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FOREST PHENOLOGICAL TRENDS IN THE MIDDLE AND HIGH LATITUDE OF THE NORTHERN HEMISPHERE

Qi Shao[1,2,3], Chao Huang[4], Jing Feng Huang[1,2,3]
[1]Institute of Applied Remote Sensing and Information Technology, Zhejiang University,
[2]Key Laboratory of Environment Remediation and Ecological Health, Ministry of Education,
College of Environmental Resource Sciences, Zhejiang University
[3]Key Laboratory of Agricultural Remote Sensing and Information Systems,
Hangzhou, Zhejiang Province
[4]Institute of Applied Ecology, Chinese Academy of Sciences

Vegetation phenology is the study of periodically recurring patterns of growth and development of plants, which affect terrestrial ecosystem carbon, energy budget balance, fire disturbance, and climate–biosphere interactions. The increases in surface temperature had already altered the extent of vegetation phenology. Vegetation phenology can make some responses to climate factors, and the current climate change has attracted more research for the trend of vegetation phenology and its causes. The purpose of this paper is to investigate the spatial and temporal trend of forest phenology at mid and high latitude in the Northern Hemisphere (50°N-90°N, 180°W-180°E) over the period 2001–2017 using Collection 6 MODIS Land Cover Dynamics (MCD12Q2) datasets. The results indicated that SOS has a significant advanced trend, EOS has a significant delayed trend and LOS showed a significant extended trend on the whole. The significant advancement of SOS and extension of LOS mainly occurred in central Russia, the north and southwest of North America. Meanwhile, EOS showed a delayed trend in the south of Russia, the north and southwest of Canada and Alaska.

Keywords: *forest phenology, climate change, MODIS, remote sensing, Northern Hemisphere, GEE.*

Introduction

The climate determines the phenology through its influence on temperature and precipitation. Climate change affects vegetation productivity changes, and it also causes changes in the biogeochemical cycle, which affect the structure of communities and ecosystems (Piao et al., 2008). According to the 2013 Report of IPCC (the Intergovernmental Panel on Climate Change), global warming is intensified with the impact of human activities (IPCC, 2014). From 1880 to 2012, the average surface temperature on a global scale increased by 0.85 °C, which affects vegetation phenology.

Vegetation phenology is a sensor of climate change (Wang, 2019). Vegetation has a better response to changes in the external environment, and this response is easy to observe, mainly in the phenological characteristics of the start of growing season, the end of season, etc. At the same time, phenological change affects the exchange of carbon, water and energy between vegetation and the atmosphere so that it is the driving force of global climate change (Loboda et al., 2017; Delbar et al., 2015; Richardson et al., 2013; White et al., 2009). Therefore, the study of vegetation phenology changes in the long-term sequence is very important.

Due to the advantages of remote sensing technology in large-area synchronous observation and periodicity at regional and global scales (Myneni et al., 1997; Zhang et al., 2003), the products based on remote sensing satellite data are produced. NDVI and EVI can well show the growth dynamics of vegetation. The most commonly used remote sensing phenological product sources are NDVI derived from the Advanced Very High Resolution Radiometer (AVHRR) (Tucker et al., 2001), NDVI derived from the Systeme Probatoire d'Observation de la Terre (SPOT), as well as NDVI and EVI derived from the Moderate-resolution Imaging Spectroradiometer (MODIS). Although the time range of AVHRR data is long, its spatial resolution is only 8 km. The SPOT NDVI dataset has a spatial resolution of 1 km. Compared with the former two, MODIS data has a higher spatial resolution, which is of great significance for the distribution study of forest phenological change trend.

Previous studies have reported hemispheric or local changes in growing seasons (Vorobev et al, 2019; Jeong et al., 2009; Jeong et al., 2011; Myneni et al., 1997; Shen et al., 2014; Zhou et al., 2001). In recent years, some researches indicated a global warming hiatus between 1998 and 2012 (Medhaug et al., 2017). Therefore, the hiatus of global warming has attracted widespread attention. For instance, Fu et al. (2015) demonstrated that the apparent response of leaf unfolding to climate warming has significantly decreased from 1980 to 2013 in seven dominant European tree species. The previous studies (Jeong et al., 2009; Jeong et al., 2011; Wang et al., 2019) found that the trend of vegetation growth season advancement has been stagnant during the global warming hiatus.

