Phenology of Qinling Forest Vegetation and Its Response to Meteorological Factors: Postprint

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Date: 2021-08-12T00:00:00+00:00

Abstract

Investigating the patterns of vegetation phenology in mountainous transition zones and the driving mechanisms underlying vegetation phenology changes is of great significance. Based on MODIS NDVI remote sensing data from 2000–2018, vegetation phenology parameters for the Qinling Mountains were extracted using the double Logistic curve fitting method. Combined with temperature and precipitation data, methods including trend analysis, correlation analysis, and redundancy analysis were employed to investigate the spatiotemporal variation characteristics of different phenological periods and their responses to meteorological factors in the Qinling Mountains. The results indicate: (1) The phenology start date in the Qinling Mountains is concentrated between days 60–102, the phenology end date is mainly concentrated between days 315–345, and the growing season length is concentrated between days 225-255. Spatially, obvious vertical zonal distribution characteristics are observed; with increasing altitude, the phenology start date, end date, and growing season length exhibit trends of delay, advance, and shortening, respectively. (2) From the perspective of interannual variation in vegetation phenology, 62.25% of the region shows an advancing trend in the phenology start date, 53.42% of the region shows a delaying trend in the phenology end date, among which 59.18% of the region exhibits an extended vegetation growing season length, with only 5.12% of the region located in the mid-eastern mid-high altitude areas showing significant extension. (3) The phenology start date in most regions shows a negative correlation with mean temperature and precipitation from February to May, accounting for 50.29% and 65.24% of the total area, respectively; the phenology end date is mainly positively correlated with mean temperature and monthly precipitation from August to November, accounting for 66.63% and 59.77% of the total region, respectively; (4) Redundancy analysis (RDA) results indicate that vegetation phenology in the Qinling Mountains is jointly influenced by concurrent and antecedent meteorological factors. Spring phenology is more affected by the phenological occurrence period than by the previous winter, and temperature and precipitation in the period preceding the phenology end date have a greater impact intensity on autumn phenology than autumn itself. The response degree of phenological changes to meteorological factors varies among different slope aspects.

Full Text

Arid Zone Research, Vol. 38 No. 4, July 2021 (ChinaXiv Cooperative Journal)

Phenology of Forest Vegetation and Its Response to Meteorological Factors in the Qinling Mountains

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Abstract: Investigating vegetation phenology patterns and their driving mechanisms in mountain transition zones is of great significance. Based on MODIS remote sensing data, this study extracted phenological parameters of forest vegetation in the Qinling Mountains from 2000 to 2018 using the double logistic curve fitting method. Combining temperature and precipitation data, we employed trend analysis, correlation analysis, and redundancy analysis to examine the spatiotemporal variation characteristics of different phenological periods and their responses to meteorological factors. The results show that: (1) The start of the growing season (SOS) in the Qinling Mountains was concentrated between days 60-102, the end of the growing season (EOS) between days 315-345, and the growing season length (GSL) between days 225-255. The spatial distribution exhibited distinct vertical zonation characteristics, with SOS delayed, EOS advanced, and GSL shortened as altitude increased. (2) Interannually, 62.25% of the study area showed an advancing trend in SOS, while 53.42% exhibited a delaying trend in EOS. The GSL lengthened in 59.18% of the region, with significantly extended areas (5.12%) located primarily in mid-to-high altitude regions of the central and eastern parts. (3) SOS was negatively correlated with mean temperature and precipitation from February to May, covering 50.29% and 65.24% of the total area, respectively. EOS was positively correlated with mean temperature and precipitation from August to November, accounting for 66.63% and 59.77% of the total area, respectively. (4) Redundancy analysis indicated that vegetation phenology in the Qinling Mountains was jointly influenced by both current-season and preceding-period meteorological factors. Spring phenology was more affected by conditions during the phenological occurrence period than by the previous winter, while temperature and precipitation in the period preceding EOS had a stronger influence on autumn phenology than autumn conditions themselves. Phenological changes on different slopes showed

varying degrees of response to meteorological factors.

