Diverse Responses of Phenology in Multi-Grassland to Environmental Factors on Qinghai-Tibetan Plateau in China

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Abstract

Revealing grassland growing season spatial patterns and their climatic controls is crucial for the understanding of the productivity change mechanism in regional terrestrial ecosystem. However, the multi-grassland phenological factors are different, which has not been well studied. In this paper, the spatio-temporal patterns of the grassland start of the growing season (SOS) and the end of growing season (EOS) were investigated using MODIS Normalized Difference Vegetation Index (NDVI) on the Qinghai-Tibetan Plateau (QTP) during 2000 to 2019. At the same time, we analyzed the factors (including extreme and mean climate, drought, solar radiation, etc.) regulating grassland phenology under ongoing climate change. The results showed that the SOS appeared first in mountain meadow, shrub-tussock, temperature steppe and desert, then in alpine steppe and alpine meadow, showed a significant advancing tendency in all types. The EOS appeared first in temperature steppe, alpine steppe and alpine meadow, then in mountain meadow, shrub-tussock and desert. Further analysis indicated that the decrease of yearly minimum value of daily minimum temperature (TNN), yearly maximum value of daily minimum temperature (TNX), Temperature vegetation dryness index (TVDI) and the increase of yearly maximum consecutive five-day precipitation (RX5day) advance the grassland spring phenology, whereas the increase of solar radiation (SR) delay the grassland spring phenology. Meanwhile, SOS and its change rate showed the trend of significant delay and decline with the increase of altitude, respectively. We also found that the decrease of TVDI, TNN and the increase of yearly mean value of temperature (MAT_MEAN), yearly mean value of daily maximum temperature (MAT_MAX) and yearly mean value of daily minimum temperature (MAT_MIN) advanced the autumn phenology. The EOS and its change rate advance and increase with increasing altitude, respectively.

Highlights

- ➢ Spring and autumn phenology in multi-grassland on the Qinghai-Tibetan Plateau were analyzed.
- ➢ Impacts of environmental factors to multi-grassland phenology were evaluated.
- ➢ Extreme temperature and drought events will delay grassland green-up in spring, while solar radiation will lead to an advancement of spring phenology.
- ➢ Annual mean temperature and drought events will advance grassland brown in autumn.

1 Introduction

Plant phenology is the natural phenomenon of seasonal development and senescence of plant leaves under the influence of environmental factors (Chen et al，2017), which reflects the periodic regulation of interaction between vegetation phenology and non-biological environment, and its occurrence time can indicate the characteristics short-term changes in the ecosystem (Liu et al，2020; Ren et al，2018; Li et al， 2018). Over the past decades, climate warming, extreme low-temperature events decreasing, and extreme high-temperature, precipitation and drought events increasing result in vegetation phenology great changes (such as vegetation germination, flowering, fruit ripening and yield development and related physiological processes changes) (Wang et al., 2019; Hong et al., 2019; Yuan et al., 2020). A series of vegetation phenology changes inevitably affect the interaction between different species and nutrient levels, and the composition in the community, which in turn affects the balance of the entire ecosystem (Shen et al., 2020). Therefore, in the era of rapid climate change, how to accurately monitor vegetation phenology on a large scale and adjust the annual cycle of plant growth to adapt to related environmental factors changes is important not only for individual survival, but also for understanding the environmental changes of phenology.

Currently, numerous studies have demonstrated that global warming promotes spring vegetation phenology, including forests and grasslands in temperate and cold regions (Zhang et al., 2021; H.Fu et al., 2020). Studies have shown that start of the growing season (SOS) was advanced every decade by an average of 0.9 d, 4.2 d, and 4.7 d in the United States, China, and Europe respectively, from 1982 to 2011 (Ahas et al., 2002; Fu et al., 2015; Rice et al., 2018; Kong et al., 2017; Fu et al., 2021; Shen et al., 2014). However, the climate warming has not resulted in a continuous or stable evolution of plant phenology. For example, Shen et al. (Shen et al., 2014) found that the vegetation SOS was delayed in the southwestern QTP, while advanced in other areas from 2000 to 2011. However, Zhou et al. (Zhou et al., 2018) found that the SS of shrub-tussock in the southeastern and desert in the northwestern region of the QTP were delayed, and end of the growing season (EOS) showed a delaying trend. Kong et al. (Kong et al., 2017) also pointed out that the vegetation SOS was advanced by 2 to 3 d and EOS was delayed by 1 to 2 d every decade on the QTP. Researchers have different conclusions on the grassland phenology. This reasons might be because the spatiotemporal distribution of precipitation and soil evapotranspiration have undergone major changes due to climate warming, but different regions and grassland types have different degree of response to this change (Fu et al., 2021; Zhou et al., 2018;Meng et al., 2017). Some studies also found that spring phenology of cold grasslands was significantly advanced with climate warming, especially in Tibet and high-latitude regions, while spring phenology of seasonally dry grasslands was advanced slowly or even delayed with climate warming (Crabbe et al., 2016; Sun et al., 2020; Nagy et al., 2013; Shen et al., 2015; Wu et al., 2016). This is because the spring phenology of cold and dry grasslands is mainly affected by temperature and moisture, respectively (Liu et al., 2016; Gao et al., 2015; Wang et al., 2019; Ren et al., 2018). The SOS is more sensitive to pre-season temperature than precipitation in relatively humid areas, but contrary to dry regions on the QTP (Wang et al., 2012; Gao et al., 2017; Scurlock et al., 1998; Zhang et al., 2019; Chen et al., 2015; He et al., 2018). Meanwhile, Studies (Li et al., 2017; Ma et al., 2016) also found that the changes of SOS and EOS were related to altitude. SOS starts early and late in low and high altitude areas, respectively (Ma et al., 2016). Although there are different studies of vegetation phenology on the QTP (Kong et al., 2017; Shen et al., 2014; Zhou et al., 2018; Meng et al., 2017), but grassland phenology and the main driving factors of how phenology changes have not been well studied. QTP as the third pole on Earth, has the largest alpine grassland ecosystem in the world. It is also one of the most important grazing zones in Asia. Its ecological process has a unique barrier effect to protect the ecological security of East Asia, (Zhang et al，2002; Yu et al，2011). However, previous research results showed that there were still great controversies about the changes and causes of phenology (Kong et al，2017; Shen et al，2014; Zhou et al，2018; Meng et al，2017), and monitoring phenology is one of the important tasks of grassland ecosystem long-term management. Therefore, we still need to pay attention to grassland phenological studies at all times.

This paper used NDVI data to identify the phenological indicators of multi-grassland and analyzed their responses to various environmental factors on the QTP from 2000 to 2019. The main objective of this research is to: (1) investigate the temporal and spatial patterns of grassland phenology; (2) analyze the characteristically changes of multi-grassland; (3) analyze the sensitivity of grassland phenology to different environmental factors and (4) assess the impact of environmental factors such as altitude, average annual climate, extreme climate, solar radiation, drought, evapotranspiration etc. on multi-grassland phenology.

2 Materials And Methods

2.1 Study Area

The Qinghai-Tibet Plateau (26°00'12"N ~ 39°46'50"N, 73°18'52"E ~ 104°46'59"E, QTP), as the highest plateau in the world, has a huge area, staggered geographical elements and strong spatial heterogeneity. There are the Himalayas in the south, Kunlun, Altun and Qilian Mountain in the north, and the Amur Plateau and Karakoram Mountain in the west. Its average altitude is more than 4 km. It is the birthplace of many major rivers in China, covering an area of about 2.57 km$\times 10^6$ km^2. The average temperature is about 20 °C in the southeast, but only - 6 °C in the northwest. As the warm and humid air flow is blocked by high mountains in the south, the precipitation is 2000 mm in the southeast and less than 50 mm in the northwest. The annual sunshine hours range from 2500 to 3200 h, the difference in temperature between day and night is significantly large, and there are dry and humid days. Winter is long and dry, and summer is cool and rainy. QTP has rich vegetation types (Zhang et al，2002; Yu et al，2011). According to the vegetation zoning data of China (Su et al，1996), it is mainly divided into 6 vegetation zones: I (mountain meadow), II (temperate steppe), Ⅲ (shrub-tussock), Ⅳ (desert), Ⅴ (alpine steppe) and VI (alpine meadow). Since 74.79% of the area is moderately vulnerable, climate change in recent years has added further uncertainty to the fragile ecological coefficient of the QTP (Ma et al，2016) (Fig．1a, 1b, 1c).

