Grassland Phenology in Different Eco-Geographic Regions over the Tibetan Plateau

Jiahua Zhang, Qing Chang, Fengmei Yao

***Abstract*—**Studying on the response of vegetation phenology to climate change at different temporal and spatial scales is important for understanding and predicting future terrestrial ecosystem dynamics and the adaptation of ecosystems to global change. In this study, the Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI) dataset and climate data were used to analyze the dynamics of grassland phenology as well as their correlation with climatic factors in different eco-geographic regions and elevation units across the Tibetan Plateau. The results showed that during 2003–2012, the start of the grassland greening season (SOS) appeared later while the end of the growing season (EOS) appeared earlier following the plateau's precipitation and heat gradients from southeast to northwest. The multi-year mean value of SOS showed differences between various eco-geographic regions and was significantly impacted by average elevation and regional average precipitation during spring. Regional mean differences for EOS were mainly regulated by mean temperature during autumn. Changes in trends of SOS in the central and eastern eco-geographic regions were coupled to the mean temperature during spring, advancing by about 7d/°C. However, in the two southwestern eco-geographic regions, SOS was delayed significantly due to the impact of spring precipitation. The results also showed that the SOS occurred later with increasing elevation, as expected, with a delay rate of 0.66 d/100m. For 2003–2012, SOS showed an advancing trend in low-elevation areas, but a delayed trend in high-elevation areas, while EOS was delayed in low-elevation areas, but advanced in high-elevation areas. Grassland SOS and EOS changes may be influenced by a variety of other environmental factors in each eco-geographic region.

***Keywords*—**Grassland, phenology, MODIS, eco-geographic regions, elevation, climatic factors, Tibetan Plateau.

I. Introduction

PLANT phenology is a seasonal phenomenon related to the interaction of plants with climate and other environmental factors, and is the rhythm of growth and development that plants have adapted to, based on surrounding environmental conditions over longer time periods [1]. Phenology is a sensitive and critical feature of vegetation and has become the best indicator for climate change studies [2], [3]. In recent years, satellite sensors have become an important tool for detecting patterns of vegetation phenology and for providing temporally continuous observations from regional to global scales [4], [5]. However, previous studies indicate that the characteristics of vegetation phenology and its impacting factors in recent years have widely changed and are different for different regions. Normalized difference vegetation index (NDVI) analysis for the period of 1981 to 2003 showed a global advancement in spring dates of 0.38 days per year [6]. In North America, SOS advanced by 3.2 days from 2000 to 2008 [7]. The spring SOS appeared earlier by 8days and lasted 4 days longer because of a marked warming during spring during 1981 to 1991 between 45°N and 70°N [4]. In the temperate region of China, the growing season has lengthened for 1982–1999 by 1.16 days per year as the greenness of vegetation has advanced in spring by 0.79 days per year [8].

The Tibetan Plateau (TP) contains a large area of alpine grassland accounting for approximately 53% of the entire region. The grassland of the TP is extremely sensitive to climate change because of the low-humidity and high-elevation conditions [9]-[14]. Yu et al. reported a non-continuous changing trend of the TP grassland as the SOS dates advanced between 1982 and mid-1990 [9], while a delayed onset of spring greenness has occurred since 2000 on the TP, which might be caused by warm wintertime conditions. However, the results indicating delayed trend were questioned [12]. By integrating three long-term time series datasets of NDVI, Zhang et al. concluded that the alpine vegetation SOS on the plateau experienced a continuously advancing trend at a rate of 1.04 d/y during 1982–2011 [13].Contrary to this, Shen et al. found no change in green-up dates after correcting for the impact of an increased non-growing season NDVI. Controversy over vegetation phenology change on the TP still exists and the reasons causing this change remain unknown. More research is needed to explore vegetation changes related to climate change on the TP [14].

All abovementioned studies regarding the overall trend of TP phenology were based on the entire area of the TP. However, under the influence of complicated environmental conditions on the TP, grassland phenology varies from region to region and has no spatial uniformity. Some studies indicated that the response of grassland phenology to climatic variability appeared to vary with vegetation type, temperature during different months, and elevation [10], [11]. However, spatial patterns of grassland phenology were far more complicated than expected from these factors alone. Proportion and distribution of grassland where SOS advanced were uncertain for different time periods and different research results were proposed [15], [16]. In order to determine a rule for the spatial variability of vegetation phenology over the TP, it is necessary to analyze the changing characteristics of vegetation phenology and its influencing factors in different regions.

