRR (1981-1999) and MODIS (2000-2014) datasets by standardizing AVHRR to the same level with MODIS, was used to calculate SOS and EOS from 1981-2014. This product was previously released by Vegetation Index & Phenology Laboratory at the University of Arizona (https://vip.arizona.edu/viplab_data_explorer.php) and has a spatial resolution of 0.05° and temporal interval of 7 days. In order to obtain high-quality NDVI time series, we first determined the background NDVI value (uncontaminated by snow and clouds) within the vegetation dormancy period at each pixel based on MODIS land surface temperature (MOD11C2, 2000-2014). Next, we took the average of the upper 50% of NDVI values within the vegetation dormancy period as the background NDVI. The envelope line of entire NDVI time series was then obtained based on a modified Savitzky-Golay filter. Finally, we fitted the reconstructed NDVI time series with a double logistic function, which has been demonstrated to be particularly well suitable to extract phenological parameters from remote sensing data. SOS and EOS were computed based on the maximum curvatures of the fitted curve at each pixel. The following figure illustrates of NDVI processing and SOS/EOS extraction. The length of the growing season (LGS) was defined as the duration from SOS to EOS.

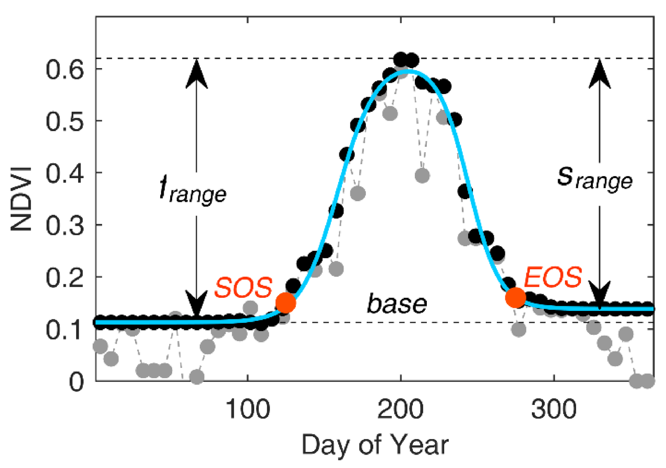

Fig. 1. Illustration of NDVI data processing and fitting to obtain the start (SOS) and end (EOS) of the growing season. The cyan curve is fitted with double logistic function. Gray dots represent raw NDVI values. Black dots represent reconstructed NDVI data after processing and smoothing.

Statistical analysis

The gridded WATCH-Forcing-Data-ERA-Interim (WFDEI) data were used to analyze climatic effects on temporal patterns of SOS and EOS. We performed a time-window analysis in each grid cell by using the *climwin* R package, with the aim to explore the best periods for climatic factors affecting grassland vegetation phenology. First, this method constructed a baseline linear model by fitting phenology time series to only "year" variables. In this step, a base Akaike Information Criterion (*AICc*) value was obtained. Second, linear regression models were established between SOS/EOS and each climatic factor (i.e. mean air temperature, cumulative rainfall, and cumulative snowfall (only for SOS)) in any time window from the predefined reference date to a certain number of days before the reference date. All model *AICc* values were then compared to the based *AICc* and the time window with the biggest reduction (*ΔAICc*) in *AICc* was identified as the best-performing time window. Third, by applying the same time-window analysis to a number of randomizations of the original climate data, the probability statistic Pc value (0~1) could be calculated to assess whether such a *ΔAICc* value for the identified best time window was obtained due to chance.