2.2 Data

2.2.1 Remote sensing data

(1) Normalization difference vegetation index (NDVI): The NDVI was derived from MODIS VI of the MOD13A1 product with a spatial resolution of 250 m and a temporal resolution of 16 d provided by the Google Earth Engine platform (https://code.earthengine.google.com/, GEE) from 2000 to 2019. The data from the standard level-3 products were synthesized into 16 d maximum values after geometric and atmospheric correction by maximum synthetic algorithm. Although the NDVI data synthesized by

maximum synthetic algorithm can be affected to some extent by the sensor observation angle, solar altitude angle, and clouds, there were still some abnormal values. Therefore, this study used the Hants method to denoise NDVI time series data, and internationally used NDVI annual mean value of 0.05 as a threshold to exclude outliers, so that pixels with an annual NDVI of less than 0.05 were excluded from the study area (He et al，2018). In this work, NDVI was used to extract phenological parameters of grassland and calculate the temperature vegetation drought index (TVDI).

(2) Land Surface Temperature (LST): LST was derived from MOD11A2 of the GEE platform, with a spatial resolution of 1 km and a temporal resolution of 8 days from 2000 to 2019. The data from LST were corrected for terrain and used to calculate the TVDI product.

(3) Evapotranspiration (ET): ET was obtained from the MOD16A2 product provided by the GEE platform with a spatial resolution of 500 m and a temporal resolution of 8 d. Daily average meteorological analysis data from MODIS and 8-d remote sensing vegetation attribute dynamics were used as input, taking into account vegetation cover, albedo, air temperature, air pressure and relative humidity, and other information. The surface evapotranspiration data were obtained using Penman-Monteith algorithm. Previous studies have shown that although MOD16A2 was overestimated or underestimated in some areas, its accuracy can meet the requirements of large-scale applications (Dong et al，2016; Kong et al，2019).

(4) Digital Elevation Model (DEM) Data: DEM from the Resources and Environmental Sciences Data Platform of Chinese Academy of Sciences (http://www.resdc.cn/Datalist1.aspx?FieldTyepID=4) with 1-km. ArcGIS was used in data processing by reclassification and extraction.

2.2.2 Phenological validation data

Phenological validation data come from the National Ecological Science Data Center (http://rs.cern.ac.cn/order/myDataOrders) including phenological observation data from Haibei Station (Fig．1b), which record the germination, flowering, seed setting, seed dispersal and leaf yellowing stages of grassland. Since the phenological period of ground observation was observed from the individual scale of plants, in order to increase the comparability of validation data, the data whose recording time is more than 30-days different from other data were excluded with reference to previous studies (Zhang et al，2021; Gao et al，2015), and the germination and wilted period of ground observation station data were defined as grassland SOS and EOS, and finally calculated as Julian day to remain consistent with remote sensing monitoring results.

2.2.3 Climate data

Climate data were acquired from China Meteorological Data Network (http://data.cma.cn/data/cdcindex). The daily data provided include daily temperature, precipitation, daily maximum/minimum temperature, precipitation, and sunshine hours over the period time of 2000- 2019. The solar radiation data was obtained based on sunshine hours. First, the quality of the selected data was controlled according to

Rclimdex, and 38 meteorological stations in the study area were selected (Fig1c). Then, the common climate indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDMI) were used to select the seven climate indices defined in Table 1, which intended to reflect the marginal state of temperature events and the extreme state of precipitation events (Wang et al2019; Frich et al 2002). Rclimdex were used to calculate the interannual time series of seven extreme climate indexes, and the Anuspline software was used to obtain the grid data.

The environmental factors determined r are shown in table 1.

Table 1. The definitions and classifications of multiple environmental factors.

Indicators.	Definitions
SR	Solar radiation
TVDI	Temperature vegetation dryness index
MAP_SUM	Yearly mean accumulated rainfall
RX1	Yearly maximum consecutive one-day precipitation
RX5	Yearly maximum consecutive five-day precipitation
DTR	Yearly mean difference between maximum temperature and minimum temperature
MAT_MEAN	Yearly mean value of temperature
MAT_MAX	Yearly mean value of daily maximum temperature
MAT_MIN	Yearly mean value of daily minimum temperature
TNN	Yearly minimum value of daily minimum temperature
TNX	Yearly maximum value of daily minimum temperature
TXN	Yearly minimum value of daily maximum temperature
TXX	Yearly maximum value of daily maximum temperature

2.3 Methods

2.3.1 Calculation method of TVDI

Price et al. (Price et al1985) and Sandholt et al. (Sanholt et al2002) found that the scatter plot between NDVI and LST was a triangle when the range of variation between vegetation cover and soil water content is large. Moran et al. (Moran et al2000) also found that there was some relationship between minimum surface temperature and vegetation cover and types. Therefore, the temperature-vegetation-drought index (TVDI) was proposed to estimate soil water on the land surface. The calculation formula of TVDI is (1):

$$TVDI = (Ts - Tsmin)/(Tsmax - Tsmin) \quad (1)$$

Where Ts is the surface temperature; Tsmax is the highest surface temperature and Tsmin is the lowest. The dry wet edge equation can be expressed as (3) and (4):

$$Tsmax = a1 + b1 * NDVI \quad (2)$$

$$Tsmin = a2 + b2 * NDVI \quad (3)$$

Where: a_1, b_1, a_2 and b_2 are the coefficients of dry and wet edge fitting equation respectively; NDVI is the normalized vegetation index.

2.3.2 Phenological extract methods

According to the characteristics of the NDVI time series curve of the QTP, the dynamic threshold method proposed by Jünsson et al. (Jönsson et al，2002) was used to set different NDVI thresholds on the pixel scale to obtain the grassland SOS and EOS of each pixel. Through repeated experiments, the extraction thresholds of SOS and EOS were 20% and 50%, respectively i.e. the threshold point of SOS corresponds to 20% of the distance between the maximum and minimum of NDVI curve in the rising stage; The EOS threshold point is 50% of the distance between the maximum and minimum values of NDVI curve.

2.3.3 Trend analysis

The Sen et al. (Sen et al，1968) trend analysis method, which can effectively reduce the influence of outliers, observation errors, and disturbance of outlier data, was used to estimate the change trend of grassland phenology on the QTP.

$$\beta = \text{Median}\left\{\frac{x_j - x_i}{j - i}\right\}, \forall\ j > i \qquad (4)$$

Where ⯑ is the change trend of grassland phenology; *Median* is the median function; i, j ($2000 \leq J \leq 2019$) is the temporal sequence of phenology, x_i and x_j represent the corresponding phenological values of i and j, respectively.

2.3.4 Importance of environmental factors analysis method

Random Forest (RF), an ensemble learning algorithm proposed by Breiman in 2001, which combines multiple decision trees to improve the regression or classification number performance of a single tree. A decision tree represents a set of constraints organized hierarchically from root to leaf (Xie et al，2015). In the Random Forest regression model, the importance of each variable was ranked by the percentage increase in mean squared error (%Inc MSE) to evaluate the influence of each independent variable on the dependent variables. First, the Ntree (number of decision trees) of the decision tree model was constructed and the mean square error of the out-of-bag (OOB) random substitution was calculated. Therefore, RF was used to rank the effects of different environmental factors on grassland phenology

2.3.5 The relationship between phenology and sensitivity environmental factors

Pearson correlation analysis method was used to analyze the correlation between sensitive environmental factors and grassland phenology in 20 years (Zhang et al，2021), and 95% significance test was carried out:

$$r = \frac{N \sum x_i y_i}{\sqrt{N \sum x_i{}^2 - (\sum x_i)^2} \sqrt{N \sum y_i{}^2 - (\sum y_i)^2}} \qquad (5)$$

Where r is the correlation coefficient; x_i is the environmental index data of i year; y_i is the grassland phenology data of i year.