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II. Data and Methods

A. Study Area

An eco-geographic regional system is a hierarchical system, which is defined by demarcation or combination of natural features based on geographic relationships and by comparing major ecosystem factors (including biological and non-biological) and geographic zonalities [17]. The system consists of three levels: temperature zone, humidity region, and natural region. Alpine grasslands on the TP are mainly distributed in five regions: HIIC1, HIIC2, HIC1, HIC2, and HIB1 (Fig. 1). The phenology research based on eco-geographic regions has significant potential to explore characteristics of spatial change and interactions of alpine grassland with various controlling factors on the TP. In this study, we have analyzed the grassland phenology characteristics of five eco-geographic regions and will discuss the following two issues: (1) multi-years mean alpine grassland phenology in eco-geographic regions of the TP for 2003–2012, including causes for regional differences; and (2) trends in phenology change in response to multiple factors in eco-geographic regions of the TP during the last ten years.

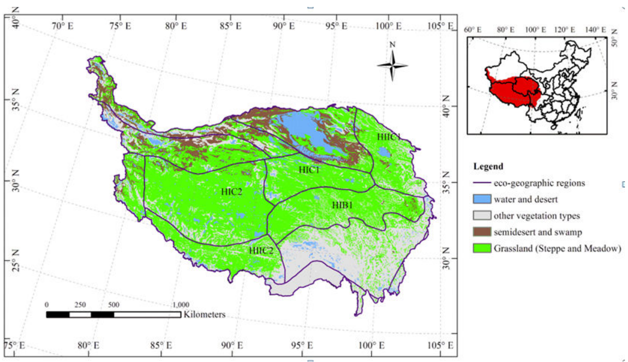

Fig. 1 Eco-geographic regions and the distribution of alpine. Grassland on the TP. HI: plateau sub-cold zone; HII: plateau temperate zone; B: sub-humid region; C: semi-arid region. The study area consists of five regions: (1) HIB1: Sichuan, Qinghai, and Xizang high mountain and valley alpine shrub-meadow region; (2) HIC1: South Qinghai Plateau and wide valley alpine meadow-steppe region; (3) HIC2: Qiangtang Plateau lake basin alpine steppe region; (4) HIIC1: Qilian Mountains of east Qinghai high mountain and basin coniferous forest and steppe region; (5) HIIC2: South Xizang high mountain and valley shrub-steppe region.

B. Datasets and Methods

The Normalized Difference Vegetation Index (NDVI) time series datasets for the Tibetan Plateau are used in this study. The datasets are MODIS 16-day MVC products (MOD13Q1) with 250 m spatial resolution, for the period of 2003 to 2012. The data are corrected for geometric error, atmospheric effects, sensor degradation, and cloud contamination. In order to produce high-quality NDVI time series datasets, the improved Savitzky–Golay (S–G) filter method was used in this study [18].

Prior to the filtering stage, the time series data were processed as follows: (1) to eliminate the soil background effect, pixels with 10-year average NDVI values of less than 0.1 were considered non-vegetated areas and were masked in MODIS NDVI data sets [19], [20]; (2) pixels covered with clouds or snow/ice that were identified in the pixel reliability data layer were replaced by linearly interpolated values using adjacent points that were not identified as noise points [21].

The daily temperature and precipitation data on the TP were collected by the China Meteorological Data Sharing Service System, and spatially distributed meteorological data were calculated with a spatial resolution of 250 m using the Inverse Distance Weighted (IDW) method. Considering elevation effects on climate, the temperature was corrected based on the digital elevation model (DEM) for the region, following the rule that there is a temperature decrease of 0.6°C for every 100m elevation increase. The DEM was SRTM3 data with a spatial resolution of 90 m. To match the resolution of the meteorological data to the NDVI data, we averaged the meteorological data to half-month values.

A dynamic-threshold algorithm was used to extract the phenology metrics [22], which include SOS and EOS for each pixel of grassland on the Tibetan Plateau. On this basis, the grassland multi-year mean SOS, EOS, and changes in their trends for different eco-geographic regions during the period of 2003–2012 were calculated. Considering the characteristics of grassland on the Tibetan Plateau, the SOS NDVI threshold was set to 20% of the distance between the minimum and maximum levels of NDVI value during the NDVI rising stage (see (1)). The EOS was determined in a similar way [16]. As an example, the extraction of SOS and EOS for 2005 is shown in Fig. 2.