In some countries and regions, the advanced onset of vegetation growing season and the accumulation of forest fuel caused by climate warming have also led to an increasing number of large and severe wildfires (Westerling et al., 2006). Therefore, the study of forest phenological changes has an essential reference for understanding the occurrence of wildfire. Accurate trend information of forest phenology is essential to understand regional-to-global carbon budgets and climate change (Peng et al., 2017). However, there are few studies on forest phenological changes at present.

Purpose of work

The main goal of this study is to investigate the change trend of forest phenology in the middle and high latitudes of the Northern Hemisphere. Furthermore, the spatial distribution of the changing trend of forest phenology in different regions is analyzed, thus making a preliminary analysis of the response forest phenology to climate change.

Area of research

The Northern Hemisphere has the largest climate warming at middle and high latitudes, which is about two times faster than other areas. Moreover, the vegetation of terrestrial ecosystems in the mid-high latitudes of the Northern Hemisphere is very susceptible to climate change. Besides, this region is relatively less affected by human activities and can better reflect the impacts of climate change on vegetation phenology. Therefore, we selected the Northern Hemisphere with latitude greater than 50° to estimate forest phenology.

Materials and methods of research

Data

Phenology data from MCD12Q2

Vegetation phenology data is obtained from the Collection 6 (C6) MODIS Land Cover Dynamics Product (MCD12Q2), which offers global land surface phenology metrics at 500 m spatial resolution and annual time step since 2001. Phenometrics is derived from time series of MODIS observed land surface greenness, particularly time series of the 2-band Enhanced Vegetation Index calculated from MODIS nadir BRDF adjusted surface reflectance (NBAR-EVI2). It contains many science data sets (SDS), including greenup, dormancy, QA_Overall and so on. In this study, QA_Overall was used to quality control, SOS was showed by green up and EOS was showed by dormancy. LOS was calculated by the difference between SOS and EOS. The dataset was accessed and processed on the platform of Google Earth Engine (GEE).

Land cover from MCD12Q1

The vegetation classification data used in this study comes from the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type Product (MCD12Q1), which provides a suite of science data sets that map global land cover at 500 m spatial resolution. It includes five legacy classification schemes, such as the International Geosphere-Biosphere Programme (IGBP), University of Maryland (UMD), Leaf Area Index (LAI), BIOME-Biogeochemical Cycles (BGC), and Plant Functional Types (PFT). The dataset of IGBP classification schemes was chosen in this study. Evergreen needleleaf forests, evergreen broadleaf forests, deciduous needleleaf forests, deciduous broadleaf forests, mixed forests, closed shrublands, and open shrublands were selected as the study plots for this research. The legend and description were showed in table 1. A multiyear stable forest-covered region was generated from annual MCD12Q1 over the period from 2001 to 2017. The dataset was processed and downloaded on the GEE platform.

Table1

MCD12Q1 International Geosphere-Biosphere Programme (IGBP) legend

Value	Name	Description
1	Evergreen Needleleaf Forests	Dominated by evergreen conifer trees (canopy >2m). Tree cover >60%.
2	Evergreen Broadleaf Forests	Dominated by evergreen broadleaf and palmate trees (canopy >2m). Tree cover >60%.
3	Deciduous Needleleaf Forests	Dominated by deciduous needleleaf (larch) trees (canopy >2m). Tree cover >60%.
4	Deciduous Broadleaf Forests	Dominated by deciduous broadleaf trees (canopy >2m). Tree cover >60%.
5	Mixed Forests	Dominated by neither deciduous nor evergreen (40-60% of each) tree type (canopy >2m). Tree cover >60%.
6	Closed Shrublands	Dominated by woody perennials (1-2m height) >60% cover.
7	Open Shrublands	Dominated by woody perennials (1-2m height) 10-60% cover.