Keywords: phenological change; meteorological factors; redundancy analysis; Qinling Mountains

Introduction

Vegetation phenology represents the seasonal growth and development rhythm formed by plants through long-term adaptation to environmental changes. Plant phenology not only reflects seasonal variations but also plays a decisive role in ecosystem carbon, water, and energy cycles. Studying the patterns of vegetation phenology change and its response to meteorological factors helps to understand and improve vegetation-climate relationships.

Based on high spatiotemporal resolution remote sensing data and normalized difference vegetation index (NDVI), scholars worldwide have conducted phenological monitoring at various scales, exploring vegetation phenology changes and their responses to meteorological factors in different regions. Remote sensing analysis of vegetation phenology changes in northern Eurasia showed that the growing season start date advanced by an average of 3.6 days, while the end date was delayed by an average of 3.6 days. Similar phenomena of advanced spring phenology, delayed autumn phenology, and extended growing seasons have been observed in Northeast China, the Qinghai-Tibet Plateau, and Northwest China, with temperature playing a dominant role in phenological changes. Additionally, precipitation is an indispensable factor affecting vegetation phenology, as studies of South American tropical rainforests have found that phenological peaks occur from the late dry season to the early rainy season. Research by Zu Jiaxing et al. using GIMMS AVHRR remote sensing data to analyze phenological responses to climate in Northeast China found that autumn phenology changes were mainly affected by precipitation. These studies demonstrate that vegetation phenology changes exhibit regional differences, and that even within the same region, phenological performance may vary depending on the time range, extraction method, and remote sensing data source used. Therefore, selecting appropriate time series and phenological extraction methods is crucial for accurately studying phenological responses to meteorological factors in specific research areas.

The Qinling-Daba Mountains constitute the main body of China' s north-south transitional zone, representing a pivotal area controlling China' s geographical pattern and spatial variation. As an important geographical and biological boundary in China, the Qinling Mountains feature significant vertical zonation, large natural geographical spans, complex and diverse vegetation types, and a relatively fragile ecosystem. Meanwhile, under global climate change, both temperature and precipitation in the Qinling region have undergone significant changes. How will these climate changes affect vegetation phenology in the Qinling Mountains? Will phenological trends be consistent with other regions? What is the relationship between phenological changes and meteorological factors? To address these questions, this study used the double logistic fitting method, combined with MODIS data and ground-based temperature and precipitation data, to extract the start, end, and length of the vegetation growing season in the Qinling Mountains from 2000 to 2018. We analyzed the trends and patterns of vegetation phenology changes and explored the spatiotemporal variations of phenology and their responses to meteorological factors, aiming to identify the key time periods influencing phenological changes in the Qinling Mountains. This research provides a reference for monitoring and protecting mountain ecosystems in the context of global change.

1. Materials and Methods

1.1 Study Area

The study area is the Qinling Mountains within Shaanxi Province ("Shaanxi Qinling"), bordered by the Wei River to the north and the Han River to the south, located between 105°30 -110°05 E and 32°40 -34°35 N. The region includes seven prefecture-level cities such as Baoji and Xi' an, with elevations ranging from 177 m to 3746 m, annual precipitation of 495–1137 mm, and annual temperatures of 12.1–14.4 °C. As a massive east-west oriented mountain range across central China, its special geographical location and complex climatic conditions have formed distinctly different vertical belts on the northern and southern slopes. The area features diverse vegetation types including evergreen broadleaf forests, coniferous and broadleaf mixed forests, and alpine meadows, as well as varied soil types such as cinnamon soil, brown soil, and yellow-brown soil.