Results

A dominated negative correlation between air temperature and SOS was found in 62.4% of the effective areas (19.8% of the whole study region), which was primarily located in the North American Grasslands and the Mongolian Grasslands (Fig. 2-3). On average, if mean air temperature within the best time-window increases by 1° C, SOS would happen 0.85 days in advance. Meanwhile, a dominant and negative correlation was also diagnosed between rainfall and SOS in 57.6% of the effective areas (9.7% of the whole study region). 1 mm increase of the total rainfall over the best time-window would lead SOS to occur earlier by 0.36 days. Additionally, we detected a significant positive effect of snowfall on SOS in the majority part of the North American Grasslands and the Mongolian Grasslands but a significant negative effect on SOS in the most part of the Middle-West Asian Grasslands.

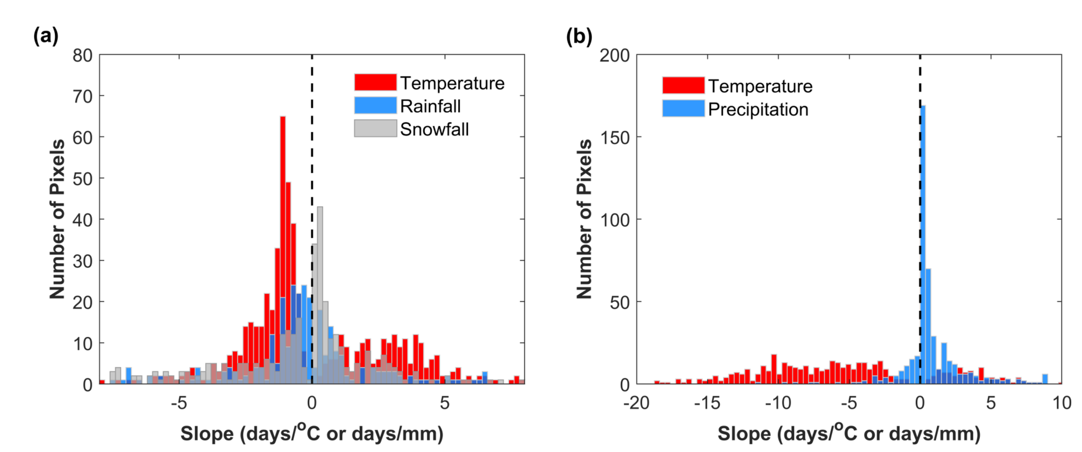

Fig. 2. Histogram of the slopes of the best linear models for (a) SOS and (b) EOS.

