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Land surface phenology of China's temperate ecosystems over 1999–2013: Spatial–temporal patterns, interaction effects, covariation with climate and implications for productivity

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ABSTRACT

Phenology is an important indicator of ecosystem functioning and has played a significant role in indicating plant productivity. Using 15-year SPOT-VGE data (1999–2013), we obtained the start (SOS), end (EOS) and length of growing season (LOS) with an improved modeling algorithm from time series of normalized difference vegetation index (NDVI) for temperate ecosystems of China (>30° N). Spatial and temporal patterns of SOS and EOS were analyzed. Furthermore, the interaction effects between phenological metrics were also considered. Using partial correlation, we quantitatively determined the contribution of climate (i.e., temperature and precipitation) on SOS and EOS in a spatially explicit way. More importantly, we also revealed the impacts of SOS and EOS on interannual variability of gross primary productivity (GPP). Our results showed that China's temperate ecosystems experienced intense phenological changes over 1999–2013 with high spatial heterogeneity. EOS was positively correlated with SOS, suggesting an earlier SOS may generally be accompanied with an earlier EOS. Spring temperature mainly controlled SOS but the role of spring precipitation on SOS cannot be overlooked. Warmer autumn delayed EOS consistently while autumn precipitation can either lead to earlier or later EOS. Unlike previous reported results, we found that both SOS and EOS had contrasting effects on annual GPP, i.e., annual GPP can either increase or decrease (depending on the location) with an earlier SOS or EOS, implying the complicated interactions between phenological changes and interannual variability of plant productivity.

1. Introduction

Vegetation phenology refers to the study of periodic plant life cycle events and how these are influenced by seasonal and interannual variations in climate (Myneni et al., 1997; Zhang et al., 2003; White et al., 2009; Morisette et al., 2009; Richardson et al., 2013). A variety of ecosystem models need the characterization of vegetation phenology (Peñuelas et al., 2009; Gonsamo et al., 2013) and misrepresentation of phenology has been shown to have significant uncertainties in modeling plant productivity (Richardson et al., 2012; Wu et al., 2013a) and land cover change studies (Liu et al., 2015). Therefore, improving plant phenology modeling approaches has received great attention in the scientific community (Friedl et al., 2006, 2010; Sonnentag et al., 2012; Wu et al., 2012, 2013a; Richardson et al., 2013; Melaas et al., 2013; Jeganathan et al., 2014).

Remote sensing technique provides convenient and timely observations at regional to global scale, and thus offers an important way to model land surface phenology efficiently. Land surface phenology (LSP) defined as the study of the timing of recurring seasonal pattern of variation in vegetated land surfaces observed from synoptic sensors (de Beurs and Henebry, 2004; Gonsamo et al., 2012b), has two commonly used important metrics namely, the start (SOS) and end of the growing season (EOS). Increasing efforts have been made to enhance the accuracy of LSP modeling and the most widely used way is to extract the SOS and EOS from time-series of remote sensing observations by fitting various logistic regression models. For example, the normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) are two frequently adopted vegetation indices to derive SOS and EOS from several platforms, including the Advanced Very High Resolution Radiameter (AVHRR) (Piao et al., 2006, 2011; Chen et al., 2014), the moderate-resolution imaging spectroradiometer (MODIS) (Zhang and Goldberg, 2011; Melaas et al., 2013; Wu et al., 2014), the digital repeat photography (Sonnentag et al., 2012), and other

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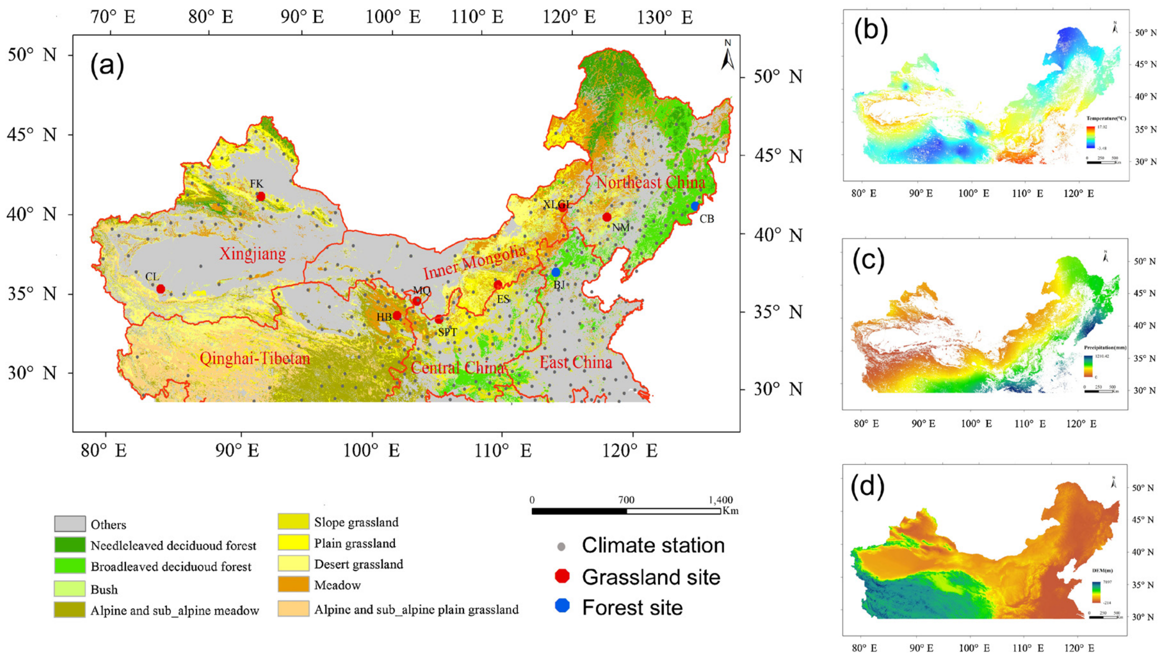