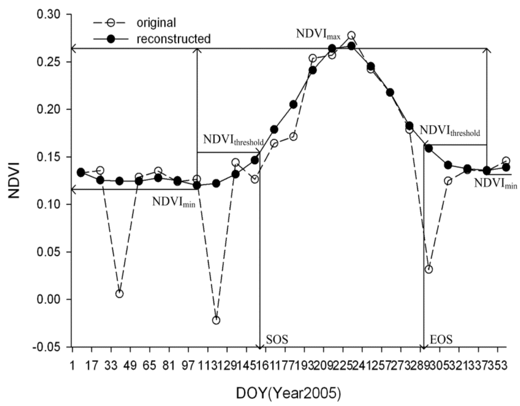

Fig. 2 Extraction of phenology metrics based on reconstructed NDVI time series

The specific steps are as follows: first, the maximum NDVI value ($NDVI_{max}$) of the year was searched; then, during the NDVI rising stage, the minimum NDVI value ($NDVI_{min}$) was obtained and 20% of the difference between $NDVI_{max}$ and $NDVI_{min}$ was set as the threshold ($NDVI_{threshold}$). The date when NDVI grows to $NDVI_{threshold}$ for the first time was defined as SOS. EOS was defined in the same way during the descending stage.

$$NDVI_{threshold} = NDVI_{min} + (NDVI_{max} - NDVI_{min}) \times 20\% \quad (1)$$

A linear regression model was used to detect trends of phenology during 2003–2012 on the TP, and the P-value was used to check for statistical significance.

III. Result and Discussion

A. *Phenology Characteristics at the Scale of the Entire TP*

1. Spatial Patterns of Phenology Characteristics

Multi-year mean status and temporal trend of grassland SOS and EOS varied greatly from 2003 to 2012 across the Tibetan Plateau were showed in Fig. 3.

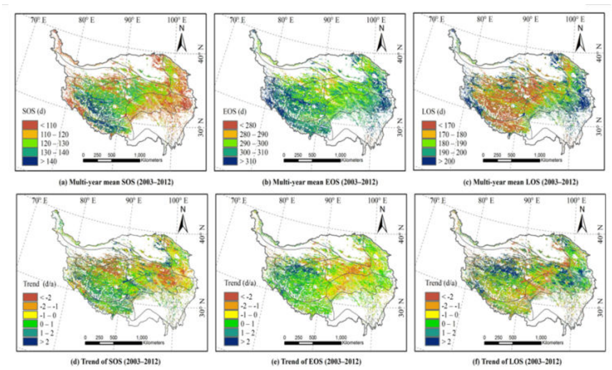

Fig. 3 Spatial patterns of phenology metrics on the TP

Grassland in the eastern and southeastern part of the TP showed earlier multi-year mean SOS and an advancing trend of SOS, with a gradually later and more delayed trend towards the northwest. Meanwhile, grassland in the southwestern part showed the latest multi-year mean SOS with the largest delay. Such spatial patterns were consistent with reported findings [11], [15], and can be well explained with the southeast–northwest water and heat gradient. However, the spatial characteristics of grassland EOS seem more complicated and showed no significant change from southeast to northwest, while most areas in center showed an advancing trend.

We analyzed the dynamic SOS and EOS trends for the entire grassland for the past 10 years. For the period of 2003–2012, SOS advanced by 0.015 d/y while EOS was delayed by 0.028 d/y. However, grassland SOS and EOS showed no continuously advancing trend. There difference change trends in different time periods.

2. Spatial Patterns of Phenology–Climate Relationships

To evaluate the relationship between phenology and climatic factors, correlation coefficients (*r*) were calculated for each pixel (Fig. 4). The results showed that the sensitivity of grassland phenology to climatic factors was not uniformly distributed on the TP. In addition, the response of grassland phenology to climate change appears to be complicated and no obvious regularity was found. Spatial patterns of SOS–climate relationships on the TP indicated that SOS has a significant negative correlation with T-Spring in the east of the TP but a positive correlation in the southwest. In the southwest, SOS showed a negative correlation with P-Spring and a positive correlation with P-winter. Finally, in the east, SOS was observed to have a positive correlation with T-Winter and a negative correlation with P-winter. Similarly, the sensitivity of grassland EOS to climatic factors was different in different parts of the TP (Fig. 5). Of the grassland EOS, 67.86% showed a positive correlation with T-Autumn as higher temperatures during autumn provided more favorable conditions for sustainable growth of grassland (Fig. 5 (a)). Nevertheless, the spatial distribution of the grassland phenology–climate relationship seemed to be consistent with the distribution of eco-geographic regions. Thus, it is necessary to analyze the characteristics of grassland phenology in eco-geographic regions and explore relationship patterns between grassland phenology and growing environment.