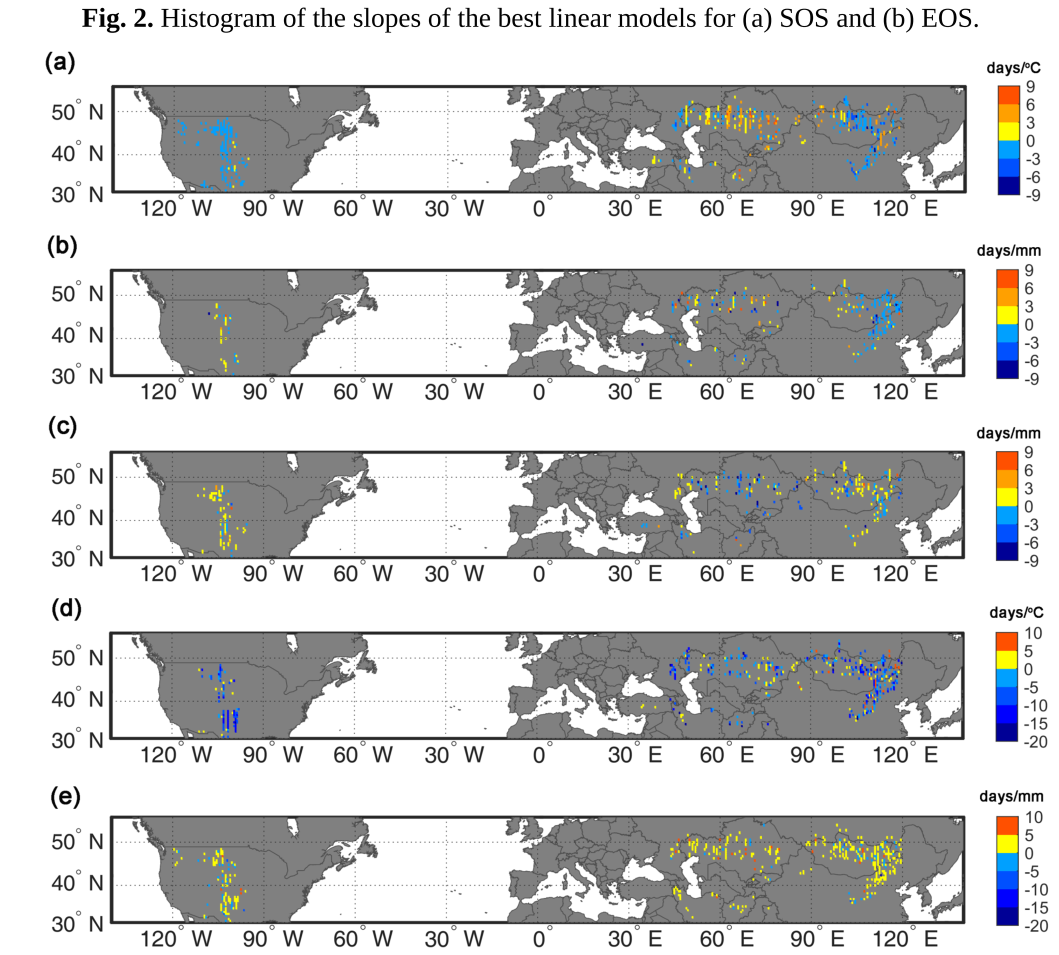

Fig. 3. Spatial pattern of the slopes of the best linear models for (a) SOS vs air temperature, (b) SOS vs rainfall, (c) SOS vs snowfall, (d) EOS vs air temperature and (e) EOS vs precipitation.

EOS was found to be significantly negatively correlated with air temperature in 74.8% of the effective areas and significantly positively correlated with precipitation in 83.7% of the effective areas. On average, air temperature within the best time-window increasing by 1 ° C would make EOS appear earlier by 5.4 days; precipitation within the best time-window increasing by 1 mm would induce EOS to occur later by 0.34 days.

For 95.2%/76.2%/69.8% of the effective grid cells, the optimal time window length for the effect of air temperature/rainfall/snowfall on SOS was limited between 1 and 60 days (Fig. 4-5). But there are also 31% of grid cells showed a longer time window (90-180 days) for the effect of rainfall on SOS in the Mongolian Grasslands (Fig. 4-5). Furthermore, we found that the time window opening date for the effect of air temperature on SOS was identified as the day 1-90 before the multi-year average SOS in 76.1% of grid cells, while the time window opening date for the effect of rainfall/snowfall on SOS was relatively evenly distributed between the 1st and 180th day before the multi-year average SOS. For 66.9%/77% of the effective grid cells, the optimal time window for the effect of air temperature/precipitation on EOS ranged from 1 to 60 days (Fig. 4-5). The time window opening date for the effect of air temperature on EOS was identified as the 90-180th day before the multi-year average EOS in 66.9% of grid cells, while the time window opening date for the effect of precipitation on EOS was mainly concentrated on the 60-120th day before the multi-year average EOS in 51.5% of grid cells.