1.2 Data Sources and Processing

1.2.1 Remote Sensing Data The MOD13Q1 dataset was used, obtained from the National Aeronautics and Space Administration (NASA) with a temporal resolution of 16 days and spatial resolution of 250 m × 250 m. The dataset was first processed using the MODIS Reprojection Tool for projection conversion and image mosaicking. The maximum value composite method was then applied to eliminate residual clouds, atmospheric effects, and solar elevation angle influences. Finally, the study area boundary was used to mask and extract the data, obtaining NDVI time-series data for the Qinling Mountains.

1.2.2 Meteorological Data Meteorological data included temperature and precipitation data from 2000 to 2018 within the study area, obtained from the China Meteorological Data Service Center and Shaanxi Meteorological Bureau. Based on station data, spatial interpolation was used to convert point data to gridded meteorological data. The study area boundary was then applied for masking to obtain temperature and precipitation interpolation data for the Qinling Mountains. Given the complex temperature conditions in mountainous areas, spatial interpolation was performed using previously researched temperature lapse rates for the Qinling region, while precipitation interpolation used ordinary Kriging.

1.2.3 Other Data The DEM data used the ASTER GDEM product with a spatial resolution of 30 m, obtained from the Geospatial Data Cloud (http://www.gscloud.cn). The elevation data underwent projection conversion, resampling, and masking to obtain DEM data with a spatial resolution of 250 m.

1.3 Methods

1.3.1 Remote Sensing Extraction of Vegetation Phenology The TIMESAT software package was used to extract vegetation phenology periods. Although the MOD13Q1 dataset processing reduced cloud and atmospheric effects, random factors such as solar zenith angle, observation angle, ozone, and aerosols still caused unclear seasonal variation trends in the curves. Therefore, this study selected the double logistic fitting method in the TIMESAT software package for processing. The logistic model was then used to extract vegetation phenological parameters from 2000 to 2018, including the start of the growing season (SOS), end of the growing season (EOS), and length of the growing season (GSL). The logistic model is expressed as:

$$y(t) = \frac{c}{1 + e^{a+bt}} + d$$

where t represents the time scale; a represents the position of the growing season start, a represents the shape and position parameters of the growing season start; a represents the position of the growing season end, a represents the shape and position parameters of the growing season end.

1.3.2 Trend Analysis A unary linear regression analysis was applied pixel-by-pixel to calculate the trend slope of SOS, EOS, and GSL from 2000 to 2018, using the following formula:

$$\text{Slope} = \frac{n \sum_{i=1}^{n} iP_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} P_i}{n \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where n is the number of years; P_i is the phenological parameter in year i; and Slope is the slope of the linear regression equation. A positive Slope indicates that the phenological parameter is delayed (or extended) overall, while a negative value indicates advancement (or shortening). A significance T-test was performed on the trends.

1.3.3 Correlation Analysis Partial correlation analysis was used to reveal the response relationship between temperature, precipitation, and vegetation phenology changes:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where r_{xy} represents the correlation coefficient between x and y, indicating the degree of correlation. $r_{xy} > 0$ indicates positive correlation, while $r_{xy} < 0$ indicates negative correlation. $\bar{x}$ and $\bar{y}$ represent the mean values of the respective variables.

1.3.4 Redundancy Analysis Redundancy analysis (RDA) is a multivariate environmental gradient analysis that examines the relationship between a response variable matrix and explanatory variables through multivariate multiple linear regression. It has been widely applied in biological, environmental, and soil research. This study selected temperature and precipitation data from the 12 months preceding SOS and EOS as meteorological factors and used RDA to quantify the relationship between phenological parameters and meteorological factors in the Qinling Mountains. RDA ordination diagrams were generated using Canoco 5 software, with Monte Carlo tests performed for significance testing. In the ordination diagram, the quadrant where an arrow is located indicates the positive or negative correlation between an environmental factor and an ordination axis. The length of the arrow line indicates the importance of the environmental factor, with longer vectors representing more significant factors. The cosine of the angle between meteorological vectors and phenology vectors represents their correlation coefficient. Arrows pointing in the same direction indicate strong positive correlation, opposite directions indicate strong negative correlation, and perpendicular orientation indicates no correlation.

