A study on land surface phenology in eastern China based on SPOT/VGT datasets

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Abstract. Vegetation phenology provides a relevant indicator of the response of terrestrial ecosystems to climate change. In this study, vegetation phenology measurements were extracted and the spatial distributions were investigated using time series SPOT/VGT NDVI datasets for eastern China. Four phenology measurements were analyzed: the start of the growing season (SOS), the end of the growing season (EOS), the length of the growing season (GSL) and the time of the peak NDVI. The SOS in the northern part of the study area occurred earlier than in the rest of the study area due to larger amounts of cropland. The EOS showed a strong latitudinal pattern, especially in the southern portion of the study area. The EOS in the northern part of the study area occurred earlier than in the rest of the study area due to larger amounts of cropland. The EOS showed a strong latitudinal pattern, especially in the southern portion of the study area. The GSL also showed a clear spatial pattern along the latitudinal gradient from north to south. The time of peak NDVI did not show a spatial pattern along the latitudinal gradient, which is likely due to the influence of vegetation types and the types of farming systems. In addition, there were no significant correlations between longitude and the four phenology measurements. SOS does not correlate with latitude, longitude or altitude, but EOS, GSL and the time of peak NDVI all correlated with latitude and altitude.

1. Introduction

Land surface phenology (LSP) both describes and characterizes the timing of the cyclical patterns of plant growth, including the biological events of budburst, flowering, fructification, leaf senescence and leaf fall [1]. These biological phenomena are genetically predetermined but are also strongly modulated by environmental conditions. The timing of the appearance of primary phenological markers in temperature- or water-constrained species can indicate responses to climate change and serve as a key parameter for understanding and modeling the interactions between vegetation and climate. The characterization of vegetation phenology at regional, national and global scales is important for many scientific and practical applications. For example, analyzing the start and end times of the growing season at a global scale can provide important indications of climate change. The spatial variation of these times can be used to assess regional variations in changing temperature and precipitation regimes. Moreover, phenological events have a large influence on the spatiotemporal

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dynamics of carbon and water cycles [2]. In recent years, the use of remote sensing images recorded over a time series using high temporal resolution, such as AVHRR, SPOT/VGT and MODIS, has become one of the most common ways to detect land surface phenology. Many studies on vegetation phenology at the regional, national and global scales have used long-term data from land observation stations and coarse remote sensing images [3-5]. Most phenology measurements calculated from satellite imagery are based on the Normalized Difference Vegetation Index (NDVI) because the NDVI is a good indicator for monitoring changes in vegetation [6-7], especially on regional and global scales [8]. This research studied four measurements of vegetation phenology in eastern China using SPOT/VGT datasets recorded over a time series.

2. Data and methods

2.1. Study area
This study focused on an approximately 903,717-square-kilometer region in eastern China, described by the longitude from 113°E to 123°E and the latitude from 21.5°N to 35.5°N. This region is located in a sub-tropical humid monsoon climate with four distinct seasons. The study area contains 38.33% of China’s total population and more than half of China’s total gross domestic product, with high population densities and increasing rates of urbanization. This study area also includes most of a north-south transect in eastern China that was selected in 2000 as the fifteenth international standard transition to study the change of terrestrial ecosystems, global climate and the relationship between socioeconomic development and land use/land cover [9].

2.2. Time series data
The time series of NDVI data from January 1999 to December 2009 (423 images total) selected in this study was derived from the VEGETATION (VGT) data from SPOT satellites and has a spatial resolution of 1 km. NDVI images (production S10) and corresponding status maps were downloaded from the VITO website (http://free.vgt.vito.be/home.php). Then, the subsets were created using the smart program, CROP_VGT (V2.0). NDVI values were converted from DN values using the formula, \[ \text{NDVI} = \frac{\text{DN} \times 0.004 - 0.1}{\text{SRTM}} \]. In addition, we used a vector province boundary map, at a scale of 1:250 000, and a digital elevation model (SRTM) derived from the Consultative Group for International Agriculture Research Consortium for Spatial Information.

2.3. Method
The time series images still contained residual noise after being processed using maximum value composites (MVC). To cope with these issues, time series images were further smoothed to remove variations and abnormalities in MatLab v.6.5 and ArcGIS v.9.3.

2.3.1. Moving average smoothing. First, we identified abnormal values, including false low values and false high values on NDVI images. The former occurs when the image cell contains a special value due to cloud cover or a scan strip. And these values could be found easily with the help of status maps. The latter occurs when the difference of NDVI between images at the same location over two continuous dekads is more than 0.6, which is unlikely to occur given the gradual nature of the process of vegetation [10]. The moving average was used to remove both the false low and high values. Two-dekad was selected as the best time step to use in calculating the moving average based on auto-correlation analysis of 100 random samples, when the raw NDVI value of an abnormal cell was replaced by the mean value of the cell 20 days before and after the abnormal value was recorded.