3 Results

3.1 Spatial patterns of multiyear mean phenology indicators

Fig．2 showed the spatial distribution of multi-grassland phenology during 2000 to 2019. Results showed that the grassland SOS was mainly concentrated in the period of 140–170 d (pixels accounted for 83.25%), and advanced gradually from south to north. The SOS after the 170th d were mainly distributed in the southernmost part of Mount Qomolangma. The SOS before the 100th d were mainly distributed in the Qaidam Basin. The SOS in the west was about 10-20 d advanced than that in the east of the Tanggula Mountains (Fig． 2a). Among them, the SOS of alpine steppe and alpine meadow was advanced than other grasslands, and concentrated after the 150th d. The SOS of mountain meadow, shrub-tussock, desert and temperate steppe was earlier than 140th d.The spatial distribution of the same grassland type was gradually delayed from northwest to southeast, but not consistent in the Mount Kallash (Fig．2b). The reason was that, Mount Kallash is located on the southern slope of the Himalayas, which when blocked by the mountain vein, and warm air flow slowly, resulting in low temperatures.

The grassland EOS was delayed from south to north. The earliest EOS was in Mount Karakoram and Kallash, and the latest EOS was around Qaidam Basin (Fig．2c). Among them, the EOS of temperature steppe, alpine steppe and alpine meadow was delayed and concentrated before 270 d, while that of mountain meadow and shrub-tussock was advanced and was essentially after 250 d (Fig．2d).

3.2 Spatial patterns of multiyear change trend of phenology indicators

The results of analyzing the grassland phenology trend in the last 20 years, showed that 60.5% of SOS had a significant advancing trend. The advancing trend of SOS was the most obvious with a trend of 1.5 d/a in the east, while not obvious in the west of Tanggula Mountains. 39.5% of SOS showed the delaying trend and distributed mainly in Mount Kallash (Fig 3a). The SOS of desert started earliest, and the alpine steppe started the latest and was fluctuated around 155 d. The SOS of other grasslands was concentrated at 140-155 d (Fig 3b).

37.15% of EOS showed an advancing trend, and the advancing rate was concentrated in 0 ~ 0.5 d/a. The EOS of shrub-tussock was relatively late, and was concentrated between 275 and 285 d (Fig 3c). The EOS of the other grasslands concentrated between 265 and 275 d, and the change was relatively stable with a small-scale increase (Fig 3d).

3.3 Variation characteristics of grassland phenology with altitude gradient

In general, altitude affects regional climate, which affects the distribution and grassland growth. Considering that the extremely high altitude area may be disturbed by snow and other uncertain factors, this study analyzed the distribution regulation and change rate of grassland phenology with an altitude of 2500-4500m and an increasing interval of 100m. The result showed that when the altitude was lower than 3100 m, the SOS advanced at a rate of 1.9 d every 100 m with altitude rising. When the altitude was between 3100 m and 3300 m, the SOS remained unchanged. For altitude greater than 3300 m, the SOS delayed by 0.01 d every 100 m with increasing altitude. The change trend became smaller with increasing altitude in altitude lower than 3600 m. When the altitude was higher than 3600 m, the advance trend of SOS decreased with altitude increasing (Fig 4a). The EOS advanced with increasing altitude, but the advancement rate was not as high when the altitude was lower than 2900 m. When the altitude was lower than 3000 m, the delaying trend of EOS increased rapidly with altitude increase. The delaying rate of EOS remained stable with increasing altitude between 3000 m and 4100 m, but increased with altitude increase in the range above 4100 m (Fig 4b).

3.4 The change traits of different environmental factors

The time course of the environmental index was shown in Fig 5. The MAP _SUM varied greatly in different years, as high as 530 mm in 2005, and decreases at a rate of (2.12 mm)/a. SR was relatively stable before 2015 and fluctuated strongly after 2015, with increasing rate of (82.19J/m2)/a. RX1day, TNN, TXX, TNX, and TVDI were decreased with proportion of (1.30°C)/a, (0.07°C)/a, (0.84°C)/a, (1.03°C)/a and (0.002°C)/a, respectively. The RX5day, MAT_MEAN, DTR, MAT_MAX, MAT_MIN and TXN were increased with proportion of (0.005°C)/a, (0.03°C)/a, (0.15°C)/a, (0.02°C)/a, (0.07°C)/a and (0.24°C)/a, respectively. In general, the temperature index mainly increases, while the precipitation and the drought index decreased (Fig 5).

3.5 The Importance of multiple environmental factors to grassland Phenology

The random forest regression algorithm (RF) could convert the value of a variable into a random number, with larger values indicating the greater importance of the variable. Based on the RF, the degree of influence of different environmental factors on grassland SOS and EOS was analyzed on the QTP. It was found that grassland SOS was mainly influenced by TXN, TNX, RX5day, TNN, TVDI and SR, and % IncMSE was more than 45 (Fig 6SOS). EOS was less influenced by environmental factors than SOS, and the main influencing factors were TVDI, TNX and MAT_ MEAN, MAT_ MAX, MAT_ MIN and TXX, and % IncMSE were more than 30 (Fig 6EOS).

3.6 Environment controls of spatial patterns of multiyear mean phenology indicators in different grasslands

Due to the different habitats and biological characteristics, the multi-grassland phenology respond differently to the various environmental factors. Fig 7 showed the correlation coefficient between phenology metrics and different sensitive environmental factors, and the results showed that there were significant positive correlations between SOS and TXN, TNX, RX5day, TNN, TVDI, but no significant negative correlations between SOS and SR. Among them, Mountain meadow had the highest positive correlation with TVDI (SOS delayed with increasing TVDI) and negative correlation with SR. The SOS of temperate steppe was positively correlated with TNX, TNN, and TVDI, but insignificant with RS. The correlation coefficient between shrub-tussock and TNN was the largest, but the correlation with other environmental factors was insignificant. There was significant positive correlation between desert and RX5day, but low correlation between desert and other environmental factors. The phenology of alpine steppe was significantly positive correlation with RX5day, TNX and TVDI. The phenology of alpine meadow had no significant influence with TXN and RS, but significantly positive correlation with TNX, RX5day, TNN and TVDI.

There was a negative correlation between EOS of multi-grassland and sensitive climatic factors. Among them, the negative correlation between phenology of mountain meadow and sensitive factors was not significant. Phenology of temperature steppe and MAT_MEAN and MAT_MAX showed a significant negative correlation. There was no significant positive correlation between phenology of shrub-tussock and TVDI and TXX, that is, EOS was delayed with the increase of TVDI and TXX. There was no significant positive correlation between phenology of desert and other environmental factors. The phenology of alpine steppe was mainly influenced by TNX and MAT_MAX. There was a significant negative correlation between phenology of alpine meadow and MAT_MIN and TVDI.