Data Analyses

The changing trend of each pixel in time series was calculated by the linear regression model (Xu et al., 2004) through IDL programming. The slope of each pixel was calculated by the unitary linear regression analysis method. The inter-annual rate of change and the inter-annual spatial distribution of each parameter in the study area were obtained from 2001 to 2017. The calculation formula is as follows:

$$SLOPE = \frac{\mathrm{n} \times \sum_{i-1}^{n} i \times X_i - \sum_{i-1}^{n} i \times \sum_{i-1}^{n} X_i}{\mathrm{n} \times \sum_{i-1}^{n} i^2 - (\sum_{i-1}^{n} X_i)^2} , \quad (1)$$

where i is serial number of year, X_i is the actual pixel value for a year. If *SLOPE* is greater than 0, the parameter is increasing trend, and vice versa.

T-test was used to evaluate the significance of the results (Li,2019). It was calculated as follows:

$$\mathrm{t} = \frac{b}{S_b} , \quad (2)$$

The b and S_b were calculated as follows:

$$\mathrm{b} = \frac{\sum_{i-1}^{n} (Xi - \overline{X}) \times \sum_{i-1}^{n} (i - \bar{i})}{\sum_{i-1}^{n} (X_i - \overline{X})^2} , \quad (3)$$

$$S_b = \frac{S_x}{\sqrt{\sum_{i-1}^{n} (X_i - \overline{X})^2}} , \quad (4)$$

$$S_x = \sqrt{\frac{\sum_{i-1}^{n}(i-\hat{i})^2}{n-2}}\ , \qquad (5)$$

where S_b is the standard deviation of regression coefficient, S_x is the standard error of estimation for regression equation.

Research results

The overall trend of forest phenology at the middle and high latitudes of the Northern Hemisphere was analyzed (fig.1). From 2001 to 2017, SOS (start of the growing season), EOS (end of growing season), and LOS (length of the growing season) had a significant trend at the $P < 0.01$ level. Consistent with the previous studies (Chen et al., 2020; Pulliainen et al., 2017; Tucker et al., 2001), we found that SOS was significantly advanced ($P<0.01$), the advance rate was 0.70 days year^{-1}. In contrast to our result, an earlier study (Wang, 2019) reported that EOS has a postponement trend at the end of growing season in the Northern Hemisphere from 1982 to 2015, but the change is not significant. However, we found that EOS showed a significant delayed trend from 2001 to 2017 with a rate of 0.27 days year^{-1}. The small differences in results may be due to differences in the study area and time range. It has been previously reported that LOS showed a postponed trend with a more pronounced change range from 1948 to 1996 (Ahas et al., 2000). In our result, LOS was significantly extended ($P<0.01$) from 2001 to 2017, the extended rate was 0.96 days year^{-1}.

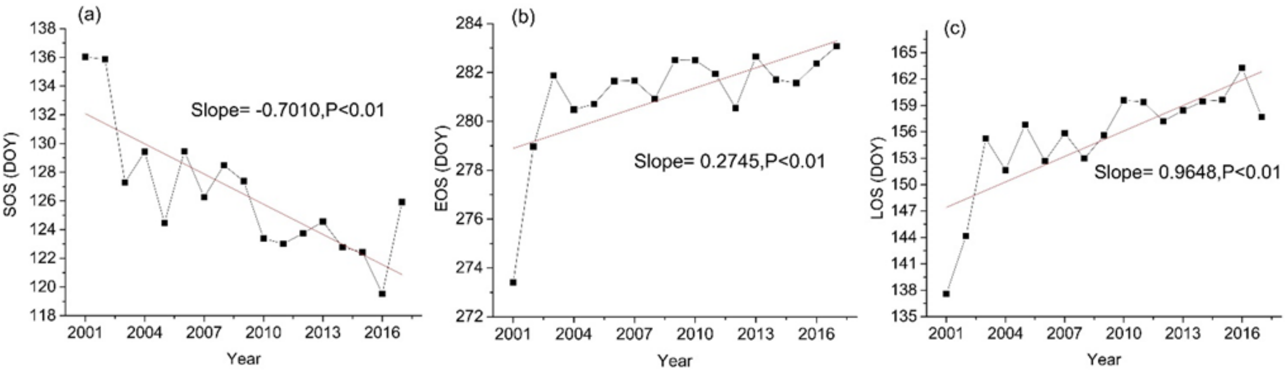

Fig.1. Vegetation phenology parameters trends. across forest area of mid and high latitude in the Northern Hemisphere(50°-90°N,180°W-180°E) from 1982 to 2014, including two snow parameters:(a) SOS (start of growing season),(b) EOS (end of growing season) and (c)LOS(length of growing season)