2.3.2. Savitzky–Golay smoothing. Next, we applied a Savitzky-Golay (SG) filtering procedure to each annual NDVI cycle, as described by Chen et al. (2004), to reduce abnormalities caused by clouds, snow and ice [10]. SG smoothing is a linear filter, which smooths data by computing the derivative of a given order, preserving peaks and other important features of the underlying signal controlled by two
parameters, SPAN and DEGREE. The SPAN is the half-width of the smoothing window. The DEGREE specifies the order of the smoothing polynomial, typically between 2 and 4. We selected seven SPANs (5, 7, 11, 13, 15, 19 and 25) and three DEGREES (2, 3 and 4), creating 21 SPAN-DEGREE combinations, for 10 random sample points. The best parameters, based on a fitting effect index, occurred using a SPAN value of 7 and a DEGREE value of 4 [10].

2.3.3. LSP extraction. Several methods for deriving phenological metrics from satellite data have been developed over the last twenty years. These methods can be divided into four main categories: threshold, derivative, smoothing algorithms and model fit [6]. Each of these methods has their own advantages and shortcomings, based on the dataset itself, climate conditions, ecoregion, land use/land cover and scale [11]. After removing abnormalities from the raw NDVI time series data using moving average smoothing, the images in our study were further processed using the SG technique. We then extracted LSP data based on the point of intersection of the NDVI curve, and the NDVI curve was calculated using a moving average with a STEP value of 12. The day of year (DOY) point of this intersection is defined as the time of the phenological event. Four measurements are extracted based on the DOY: time of onset of greenness (SOS), time of end of greenness (EOS), growing season length (GSL) and time of peak NDVI. SOS and EOS are defined by the DOY points at which the smoothed time series curve crosses a curve created by an autoregressive moving average model. GSL is defined as days from SOS to EOS. The time of peak NDVI describes the time of the most vigorous growth of land surface vegetation. Mean vegetation phenology measurements were calculated over the time series from 1999 to 2009 to remove any mistakes caused by intra-annual variability of remote sensing images.

3. Results and analysis
We found that the spatial pattern of LSP was relatively constant, with little inter-annual variation over the study period. The stable LSP is primarily due to the minor magnitude of climate fluctuations in this region. The mean LSP is displayed in figure 1.

3.1. SOS
Land surface vegetation phenology is highly correlated with land use/land cover and climate environment at the regional scale. As shown in figure 1a, the earliest SOS occurred in early January in two regions: (1) southern Jiangxi, Fujian, Guangdong and Taiwan, due to large amounts of coniferous, evergreen broad-leaved and montane mixed evergreen and deciduous broadleaved forests; and (2) central Henan and northern Anhui, due to large areas of cropland and their resultant early growth and high NDVI in winter. As a whole, however, SOS gradually increases from south to north, except for a large area of cropland, consisting of winter wheat, in the Henan and Anhui provinces. This spatial pattern is largely explained by the latitudinal temperature gradient, which results in vegetation growing earlier in lower latitudes. In addition, SOS shows an obvious vertical distribution along the elevation gradient: SOS occurs later in the year at higher altitudes, including the Dabie Mountains, the Huangshan Mountains on the border of Anhui and Jiangxi provinces, the Wuyi Mountains on the border of Zhejiang and Fujian provinces and the Mufushan Mountains on the border of Hubei and Jiangxi provinces.

3.2. EOS
The spatial pattern of EOS corresponds with the latitudinal gradient (figure 1b). Due to the large amount of evergreen broad-leafed forest, vegetation ceases growing late in southern latitudes, especially in Fujian, Guangdong and Taiwan. In some areas, the EOS can be 360 DOY, meaning that the vegetation has not stopped growing even at the end of the year. However, vegetation senescences early in the Huaihe river basin, especially in southern Henan and northern Anhui, where the autumn harvest of some grains (e.g., maize and rice) before the seeding of winter wheat results in vegetation growth ending in late September (EOS = 270 DOY). EOS also varies with elevation, especially in
areas where SOS showed a similar pattern. In these areas, there is little artificial vegetation (e.g., crops and landscape vegetation) and a predominance of natural and semi-natural vegetation. Further, coniferous forest abundance also increases with altitude. For these reasons, land surface vegetation senesces later at higher altitudes.