4 Discussion

4.1 Trends in grassland phenology

We analyzed the dynamics of different grasslands phenology on the QTP from 2000 to 2019. The results showed that the SOS had a significant advance trend in the eastern and central areas with lower altitude, but an extremely insignificant change in the southwestern areas with altitude above 5000 m. This study suggested that climate variables (such as precipitation, extreme climate, and evapotranspiration) might be related to the changes in the advanced SOS and global warming, and the spring phenology changes could not be used directly as an indicator of climate warming. Therefore, it is impossible to answer climate warming questions using only phenological metrics, especially in high altitude area of southwest QTP. EOS was significantly delayed, especially in the Southwestern regions, but not obvious in the central and northern regions (main grassland types are desert, temperate steppe, alpine steppe and alpine meadow). Previous studies found insignificant change in EOS, but temperate steppe showed a significant change (Li et al，2018; Yang et al，2015).In this study, it was found that the desert EOS was delayed, and the trend was more obvious, but the changes in other regions were not obvious. At the same time, a recent study by Professor He of the State Key Laboratory of Grassland Agroecosystems of Lanzhou University found that the QTP had experienced long-term and rapid climate change over the past 50 years, and climate warming had promoted the early SOS of alpine vegetation, which resulted in an increase biomass in the spring but accelerated growth in the middle of the growing season, leading to a water deficit and accelerating the progression of the EOS. This conclusion was consistent with the findings of many researchers such as Huang et al. (Huang et al，2019) and Ma et al. (Ma et al，2016), but it contradicts with the results of Meng et al. (Meng et al，2017) and Zhou et al. (Zhou et al，2018). Scholars have different results on the grassland phenology, whose reason might be that the study period was different, which leaded to inconsistent results. Secondly, it might be due to diverse temporal and spatial distribution pattern of environmental factors in different regions. Although warming temperatures had greatly changed spring phenological events, different regions and multi-grassland respond differently to this change. For example, climate warming promotes spring phenology of cold grasslands, especially in high latitude regions, while spring phenology in seasonally dry grasslands advanced slowly or even delayed with the climate warming. This was mainly because the spring phenology of cold and dry grasslands was more sensitive to temperature and moisture, respectively (Kong et al，2017; Fu et al，2021; Shen et al，2014).

4.2 Relationship between grassland phenology metrics and altitude

Grassland phenology change was periodic and continuous dynamic process. There are many factors impacting phenological changes (Ren et al，2018; Shen et al，2014). Studies have found that the grassland phenology changes significantly and exist differently in grassland growth rates on different altitudinal gradients on the QTP (Liu et al，2020; Shen et al，2014). We also found that SOS was gradually advanced at a rate of 1.9 d per 100 m with the increase of altitude in areas below 3100 m. In areas with altitude higher than 3300 m, SOS was gradually delayed and the change rate of SOS showed significant differences with changing altitude. Grassland EOS delayed with increasing altitude, but there were obvious differences in the rate of delay. Our research results were more consistent with the conclusions of Li et al. (Li et al，2017) and Park et al. (Piao et al，2003) that altitude had an important influence on grassland phenology on the QTP. Not only did temperature decrease with increasing altitude, but related studies have also found that the rate of warming was greater at high altitude than low altitude (Li et al，2017). In this study, it was also found that the response of grassland SOS to temperature was more significant than that of precipitation and showed a significant positive correlation with temperature. In the lower altitudes of Qinghai, Gansu and Xinjiang, SOS was positively correlated with temperature, but SOS showed a significant negative correlation with temperature at higher altitudes of Tibet. In Gansu around Qaidam Basin, temperature and precipitation have a lagging effect on EOS. There were some spatial differences in the grassland phenology at different altitudinal gradients on the QTP due to the spatial differences of temperature and precipitation in latitudinal zone. In the eastern regions with lower altitude, grassland SOS showed a significant advance trend, while in these areas of the south and west higher altitude, grassland SOS showed delaying trend, which may be the result of the combined effect of increasing temperature.

4.3 Relationships between grassland phenology metrics and environmental factors

Temperature and precipitation were considered important climatic factors affecting grassland phenology (Gao et al., 2015; Wang et al., 2019), but compared to average climate change, the occurrence of extreme weather events and droughts was sudden, predictable and destructive, and might have a greater impact on the grassland phenology. Therefore, it might affect the structure, composition and function of terrestrial ecosystems severely due to sudden environmental factors change, thereby affecting the grassland growth cycle, grassland productivity and yield (Yuan et al., 2020; Shen et al., 2020; Nagy et al., 2013). But there were few studies on the effects of drought, evapotranspiration, solar radiation and extreme climate on grassland phenology on the QTP. This study analyzed the sensitivity of grassland SOS and EOS to various environmental factors based on the random forest algorithm. The results showed that grassland SOS was mainly influenced by TXN, TNX, RX5day, TNN, TVDI and SR, while EOS was mainly influenced by TVDI, TNX, MAT_MEAN, MAT_MAX, MAT_MIN and TXX (Fig. 6).

The relationship between the sensitive environmental factors and phenology was analyzed: ①SOS of multi-grassland was positively correlated with TXN, TNX, RX5day, TNN and TVDI, and negatively correlated with SR. According to the changes in environmental indicators (Fig. 7), the decrease in TNN, TNX, TVDI and RX5day and the increase in TXN and SR could advance the grassland SOS. This conclusion also further confirmed that higher temperatures were required for grassland dormancy and spring regeneration, and the increase in temperature increases the warmth of grassland germination and leaf expansion (Luedeling et al., 2009; Zhang et al., 1995). And some studies have also found that the increase in temperature increases the decomposition rate of soil organic matter and the nutrients in the soil are more easily mineralized and made available to the grassland, which was conducive to the entry of grassland to phenological phase (He et al., 2018). Some studies have found that spring temperature increased affects grassland growth in arid areas due to water stress in the soil, resulting in restricted grassland growth and delayed phenology [54], which depends on temperature, solar radiation and precipitation matching grassland phenology with factors such as soil type. These above conclusions could provide a theoretical basis for the research conclusions of this paper. ②EOS was mainly negatively correlated with TVDI, TNX, MAT_MEAN, MAT_MAX, MAT_MIN and TXX. According to the changes in environmental indicators (Fig. 7), the main reason for the grassland EOS change might be the decrease in average annual TVDI and the increase in annual average temperature, annual maximum temperature, annual minimum temperature and extreme daily maximum temperature on the QTP. Some studies have shown that grassland in arid and semi-arid areas consists mainly of xerophytes and strong xerophytes. Therefore, the influence of precipitation on EOS was much greater than the influence of temperature on EOS in the growth phase, mainly because precipitation could alleviate water stress in the soil so that grass cannot enter the yellowing phase earlier, and the increase in temperature decreases the moisture content of the soil, causing grassland to enter the yellowing phase earlier (Wang et al，2016). Grasslands were mainly located in dry areas in eastern and northern regions of the QTP. The growth of grassland in summer was highly stressed by drought. After autumn, the temperature dropped rapidly and the growth period of grassland was shorter. The results of this study further showed that the main influence to EOS was temperature on the QTP, and Liu et al (Liu et al，2016) also confirmed that the grassland demand of water decreases in autumn and the temperature rose increases the activity of photosynthetic enzymes and slowed down the decomposition of chlorophyll. This conclusion also showed that increasing in different temperature were also important factors that lead to grassland EOS changes.

4.4 Differences of grassland phenology between ground-monitoring, previous studies and remote-sensing inversion

On the QTP, the limiting precipitation, strong solar radiation and high evaporation result in sparse grasslands growth in some regions. Grassland coverage in these regions is low, less than 20% and even less than 5% in some regions. Therefore, the background information may be contaminated by the target signal (mainly soil). In desert coverage regions, the sensitivity of the sensor to the detection of grassland spectral information is reduced, with weak absorption valleys and reflection peaks, which leads to the grassland spectral information collected from remote sensing images to be extremely weak and difficult to detect. MOD13Q1 product covers a large area, and there may be some errors in the process of inversion. Thus, in Fig，8 and Table 2, the correlation coefficient (r) between remotely sensed grassland SOS and ground-measured SOS was 0.637 ($P<0.05$), the Bias was 0.321 and the RMSE was 5.95 d. The r between remotely sensed EOS and ground-measured EOS was 0.776 ($P<0.05$), the Bias was 0.241 and RMSE was 5.07 d. Validation results showed that remotely sensed SOS and EOS provided earlier data than ground-based observations, but the results were well correlated. At the same time, the results of the whole QTP were compared with the results of Deng et al. (Deng et al，2020), Ma et al. (Ma et al，2016), Li et al. (Li et al，2014) and Kong et al. (Kong et al，2017). Li et al. (Li et al，2014) found that the EOS was concentrated at 240-300 d in the Qinghai Basin, which was quite different from our results, but the results of this study were similar to those of Deng et al. (Deng et al，2020) and Kong et al. (Kong et al，2017). The distribution was more consistent. The reason could be that Li et al. (Li et al，2014) used EVI data and the main area, but this article and other researchers used NDVI data. The used of difference VI led to large differences in the phenology extraction. In addition, the phenological data from ground stations were used to verify the calculated phenological results. These results indicated that phenology data can be used to obtain the grassland SOS and EOS on the QTP.