2. Results and Analysis

2.1 Spatial Distribution of Average Phenology

The spatial distribution of multi-year average phenology parameters in the Qinling Mountains from 2000 to 2018 shows that SOS was concentrated between days 60-102 (late February to early April), accounting for 94.36% of the study area. SOS exhibited a pattern of delay from low-altitude areas on both northern and southern sides toward the central high-altitude region. The low-lying areas of the northern slope showed SOS earlier than day 88, while high-altitude areas and regions near ridgelines showed SOS later than day 102. EOS occurred on average on day 304 on the northern slope and day 325 on the southern slope, with the northern slope averaging 21 days earlier than the southern slope. The Hanzhong Basin and Ankang Yuehe River Valley showed earlier EOS, likely due to their low-lying terrain, developed agriculture, and shorter crop growth periods compared to forest vegetation. The GSL showed a gradual shortening pattern from both sides toward the ridgeline, except for some low-lying areas on the northern and southern sides. Overall, the phenological distribution pattern showed good consistency with altitude and topography: higher altitudes corresponded to later SOS, earlier EOS, and shorter GSL.

2.2 Trend Analysis

The interannual variation trends of phenological parameters in the Qinling Mountains revealed that 62.25% of the region showed an advancing trend in SOS, while 37.75% showed a delaying trend. However, the degree of advancement or delay was relatively small, with only 2.12% of the region showing significantly advanced SOS ($P < 0.05$) and 3.26% showing significantly delayed SOS ($P < 0.05$). Significantly delayed SOS was mainly distributed in low-altitude areas at the northern and southern foothills and in several southern regions heavily affected by human activities.

EOS primarily showed a delaying trend (53.42%), with T-test results indicating that most regions exhibited non-significant delaying or advancing trends (83.37%). Significantly delayed areas ($P < 0.05$) accounted for 7.62%, mainly distributed in low-altitude areas at the northern foothills. Significantly advanced areas comprised only 2.95% ($P < 0.05$), primarily located in the central and eastern parts of the region.

The GSL showed a lengthening trend in 59.18% of the region and a shortening trend in 40.82%. T-test results showed that changes in forest vegetation GSL were generally non-significant, with significantly lengthened areas ($P < 0.05$) accounting for 5.12% and mainly concentrated in mid-to-high altitude regions of the central and eastern parts. Significantly shortened areas ($P < 0.05$) accounted for only 1.56%, distributed in low-lying areas vulnerable to human disturbance.

2.3 Correlation Analysis Between Phenology and Meteorological Factors

Since climate change and phenological change exhibit temporal lags, and previous studies have shown that phenological periods are significantly correlated not only with current-season temperature but also with preceding-period temperature, this study selected temperature and precipitation data from the 12 months preceding SOS and EOS as meteorological factors for RDA.

The spatial correlation analysis between SOS and monthly temperature and precipitation revealed that most areas of the Qinling Mountains showed negative correlations between SOS and current-period temperature and precipitation, accounting for 50.29% and 65.24% of the total area, respectively. In terms of significance, the area where SOS was significantly correlated with temperature accounted for 12.43%, indicating that lower temperatures and reduced precipitation delayed vegetation SOS. Spatially, February–May mean temperature had negative effects on SOS in most western and northern regions, while mean precipitation showed positive correlations with SOS in low-altitude areas of the northern slope, with evenly distributed positive and negative correlations elsewhere. This may be because the western region has higher altitudes and the northern region has higher latitudes, where slower temperature recovery delays SOS compared to the southern slopes of the Qinling Mountains.