![Figure 1](image)

**Figure 1.** The spatial patterns of vegetation phenology in eastern China.

### 3.3. GSL

GSL describes the amount of time between the end of and the onset of greenness and is strongly controlled by both SOS and EOS. As shown in figure 1c, GSL varies with latitude, corresponding to north-south variations in temperature and water conditions. GSL lasts more than 330 days in the southern part of the study region along latitude 28° N. High GSL values are especially prominent in southern Jiangxi, northeastern Guangdong and most parts of Fujian and Taiwan, where the annual average temperature is approximately 12.6°C, rainfall is abundant, and large areas of sub-tropical evergreen broadleaf forest exist in the mountains. These factors produce high GSL values, due to early SOS and late EOS. In particular, evergreen broadleaf forest has high NDVI throughout the entire year, resulting in an extremely long growing season. However, GSL is only 220 days in the northern portion of the study area, including southeastern Henan and northern Anhui. In these areas, crop rotations that occur in late autumn may stop the growth of land surface vegetation and result in short GSL values. In...
addition, GSL shows a significant pattern corresponding to elevation gradients, such that GSL decreases with increasing altitude.

3.4. Time of peak NDVI
Unlike the three land surface phenology measurements described above, the time of peak NDVI shows no obvious spatial pattern along latitudinal gradients (figure 1d), corresponding instead primarily to land surface vegetation types. For instance, annual and perennial plants and crops with two-year, two three-cooked or cooked farming lead to different NDVI curves (e.g., single peak as compared to multi-peak) and correspondingly different times of peak NDVI. The earliest time of peak NDVI occurs in early April, in the drainage area of the Huaihe River basin, as a result of a vigorous growing season (e.g., wheat-booting stage) in the first half of the year. The latest time of peak NDVI occurs from the middle of September to early October in southern Fujian and eastern Guangdong, where two-year crops are planted. For instance, double-cropping rice is in the boot stage from late September to early October, resulting in heavy foliage. Because different vegetation types have different NDVI trends during the year (e.g., single or multi-peak curves), some regions may appear to show a multi-peak NDVI. For deciduous broadleaf forests, NDVI is described by a single peak curve. The evergreen broad-leaved forest also shows a single peak NDVI curve, but peak NDVI is less obvious due to high NDVI throughout the year. For crops with a two-year, two three-cooked or cooked farming, there are two or more NDVI peaks during each year. The time of peak NDVI correlates with elevation. Vegetation shows peak NDVI from early June to the middle of July primarily in the Wuyi mountain, Lushan mountain, Dabie mountain and Huangshan mountain.

3.5. Correlation between LSP and geographical location
500 random samples were selected to measure the correlation between LSP and geographical location, which is described by latitude, longitude and altitude. Multiple linear regression was performed using the stepwise regression method [12]. The result showed no significant correlations between longitude and the four phenology measurements, and SOS did not correlate with latitude, longitude or altitude. However, EOS, GSL and time of peak NDVI all correlated with latitude and altitude (table 1). These correlations indicate that (1) vegetation growth shows no clear pattern along the longitudinal gradient and (2) SOS is largely influenced by vegetation types. For example, SOS of winter wheat in the north occurs early, similar to SOS of southern areas of the study region that are covered with evergreen broad-leaved forest. Crops and farming systems disturb the natural SOS patterns along latitudinal and altitudinal gradients [13]. In fact, SOS shows a clear spatial pattern along latitudinal gradients except in northern croplands, in figure 1a. Through the method of stepwise regression, SOS and longitude were eliminated, showing that the other three phenology measurements were correlated with latitude and altitude.

| Phenology | Constant | Latitude | Altitude | Multiple R² | F       | Sig.  |
|-----------|----------|----------|----------|-------------|---------|-------|
| EOS       | 452.567  | -4.016   | 0.011    | 0.696 (P<0.01) | 232.872 | 0.000 |
| GSL       | 396.923  | -3.784   | -0.015   | 0.469 (P<0.01) | 70.130   | 0.000 |
| Time of Peak NDVI | 307.157 | -2.866   | -0.030   | 0.268 (P<0.01) | 19.244   | 0.000 |

4. Conclusion
Overall, SOS gradually increases from south to north, except for a large area of cropland in the Henan and Anhui provinces. EOS shows a strong latitudinal pattern, especially in southern areas, such as southern Jiangxi province, southern Fujian province, eastern Guangdong province and Taiwan province. EOS also shows a significant pattern with elevation changes. GSL shows a clear latitudinal pattern and gradually decreases with increasing altitude. The time of peak NDVI showed no obvious spatial pattern along latitudinal gradients and instead depends on land surface vegetation types and the presence of agricultural lands. In addition, there were no significant correlations between longitude
and the four phenology measurements, and SOS did not correlate with latitude, longitude or altitude, whereas EOS, GSL and time of peak NDVI were all correlated with latitude and altitude.

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