Table 2 Comparison of phenological results between this paper and other studies

Study area	study phase	SOS(d)	EOS(d)	Data Resources	Literature Reference
QTP	1999~2009	120~170	250~300	SPOT	Deng et al，2020
QTP	1982~2015	130~180	280~330	GIMMS NDVI	Ma et al，2016
Qinghai lake watershed	2001~2012	110~150	240~300	MODIS EVI	Li et al，2014
QTP	1982~2013	115~125	260~300	GIMMS NDVI3g	Kong et al，2017
QTP	2000~2019	140~170	250~280	MODIS NDVI	This paper

4.5 Limitations and future directions

This study attempted to explore how multi-grassland were influenced by multiple environmental factors on the QTP. However, the grassland type are abundant, with significant vertical zonality, and different grassland types and flowering functional groups have diverse sensitivity to different environmental factors change on the QTP, such as sherry et al. (Sherry et al，2007) found that grasslands of early flowering functional group were more sensitive to cooling. Wang et al. (Wang et al，2014) found that grassland mid-flowering functional group were more sensitive to temperature increasing than decreasing, and the phenological period of species had the different response to environmental factors. Even under the same hydrothermal conditions, especially in the alpine zone, the germination and phenological characteristics of multi-grassland were also different. Although we conducted some useful research on the response of multi-grassland to environmental factors change based on relatively remote sensing data on the QTP, we neither considered the differences in individual characteristics of grasslands affected by environmental factors, nor the influence of factors such as rainfall duration and soil water-holding capacity on grassland phenology such as the findings of Cong et al. (Cong et al，2013) and Jin et al. (Jin et al，2009). This study presented different environmental factors on an annual scale without considering seasonal characteristics. In the future research, we should also consider whether phenological periods of multi- grassland have different responses to seasonal environmental factors from the seasonal scale.

5 Conclusions

Our study of multi-grassland spring and autumn phenology constitutes an important framework for the analysis of how ecosystems respond to different environmental factors on the QTP from 2000 to 2019. Generally, the grassland SOS change was mainly related to the decrease of TNN, TNX, TVDI and the increase of RX5day and SR. The grassland EOS change was mainly related to the decrease of TVDI, TNN, MAT_MEAN, MAT_MAX and MAT_MIN. Furthermore, SOS and EOS were more sensitive to drought and extreme climate and varied with different grassland types. This study indicated that grassland will be most susceptible to future extreme climate and mega-drought events on the QTP. The comparative analysis of how multi-grassland phenology responds to different environmental factor has provided a template for further studies to measure and predict the response of grassland to future climate conditions. Further research is still needed into how season multiple extreme climate and drought may conjointly influence the dynamics of multi-grassland phenology.

Declarations

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Author's Contribution Gexia Qin: Conceptualization, Investigation, Data Curation, Writing Original Draft. Jing Wu: Term, Resources, Supervision, Project administration, Funding acquisition. Chunbin Li: Writing - Review & Editing. Adu Benjamin: Writing - Review & Editing.

Availability of data and material The datasets analyzed during the current study can all be obtained from publicly accessible archives.

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Conflicts of Interest The authors declare that they have no competing interests.

Code availability The code generated during the current study available from the first author on reasonable request.

Informed Consent Statement Not applicable.

Ethics approval We guarantee that the work described has not been submitted elsewhere for publication, and all the authors listed have approved to submit the manuscript.

Consent to participate The Author agrees to publication in the Theoretical and Applied Climatology and also to publication of the article in English by Springer in Theoretical and Applied Climatology.

Consent for publication The author confirms that its publication has been approved by the responsible authorities at the institution where the work is carried out.

Consent to participate The author agree to participate in Theoretical and Applied Climatology

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Figures

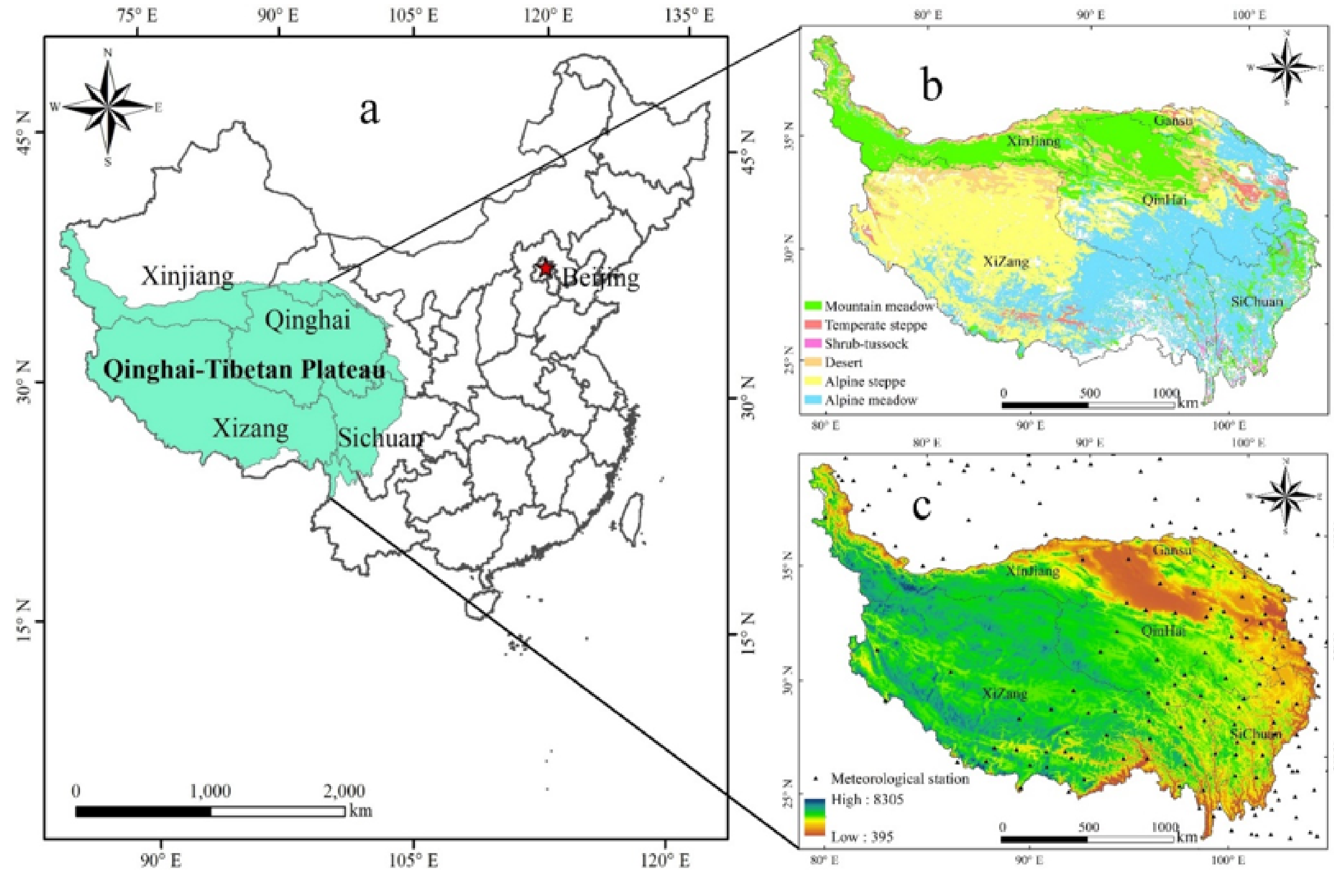


Figure 1

Geographic location of the study area (a), indicates the grassland types (b) and the distribution of altitude and meteorological stations (c) on the QTP++++++++++++++++++0

