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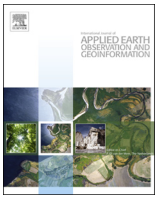

Biological and climate factors co-regulated spatial-temporal dynamics of vegetation autumn phenology on the Tibetan Plateau

Jiaxing Zu[a,b], Yangjian Zhang[a,b,c,*], Ke Huang[a], Yaojie Liu[a,b], Ning Chen[a,b], Nan Cong[a]

[a] Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China
[b] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, China
[c] Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing, China

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ABSTRACT

Climate change is receiving mounting attentions from various fields and phenology is a commonly used indicator signaling vegetation responses to climate change. Previous phenology studies have mostly focused on vegetation greening-up and its climatic driving factors, while autumn phenology has been barely touched upon. In this study, vegetation phenological metrics were extracted from MODIS NDVI data and their temporal and spatial patterns were explored on the Tibetan Plateau (TP). The results showed that the start of season (SOS) has significantly earlier trend in the first decade, while the end of season (EOS) has slightly (not significant) earlier trend. In the spatial dimension, similar patterns were also identified. The SOS plays a more significant role in regulating vegetation growing season length than EOS does. The EOS and driving effects from each factor exhibited spatially heterogeneous patterns. Biological factor is the dominant factor regulating the spatial pattern of EOS, while climate factors control its inter-annual variation.

1. Introduction

Vegetation phenology is finely tuned to environments and has a close relationship with climates (de Jong et al., 2011; Garonna et al., 2016). Shifts in phenology also affect feedbacks of vegetation to climate by influencing regional to global carbon budgets, fluxes of water, and energy balance (Ganguly et al., 2010; Richardson et al., 2013; Wang et al., 2017). Previous phenology studies have been mainly focused on start of season (SOS) and some showed earlier spring extended growing season length over the past three decades (Park et al., 2016; Piao et al., 2007; Wang et al., 2017). The end of season (EOS) can play an equally important role in determining growing season length, while its changes remain less studied. The reason might lie in that autumn phenology is controlled by a complexity of environmental and biological factors (Barichivich et al., 2013; Liu et al., 2016; Way and Montgomery, 2015). Researches on EOS changes are essential to improve autumn phenology models and enrich our understanding on carbon cycles in the context of ongoing global climate changes.

Remote sensing can deliver valuable information in monitoring vegetation dynamics of a variety of ecosystems, including grasslands, forests and croplands (Gonsamo and Chen, 2016; Zhao et al., 2015). Phenology analysis facilitated by remote sensing-based NDVI data have been conducted at various spatial scales (Butt et al., 2011; Fu et al., 2014a; Jeong et al., 2011). Vegetation phenology exerts significant effects on ecosystem productivity (Dragoni et al., 2011; Duveneck and Thompson, 2017; Schwartz et al., 2006; Wu et al., 2013). It has been suggested that earlier trend of spring phenology enhances vegetation activity and increases spring carbon uptake (Wang et al., 2017; Wolf et al., 2016), while warming autumn offset parts of increased spring carbon dioxide uptake by stronger ecosystem respiration (Piao et al., 2008). Meanwhile, extended growing season length is positively correlated with GPP and NPP (Kang et al., 2016; Piao et al., 2007). Clearly, growing season length is influenced by SOS and EOS, while their relative contribution to the growing season length varies geographically. In the Northern Hemisphere, the EOS variations are greater than those of SOS. It indicates that lengthened growing season was mainly attributed to EOS (Garonna et al., 2014; Tang et al., 2015b). While at the circumpolar scale, contributions of autumn phenology to growing season length are stronger than those of spring phenology (Park et al., 2016; Zhao et al., 2015). In view of these scenarios and their varying contributions to carbon cycling, knowledge on the relative role played by SOS and EOS is essential to climate change research.

Compared with SOS, variations of EOS and its driving factors are more elusive (Che et al., 2014; Gallinat et al., 2015). Previous studies

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[*] Corresponding author at: Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China.
E-mail address: zhangyj@igsnrr.ac.cn (Y. Zhang).

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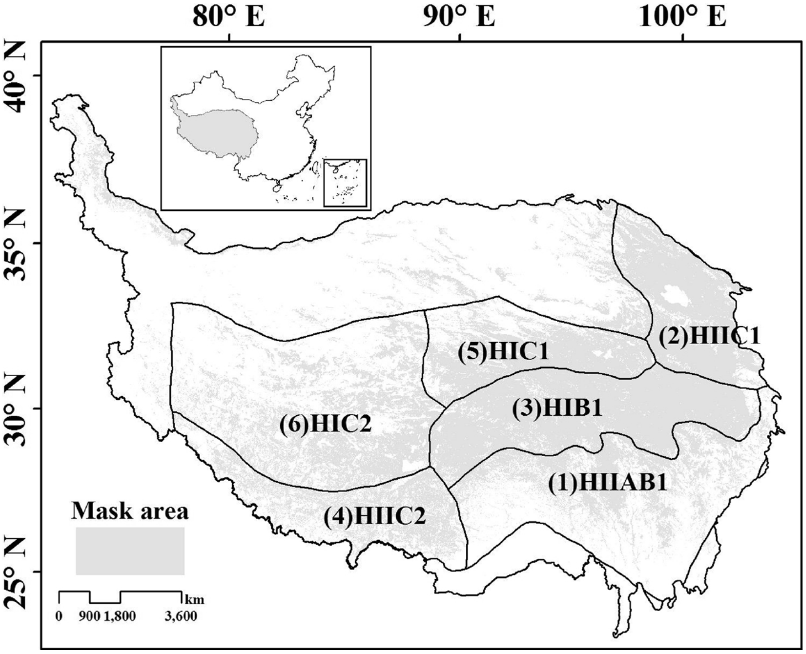