Fig. 1. Descriptions of the (a) study area, (b) mean temperature, (c) total precipitation and (d) elevation of this region. Abbreviations in (a) indicates pehnology sites and details are provided in Table 1.

ground-based sensors and observation networks (Ryu et al., 2014; Soudani et al., 2012). Other vegetation indices are also reported to be useful in characterization of LSP, such as the MERIS Terrestrial Chlorophyll Index (MTCI) (Dash et al., 2010; Atkinson et al., 2012) and the perpendicular vegetation index (PVI) (Guyon et al., 2011). Apart from a single vegetation index from a single data source, recent works found that it might be useful to combine multiple indices (Gonsamo et al., 2012a) or multiple sensors (Walker et al., 2012, 2014).

Temperate China (>30° N) covers a larger area with diverse terrestrial ecosystems, substantially contributing to regional carbon sequestration (Piao et al., 2009). Climate change over the past decade has been suggested to greatly impact the LSP of temperate China (Piao et al., 2006; Chen et al., 2014). However, there are several uncertainties/limitations in previous analyses over this region. First, most researches detected the SOS and EOS from time-series of NDVI, while a solid validation of these phenological modeling using ground measurements was missing (Cong et al., 2012), which proposed questions to the simulated spatial and temporal patterns of phenology. Second, the currently widely used logistic method for detecting vegetation phenology may be misleading since vegetation growth under natural conditions is controlled by multiple environmental factors and often does not follow a well-defined S-shaped logistic temporal profile (Cao et al., 2015). Third, previous studies may only focused on the long trend of NDVI (e.g., detecting turning points), but failed to identify the drivers of such change, especially in a spatially explicit way (Piao et al., 2006; Chen et al., 2014). Fourthly, most LSP works to date only focus on the impacts of climate on phenology, while the interaction effects between phenological transitions and their long-term impacts on plant productivity have not been investigated. Here we present an evaluation of the phenological modeling using the 15-year NDVI records observed from the SPOT-VEGETATION over this region. An improved SOS and EOS extraction strategy was developed and was compared with the previous method reported in Zhang et al. (2003). The overall objectives of this study are (1) to develop a new algorithm for LSP modeling using NDVI time-series, (2) to analyze the spatial and temporal patterns of SOS and EOS of temperate terrestrial ecosystems of China, (3) to identify the drivers of SOS and EOS using spatially explicit climate data and the interaction effects between phenological metrices, and (4) to quantitatively determine the impacts of phenological changes on regional plant productivity.

2. Materials and methods

2.1. Study region

We focus on temperate China (>30° N, Fig. 1a) where climate change has accelerated over the past decade (Piao et al., 2010). This area covers seveal ecoregions of China comprised of various land cover and plant functioal types, including broadleaf deciduous forests, needleaf deciduous forests, plain grassland, alpine and subalpine meadows. The ranges of mean temperature, totoal annual precipitaion and elevation of this region are shown in Fig. 1b–d). We obtained ten sites which have ground observed phenology records and detailed descriptions of these sites are given in Table 1. The ground sites consisted of the main terrestrial ecosystems in this region and well represented the spatial distribution landcover.

2.2. Climate data and interpolation

Climate data over this region were obtained from the China Meteorological Data Sharing and Service System (http://cdc.cma.gov.cn/home.do). Monthly mean temperature and total precipitation were acquired for 391 monitoring stations and the Kriging method was adopted for spatial interpolation (Tabios and Salas, 1985). We defined the spring tempereaure as the mean observtion for March–May and autumn temperature as the mean of September–November while the spring and autumn precipitations were defined as the total precipitation the same months.

2.3. Remote sensing observation and improved land surface phenology algorithm

The SPOT-VGT NDVI data used in this study were 1 km 10-day composite data (S10) in Plate-Carree Projection for the years 1999–2013. The NDVI data were obtained from the free