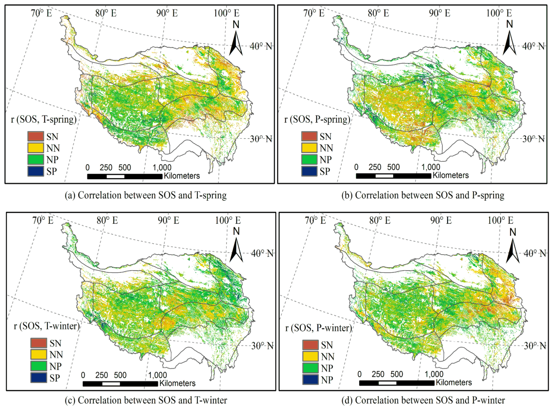

Fig. 4 Spatial pattern of SOS–climate relationship on the TP; SN and SP: significant negative & positive correlation ($p < 0.05$), respectively; NN and NP: non-significant negative & positive correlation, respectively

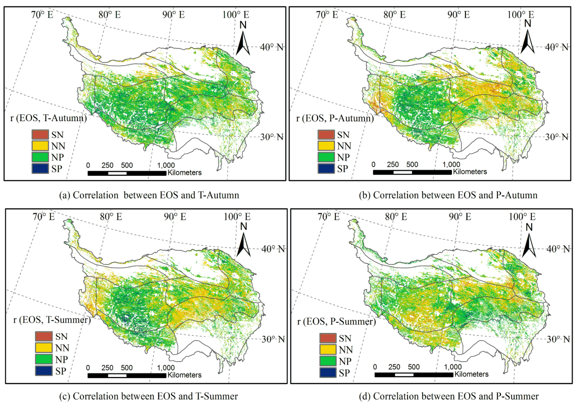

Fig. 5 Spatial pattern of EOS–climate relationship on the TP

B. *Phenology Characteristics in Eco-geographic Regions*

The dynamics of grassland phenology in different eco-geographic regions were calculated and were shown in Fig. 6, including multi-year mean SOS and EOS and trend of SOS and EOS for each eco-geographic region.

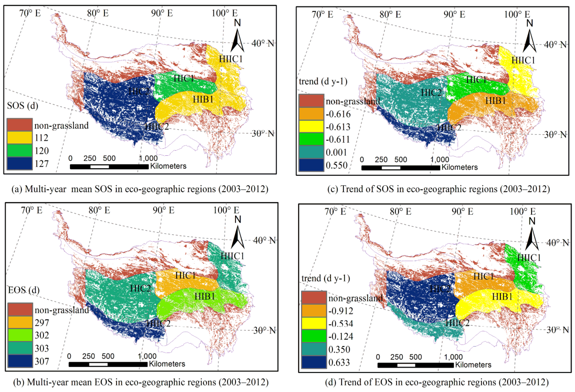

Fig. 6 Characteristics of grassland phenology metrics in different eco-geographic regions of the TP during 2003–2012. (a) & (b): multi-year mean SOS and EOS; (c) & (d): multi-year change in trends for SOS and EOS

The results indicate that grassland phenology has different characteristics in each of the five chosen eco-geographic regions on the TP. In order to explore possible causes for these differences, we analyzed meteorological and geomorphological factors in the different regions. Considering that for most of the alpine grassland, SOS is between April and May, the mean temperature and precipitation for these two months (T-Spring and P-Spring) were used in estimating the influence of meteorological factors on spring phenology. For the autumn phenology (EOS), the meteorological factors for September and October were selected (T-Autumn and P-Autumn). Temperature and precipitation were calculated using data from the China Meteorological Data Sharing Service System.