For the SOS, 79.41% of the area showed an advancement trend. 15.50% pixels were significantly advanced, which mainly distributed in central Russia, the north and southwest of North America. 20.59% of the pixels had a delayed trend and 0.32% were significantly delayed. The reason for this result may be the melting period of snow in the Northern Hemisphere high latitudes, which is significantly advanced with the warming of the climate, thus leading to the advancement of the spring phenology of vegetation (Pulliainen et al., 2017).

EOS showed an advanced trend of 32.06% on the study area; 67.94% of the area showed a delayed trend. The delayed pixels accounted for a greater proportion of the pixels than the earlier ones. Among them, 1.75% of pixels were significantly advanced and distributed in north central Russia. 10.51% pixels were significantly delayed, mainly distributed in the south of Russia, north and southwest of Canada and Alaska.

For the LOS, 22.19% of LOS has a short trend, and 77.81% of LOS showed an extended trend. Among them, 0.92% of pixels were significantly short and 19.54% of pixels were significantly extended. The spatial distribution is roughly similar to that of SOS. It is worth mentioning that the significantly extended area of LOS is greater than that of EOS, resulting from a synergistic effect with the advancement of SOS.

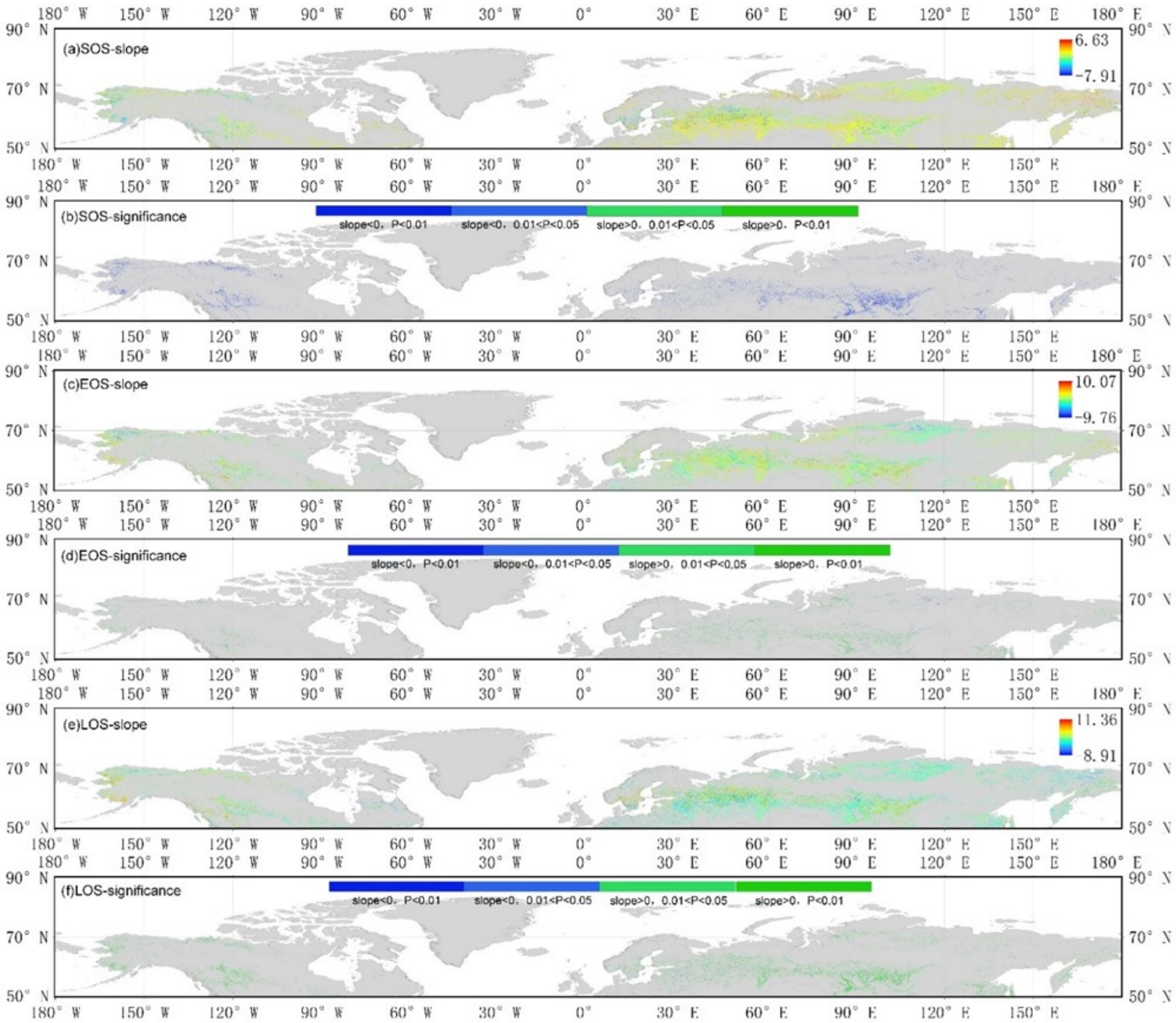

Fig. 2. Spatial patterns of vegetation phenology parameters trend across forest area of mid and high latitude in the Northern Hemisphere (50°-90°N,180°W-180°E), including:(a) slope of SOS (start of growing season), (b) significance of SOS, (c) slope of EOS (end of growing season), (d) significance of EOS, (e) slope of LOS (length of growing season) and (f) significance of LOS (length of growing season)

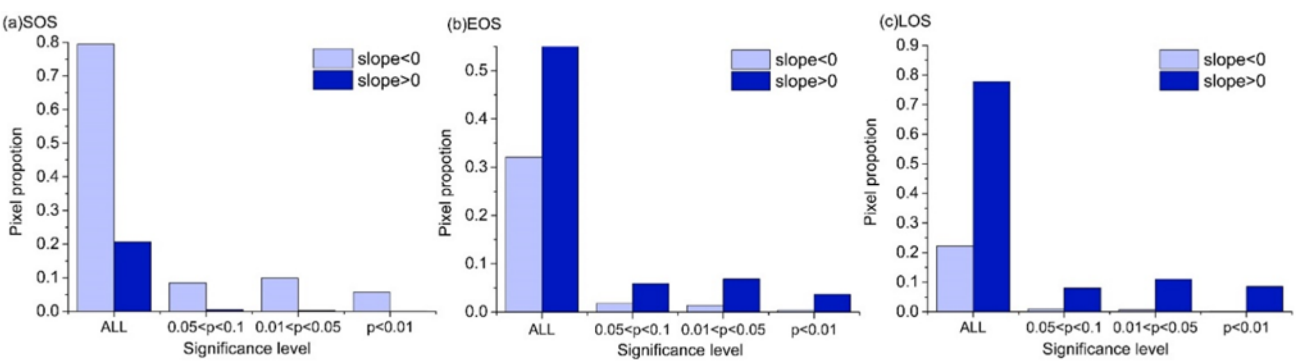

Fig. 3. The proportion of changing trend pixels at different significance levels in ALL pixels in the study area. ALL represents the total number at ALL significance levels, slope<0 represents the advanced trend of parameters, and vice versa, including: (a) SOS, (b) EOS, (c) LOS

Conclusions

Based on long-term satellite data, our results found that SOS has a significant advanced trend, EOS and LOS has a significant delayed and extended tendency throughout the period 2001–2017 on the forest area of mid and high latitude in the Northern Hemisphere (50°N-90°N,180°W-180°E) on the whole. The significantly advanced SOS and extended LOS are mainly distributed in central Russia, the north and southwest of North America. The significantly delayed EOS is mainly distributed in the south of Russia, the north and southwest of Canada and Alaska.

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