EOS in most areas showed positive correlations with current-period temperature and precipitation, accounting for 66.63% and 59.77% of the total area, respectively. For areas with significant changes, temperature and precipitation in August–November were positively correlated with EOS in 50.15% of the region, indicating that increased temperature and precipitation delayed autumn phenology. Spatially, areas where EOS was delayed with increasing temperature were mainly located in high-altitude regions, demonstrating consistency between phenological changes and terrain relief.

3. Discussion

Surface vegetation is a vivid indicator of regional ecological health. Macro-scale remote sensing data enables dynamic monitoring of forest vegetation and retrieval of plant phenology changes in mountain ecosystems, as well as analysis of their response to meteorological factors. Our analysis revealed that vegetation phenology in the Qinling Mountains from 2000 to 2018 mainly showed trends of advanced SOS, delayed EOS, and extended GSL, consistent with findings from other scholars. Temperature rise enhances solar radiation and brings forward effective accumulated temperature, thereby advancing spring phenology. SOS on both northern and southern slopes was controlled by precipitation from the previous December to current January, showing negative correlations. This may be because the Qinling Mountains are located inland with low winter precipitation that falls mainly as snow, increasing surface albedo and consuming heat for snowmelt, which lowers surface temperature and delays spring phenology. Autumn phenology in the region was positively correlated with August–November temperature and precipitation. Sufficient light benefits photosynthesis, while increased precipitation raises soil moisture content, increasing available water resources for vegetation growth, thereby extending the growing season and delaying EOS.

To validate our results, we compared remote sensing-derived phenology with ground observations from Xi’ an Station. Using phenological data for four deciduous tree species (Populus tomentosa, Pyrus betulifolia, Aesculus chinensis, and Bothrocaryum controversum) from 2000 to 2018, we found the average leaf unfolding date was day 88 and the full leaf coloration date was day 316, which basically matches the concentrated days of remotely sensed SOS and EOS. This indicates that MODIS13Q1 products can reflect forest phenology characteristics in the Qinling Mountains and are suitable for vegetation dynamic monitoring. Although remote sensing phenology reflects large-scale overall vegetation phenology periods while ground observations are typically single-species or single-site data, creating a spatial scaling issue, both show good correspondence in phenological timing. Therefore, developing a reasonable scaling method for accuracy verification between remote sensing and ground phenological data represents a key focus for future research.

4. Conclusions

Using the double logistic fitting model, combined with MODIS data and ground temperature and precipitation data, this study extracted the start, end, and length of the vegetation growing season in the Qinling Mountains from 2000 to 2018, analyzed phenological trends and patterns, and explored spatiotemporal variations and responses to meteorological factors. The main conclusions are:

1) SOS in the Qinling Mountains was concentrated between days 60-102 (late February to early April), showing a pattern of delay from low-altitude areas on both sides toward mid-to-high altitude regions. EOS was concentrated between days 315–345, and GSL between days 225–255, showing a gradual shortening pattern from both sides toward the ridgeline. Overall, the phenological distribution pattern showed good consistency with altitude and terrain: higher altitudes corresponded to later SOS, earlier EOS, and shorter GSL.

2) Interannually, 62.25% of the region showed an advancing trend in SOS, while 53.42% exhibited a delaying trend in EOS. The GSL lengthened in 59.18% of the region, with significantly extended areas (5.12%) located primarily in mid-to-high altitude regions of the central and eastern parts.

3) SOS was negatively correlated with February–May mean temperature and precipitation in most areas, accounting for 50.29% and 65.24% of the total area, respectively. EOS was positively correlated with August–November mean temperature and precipitation, accounting for 66.63% and 59.77% of the total area, respectively.

4) RDA results indicated that vegetation phenology in the Qinling Mountains was jointly influenced by both current-season and preceding-period meteorological factors. Phenological changes on different slopes showed varying response degrees. SOS on the northern slope was mainly affected by February–April temperature and previous December–January precipitation, while SOS on the southern slope was mainly affected by February–March temperature and previous December–January precipitation.

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Note: Figure translations are in progress. See original paper for figures.