1. Multi-year Mean SOS and EOS

As shown in Fig. 6 (a), the multi-year mean SOS of the three regions located in central and eastern part of the TP (HIIC1, HIC1, HIB1) are earlier than those of the two southwestern regions (HIC2 and HIIC2), with a maximum time difference in SOS of 15d (Fig. 6 (a)). Compared to HIIC2, the multi-year mean SOS for HIIC1 was much earlier due to higher temperature, lower elevation, and more precipitation. Similarly, among the three plateau sub-cold zone regions, HIB1 showed the earliest SOS because of its high spring temperatures, more precipitation, and lowest average elevation. However, HIC1 showed an earlier SOS than HIC2, in spite of its lower spring temperature, which might be severely affected by higher precipitation. Multi-year mean SOS of HIIC1 and HIIC2, which both belong to the plateau temperature zone, were not earlier than in the other three plateau sub-cold zone regions (HIC1, HIC2, HIB1). This may be attributed to the differences between regional average elevations. Furthermore, T-Spring in HIB1 was considerably lower than in HIIC1 and HIIC2, but multi-year SOS of HIB1 was not later than in those regions, which might be due to abundant precipitation in the sub-humid region. In other words, it appears that precipitation is not the primary controlling factor for SOS in the eco-geographic regions located in the sub-humid region. Accordingly, multi-year mean SOS of eco-geographic regions of the TP may not be simply affected by a single factor.

A linear regression analysis was used to explore the relationship between the regional multi-year mean SOS and regional environmental factors (average elevation, T-Spring, and P-Spring). The results showed that the alpine grassland's multi-year mean SOS is significantly impacted by P-Spring, and the influence of average elevation and T-Spring is insignificant. Meanwhile, if there is more spring precipitation, SOS appeared earlier in the same temperature zone. Thus, our findings are in agreement with published results that precipitation is a main controlling factor for plant growth on the Tibetan Plateau [23].

As shown in Figs. 6 (b) and (d), grassland EOS in HIC1 appeared earliest and has the most obvious trend in advancement. Linear regression between multi-year mean EOS and regional climate factors in the selected eco-geographic regions were calculated. The results show that the multi-year mean EOS is almost consistent with the T-Autumn status of the eco-geographic regions. However, the correlation with both regional P-Autumn and average elevation is insignificant. Affected by temperature, multi-year mean EOS in plateau sub-cold zone regions was earlier than in plateau temperate zone regions. Moreover, multi-year mean EOSs showed relatively smaller differences between each another compared to multi-year mean SOSs.

2. Multi-Year Trends of SOS and EOS

Over the past ten years, the SOS and EOS of all central and eastern TP eco-geographic regions (HIIC1, HIC1, HIB1) showed a significant advancing trend, while the southwestern regions (HIC2, HIIC2) showed delaying trend (Table I).These results are very similar to results from previous studies, which reported that areas with advancing SOS and EOS are mainly distributed in the eastern part of the plateau [11], [15]. Changes of annual mean SOS, T-Spring, and P-Spring for different regions during 2003–2012 are shown in Fig. 7. Spring temperature in all study regions showed an increasing trend under the influence of global warming. Now the question arises how changes in meteorological factors might affect grassland phenology in different eco-geographic regions. Regression models for regional annual mean SOS and regional annual mean meteorological factors (P-Spring, T-Spring) were calculated (Table I).

The regression results indicate that the dominant factors for grassland phenology are different even within the same temperature zone or within the same humidity region.

In addition, SOS trends in the central and eastern regions (HIIC1, HIC1, HIB1) showed a considerable negative relationship with T-Spring, advanced by about 7 days/°C, and were influenced by the climate warming during the last decade. However, trends of SOS in the two southwestern regions (HIC2, HIIC2) were obviously regulated by P-Spring. This phenomenon may be explained by a lack of precipitation in the western regions. As already known, the topography in the HIC2 and HIIC2 regions is very complex, elevations are higher, the terrain is mountainous, and climatic conditions are strongly impacted by geography. Moreover, HIC2 is surrounded by high mountains, and HIIC2 is passed through by Himalayas, the climate in north and south sides of the mountains remained quite different. Among the five study regions, P-Spring in HIC2 is lowest, which may be the reason why SOS in HIC2 is more sensitive to a decrease in spring precipitation.

TABLE I
LINEAR REGRESSIONS FOR START OF SEASON (SOS) AND MEAN SPRING TEMPERATURE (T-SPRING) AND MEAN SPRING PRECIPITATION (P-SPRING)

Regions	Regression model	r^2	p
HIIC1	SOS=-7.583T-Spring+133.96	0.362	0.066
	SOS=0.068P-Spring+103.82	0.051	0.531
HIIC2	SOS=0.824T-Spring+125.47	0.023	0.676
	SOS=-0.087P-Spring+134.16	0.395	0.052
HIC1	SOS=-7.182T-Spring+110.23	0.362	0.066
	SOS=-0.141P-Spring+130.81	0.111	0.347
HIC2	SOS=-2.525T-Spring+126.30	0.120	0.326
	SOS=-0.191P-Spring+137.48	0.376	0.059
HIB1	SOS=-7.092T-Spring+117.48	0.040	0.050*
	SOS= 0.077P-Spring+124.02	0.041	0.573

In a comparison between EOS and SOS, the response of EOS to meteorological factors was much more complex. It seemed that the changes of EOS trends in the western regions (HIC2, HIIC2) were more related to autumn temperature, while the other regions showed no strong correlations with T-Autumn or P-Autumn.