Fig. 1. Mask area and eco-regions. (1) HIIAB1: Western-Sichuan and Eastern-Tibet mountains and valleys region. (2) HIIC1: Eastern Qinghai-Qilian mountains region. (3) HIB1: Guoluo-Naqu Alpine region. (4) HIIC2: Southern-Tibet mountains region. (5) HIC1: Southern-Qinghai plateau valley region. (6) HIC2: Qiangtang plateau lake basin region.

have noted that warmer temperature would benefit vegetation growth and thus postpone onset of senescence (Jeong et al., 2011; Piao et al., 2006). In water constrained areas, increased temperature exacerbates moisture stress on vegetation and its limitation effects (Tang et al., 2015a; Yang et al., 2015). Solar radiation can also exert considerable influences on autumn vegetation activity by retarding abscisic accumulation and increasing photosynthetic active radiation (PAR), subsequently slowing leaf senescence (Kong et al., 2017; Liu et al., 2016). On the other hand, for ecosystems receiving inadequate autumn solar radiation, contribution effects of extending autumn phenology and promoting photosynthesis from other climatic factors are weakened (Richardson et al., 2010). Besides climate factors, biological factors can also affect EOS due to a fact that plant life-cycle stage depends on the previous ones. Both field experiments and model results showed that vegetation SOS regulates EOS (Cong et al., 2016; Fu et al., 2014b; Keenan and Richardson, 2015; Liu et al., 2016). The peak growth in summer, conventionally indicated by maximum NDVI, can also cause lag effects on subsequent autumn phenology (Wolf et al., 2016). Our current knowledge on the physiological mechanism of EOS is in shortage in regard to the complex interactions among these driving factors. It severely undermines our capacity in predicting growing season length.

Response of vegetation ecological processes to climate change can exhibit nonlinear (Park et al., 2015). The boosted regression trees (BRT) is a relatively new technique and can account for the non-linear processes largely (Elith et al., 2008). One advantage of the BRT model lies in its capability handling different types of predictor variables without prior data transformation or outliers elimination. Due to its high efficiency in handling a mixture of climate and other types of variables, recently the BRT has been widely applied on ecology researches (Leathwick et al., 2006; Liu et al., 2013).

The Tibetan Plateau represents an extreme environment due to its cold, dry and high altitude conditions. Over the past decades, temperature has been rising on the TP significantly and caused obvious impacts on vegetation growth (Yu et al., 2010; Zhang et al., 2013). However, our knowledge on confounded effects from physiological and biological factors on autumn phenology is still in severe shortage (Shen et al., 2015). To fill the gap, this study was aimed to investigate the temporal trends of vegetation EOS and their spatial variability on the TP, as well as the relative contributions of biological and climate factors. Specifically, the objectives were to: 1) quantify the relative contribution of SOS and EOS to growing season length; 2) identify the main biological and climate driving forces on autumn phenology. The findings of this study would shed light on the mechanisms behind the EOS dynamics.

2. Methodology

2.1. Study area and data sources

The Tibetan Plateau is located in the southwest China, and its main part includes Qinghai and Tibet provinces. Its spatial extent spans from 25.9 to 35.8°N to 73.4 to 104.6°E, covering a total area of $2.58 \times 106\ \mathrm{Km}^2$. Precipitation decreases from more than 1000 mm in southeast to 100 mm in northwest and reaches the maximum in summer, while annual mean temperature increases from lower than −8 °C to 8 °C from northwest to southeast. Steppe and meadow make up most of the land cover on the TP.

The MODIS NDVI dataset (MOD13A2) was utilized in extracting vegetation phenology from 2000 to 2015 (https://ladsweb.nascom.nasa.gov/search/). The 16-day temporal resolution data produced by MVC (Maximum Value Composite) method can eliminate noises caused by cloud, atmosphere and solar elevation angle to some extents. Daily temperature and precipitation data with a spatial resolution of $0.1^\circ \times 0.1^\circ$ was provided by Cold and Arid Regions Science Data Center (http://westdc.westgis.ac.cn) at Lanzhou. To fit all data to the same resolution, we resampled climate data to the same resolution as MODIS data. Moreover, eco-region data is provided by Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn).

Considering the low accuracies of NDVI data in extracting phenology for sparsely or densely vegetated lands, only pixels meeting the following criterions were included in the further phenology analyses: 1) the maximum NDVI value occurs between July and September; 2) the maximum averaged monthly (6–9) NDVI value is no less than 0.2; 3) the average winter NDVI value is less than 0.3 (Ding et al., 2016; Shen et al., 2014). These rules can minimize the data uncertainties. Fig. 1 shows the masked area and eco-regions on the TP.