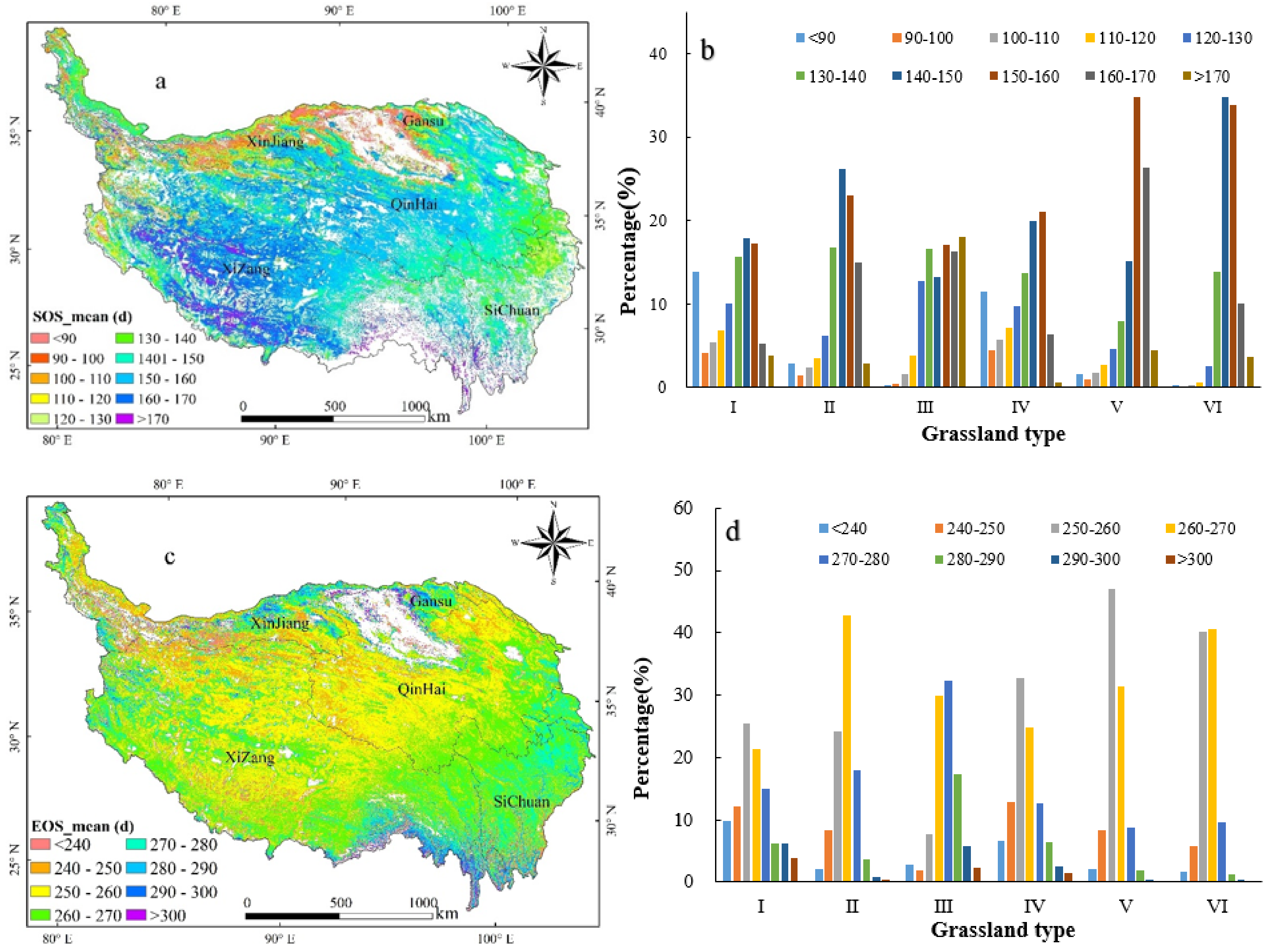


Figure 2

Spatial distribution of grassland start of the growing season (a) and end of the growing season(c), statistical map of multi-grassland of start of the growing season (b) and end of the growing season(d) on the QTP from 2000 to 2019.

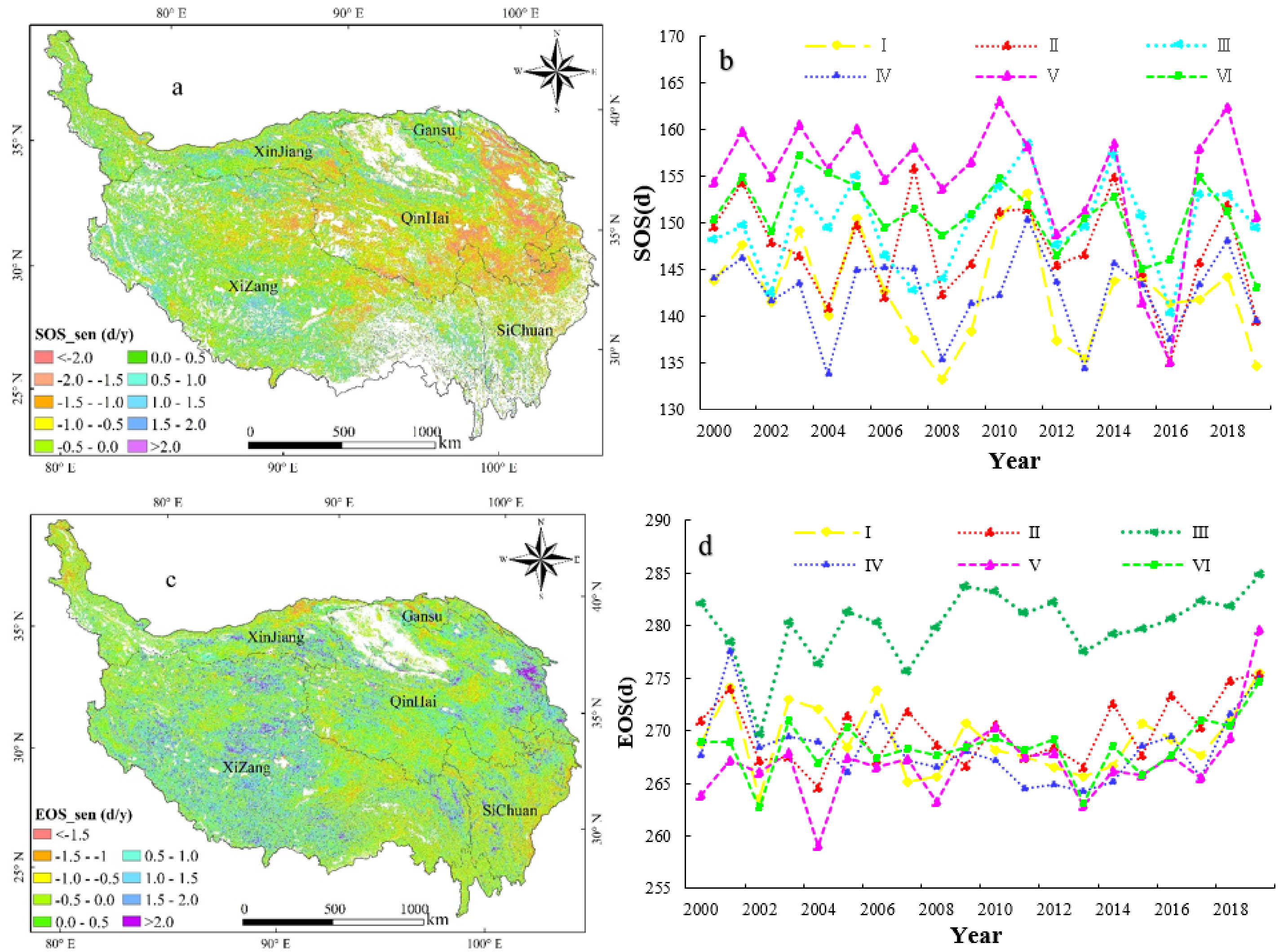


Figure 3

Spatial distribution of change trend of start of the growing season (a) and end of the growing season(c), statistical change trend of multi-grassland of start of the growing season (b) and end of the growing season (d) on the QTP from 2000 to 2019