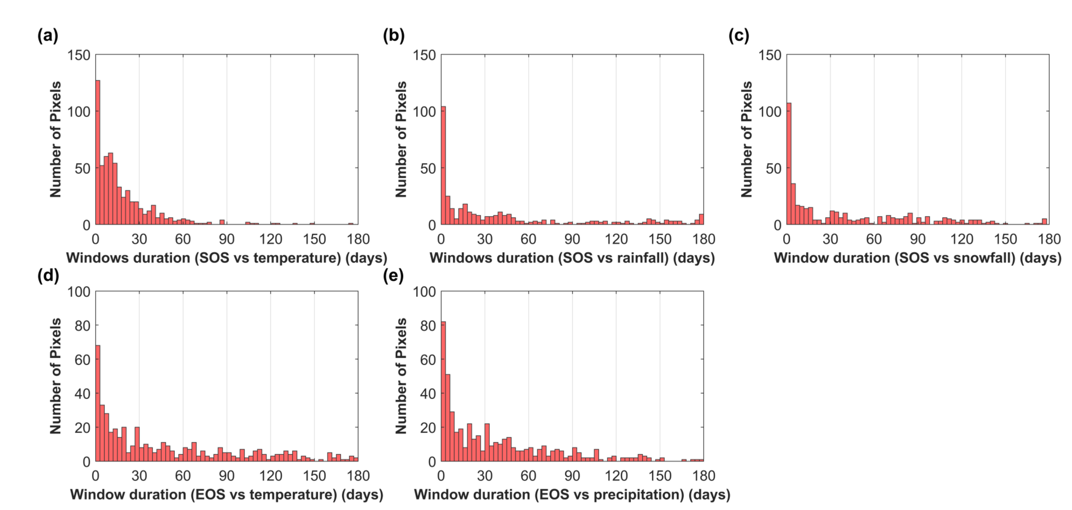

Fig. 4. Histogram of the time window durations for (a) SOS vs air temperature, (b) SOS vs rainfall, (c) SOS vs snowfall, (d) EOS vs air temperature and (e) EOS vs precipitation.

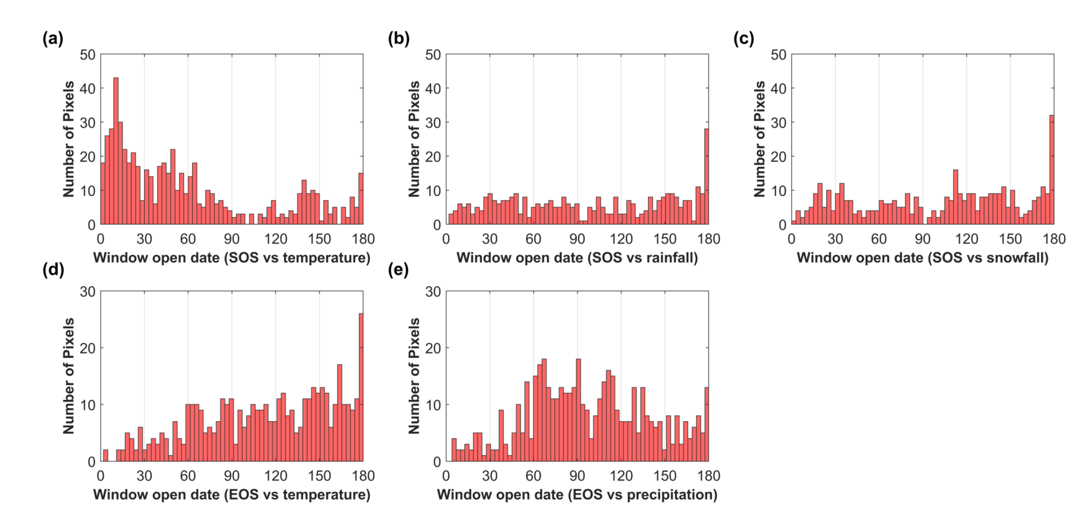

Fig. 5. Histogram of the time window opening dates for (a) SOS vs air temperature, (b) SOS vs rainfall, (c) SOS vs snowfall, (d) EOS vs air temperature and (e) EOS vs precipitation.

Conclusion

(1) Air temperature and precipitation exhibited a relatively stronger control on SOS and EOS, respectively.

(2) The influencing time of water conditions on SOS is earlier and longer than thermal conditions.

(3) EOS primarily depends on spring thermal conditions and autumn water availability.