C. Relationship between Phenology and Elevation

1. Relationship between Multi-Year Mean Phenology Characteristics and Elevation

Elevation was divided into units of 100 m for each level and vegetation phenology characteristics in different units were investigated (Fig. 7).

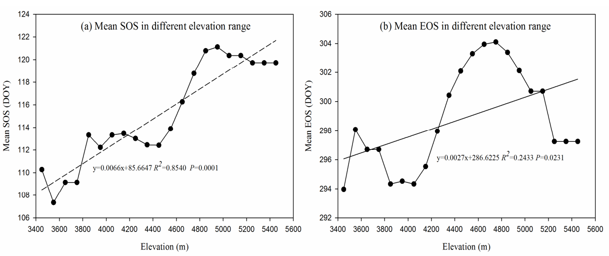

Fig. 7 Multi-year mean SOS and EOS (2003–2012) for different elevation units

The results (Fig. 7 (a)) show that, as expected, SOS occurs later with increasing elevation, and the rate of SOS change was 0.66 d/100 m for 2003–2012. However, SOS was not delayed continuously with a rise in elevation, but remained unchanged at elevations above 5000 m. Based on these observations; we conclude that vegetation phenology changes are more sensitive to global change in low-elevation areas. The results of least square fitting show no significant linear relationship between EOS and elevation (Fig. 7 (b)). Interestingly, EOS advances with an increase of elevation in high-elevation areas (above 4800 m) whereas it is significantly delayed in low-elevation areas. This may be because plant growth is affected by a number of environmental factors and highlights the diversity of physiological and ecological characteristics of a region [24].

2. Relationship between Phenology Trends and Elevation

For each elevation unit, the rate of phenology change was analyzed (Fig. 8). Results show that SOS advanced during 2003–2012 in low-elevation areas but showed a gradual delayed trend at higher elevations (above 4800m), while EOS was delayed in low-elevation units but advanced in high-elevation units. In Fig. 8, the slope of the trend for low-elevation units was greater than that for high-elevation units, which indicates that SOS and EOS changed more significantly in the low-elevation areas than in the high-elevation areas.

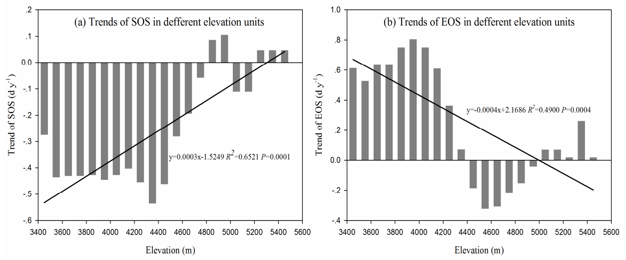

Fig. 8 Changes in trends of mean SOS and EOS (2003–2012) for different elevation units

IV. CONCLUSION

In this study, we have extracted the phenology metrics (SOS and EOS) of alpine grassland for different eco-geographic regions of the Tibetan Plateau based on 250-m, 16-day MODIS NDVI time series from 2003 to 2012,and analyzed the response of phenology to meteorological and geomorphological factors, as well as phenology changes in grassland regions of the plateau. The grassland phenology characteristics varied in different eco-geographic regions. There is no clear evidence that precipitation was the dominating factor in the arid regions or that temperature was the dominating factor in the cold regions. In the central and eastern three regions, multi-year mean SOS occurred earlier and showed an advancing trend, while in the southeastern regions; multi-year mean SOS occurred later and showed a delaying trend over the past 10 years. Our analysis shows that precipitation was a significant cause for the multi-year mean SOS differences between eco-geographic regions, with average elevation differences being of secondary importance. Temperature, in contrast, caused multi-year mean EOS regional differences. However, the response of phenology trends to meteorological factors was not the same in all study regions over the past decade. Further study is needed on human-induced grassland degradation, which is still expanding and has a significant effect on vegetation phenology [25]. Deciphering the impacts of various environmental and anthropogenic factors on vegetation phenology of the TP remains a challenge for further studies.

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