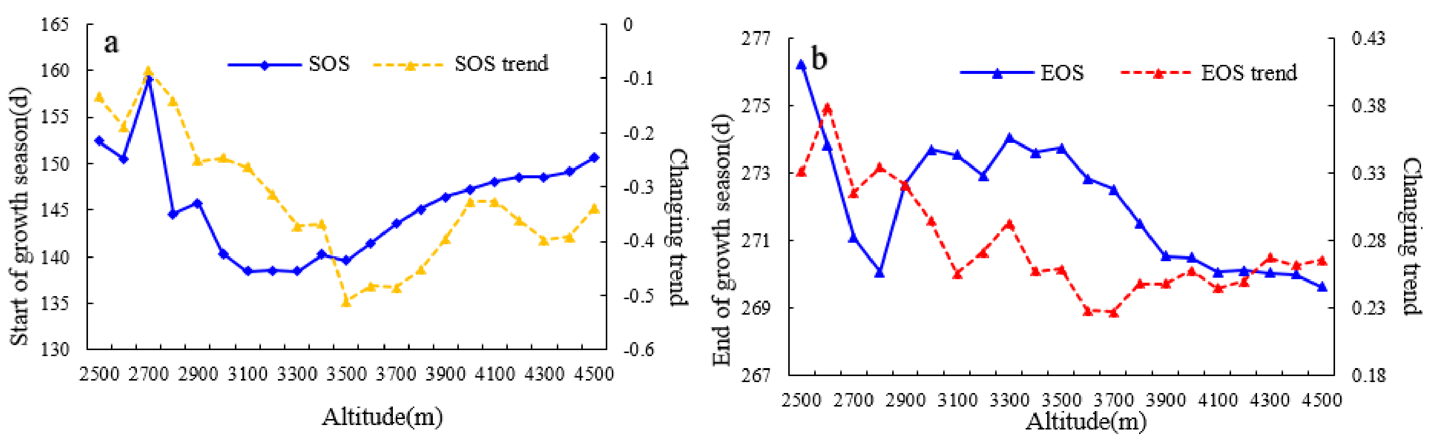


Figure 4

Relationship between start of the growing season (a), end of the growing season(c) and altitude of the QTP from 2000 to 2019

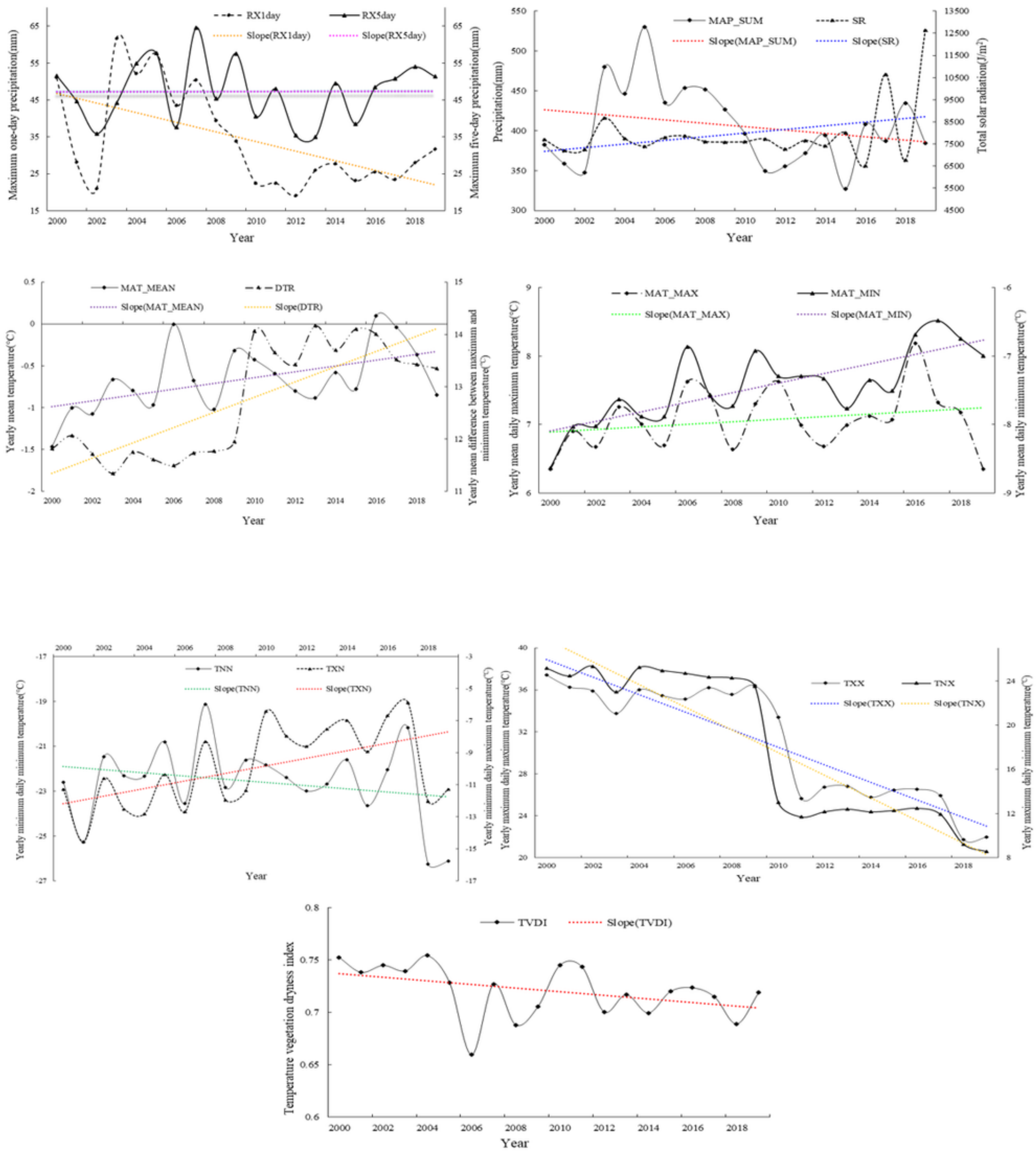


Figure 5

The temporal variation characteristics of environmental indices

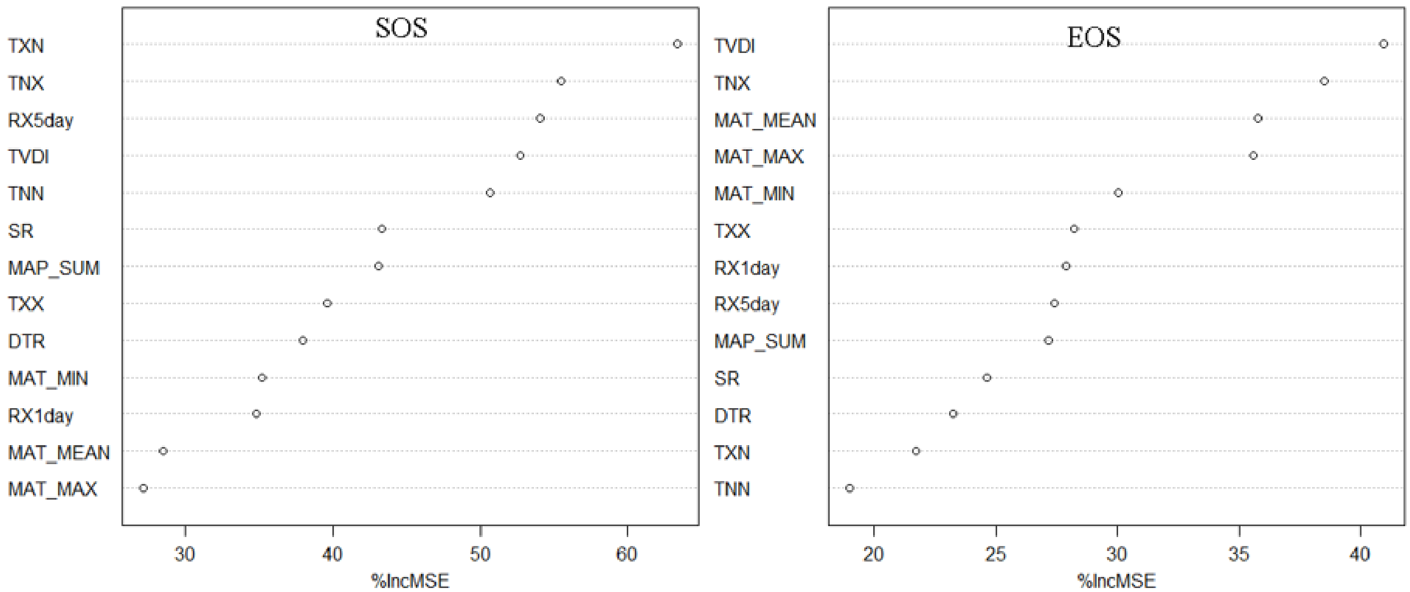
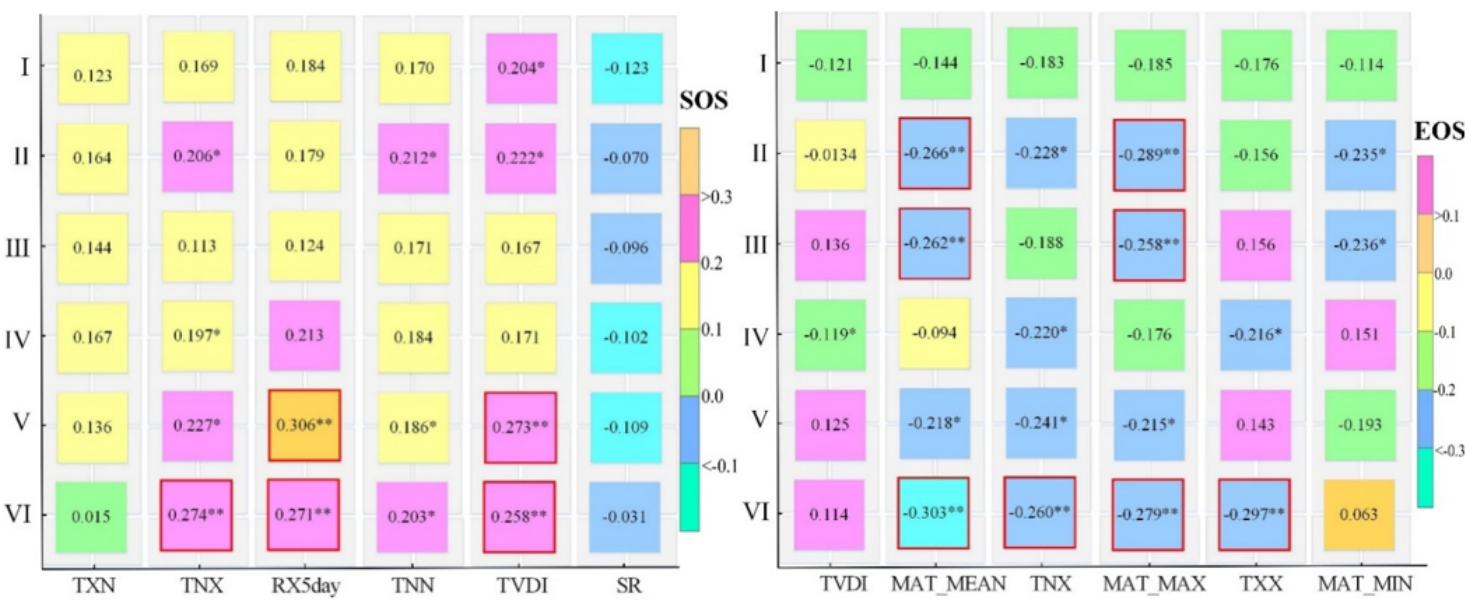


Figure 6

The importance of the multiple environmental factors to the phenology parameters start of the growing season (SOS) and end of the growing season (EOS), estimated as the percentage increase in the mean square error (% Inc MSE) of the multi-grassland.



Note: I: mountain meadow; II: temperate steppe; III: shrub-tussock; IV: desert; V: alpine steppe; VI: alpine meadow

Figure 7

The relationship between phenology and sensitivity climatic factors

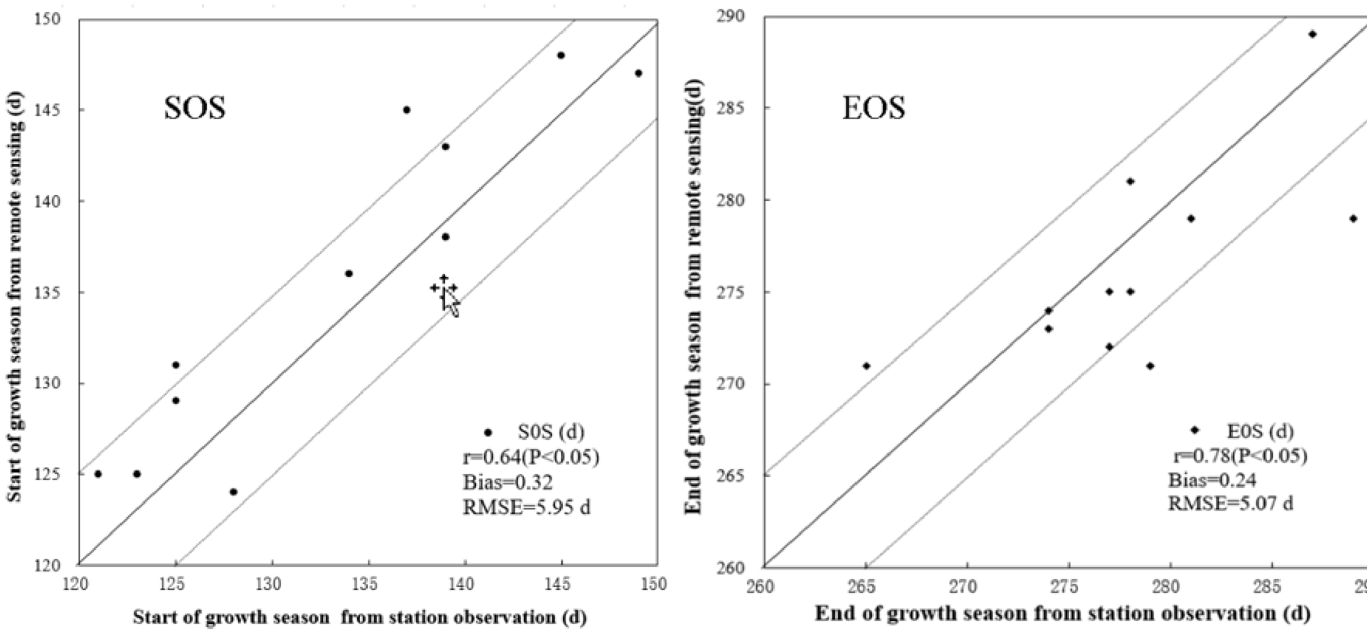


Figure 8

Comparison of start of the growing season (SOS) and end of the growing season (EOS) monitoring results and site measurement data on the QTP

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- GraphicalAbstract.jpg