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Original article

Urban vegetation phenology analysis using high spatio-temporal NDVI time series

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ABSTRACT

Most of current products can partially reach the requirement of high spatial and temporal resolution needed in urban applications. Fortunately, the new generation of satellite in a form of constellation, e.g. Europe's Sentinel-2, China's HJ-1A/B and GF-1/6, is expected to provide more frequent observations (< 1 week) with a higher spatial resolution (< 30 m). Consequently, a proper method should be selected to construct high spatio-temporal time-series NDVI and to derive phenological features for urban applications. In this study, a high spatio-temporal NDVI product for urban scale vegetation time series is conducted based on HJ-1A/B data. Three related issues, i.e. the optimal filter, time series decomposition, phenological features derivation are addressed. In addition, the effect of spatial and temporal resolution on the phenological features extraction is also discussed according to the comparison between the derived NDVI product and that extracted from MODIS. The results show that the Savitzky-Golay (S-G) filter is the best filter for the reconstruction of HJ NDVI time series. There is some difference for phenology derivation using "season" and "season + trend" depending on the absence/presence of breakpoints in the curve. The spatial details of phenological features can be built by the high-spatial time-series NDVI, showing a great potential in urban applications. Compared with the MODIS NDVI time series, HJ NDVI time series can get more detail information than overall phenological features because of its high spatio-temporal resolution.

1. Introduction

Vegetation is of particular interest as it presents a versatile resource for effectively managing and moderating a variety of problems associated with urbanization. Urban vegetation serves a multitude of urban ecosystem functions (Bolund and Hunhammar, 1999). As a main characteristic which is the expression of the seasonal cycles of plant processes and their connections to climate change (temperature and precipitation), vegetation phenology is increasingly significant for a variety of scientific applications nowadays. The timing of phenological events can be used to document and evaluate the effects of climate change on both individual plant species and vegetation communities (IPCC, 2007). To study the features of urban vegetation phenology can better understand the ecological status of the city, the occurrence time of urban vegetation phenology can reflect the response of urban vegetation ecosystem to urban temperature change and precipitation.

Remote sensing provides a great opportunity to understand the vegetation phenology in different resolutions. The product of moderate-resolution imaging spectroradiometer Normalized Difference Vegetation Index (MODIS NDVI) time series data is one of the most popular data source (Zhang et al., 2003). The initial use of MODIS NDVI time series in monitoring global vegetation phenology was carried out (Reed et al., 1994; Moulin et al., 1997; Zhang et al., 2003), followed by increasingly number of applications at regional area (Hird et al., 2009; Shuai et al., 2013; Ma et al., 2013a,b; Jeganathan et al., 2014; Hilker et al., 2015) or global scale (Reed et al., 1994; Moulin et al., 1997; Brown et al., 2012). GIMMS NDVI is another similar data set that is widely used to detect the trend change of vegetation (Peng et al., 2012; Forkel et al., 2013; Jamali et al., 2015; Detsch et al., 2016). Relative to coarser spatial resolution data sources such as MODIS and GIMMS, Landsat series are able to resolve much greater fine-scale geographic variability in phenology (Melaas et al., 2013). Wulder et al. (2009) concluded that Landsat TM and its successive ETM+ have spatial (30 m), spectral and radiometric qualities that are especially well suited for ecological characterization.TM and ETM+ data have been systematically acquired for many portions of the globe since the launch of Landsat 5 in 1984, and thus a rich archive is available for analysis (Vogelmann et al., 2012). Therefore, some researchers paid attention to

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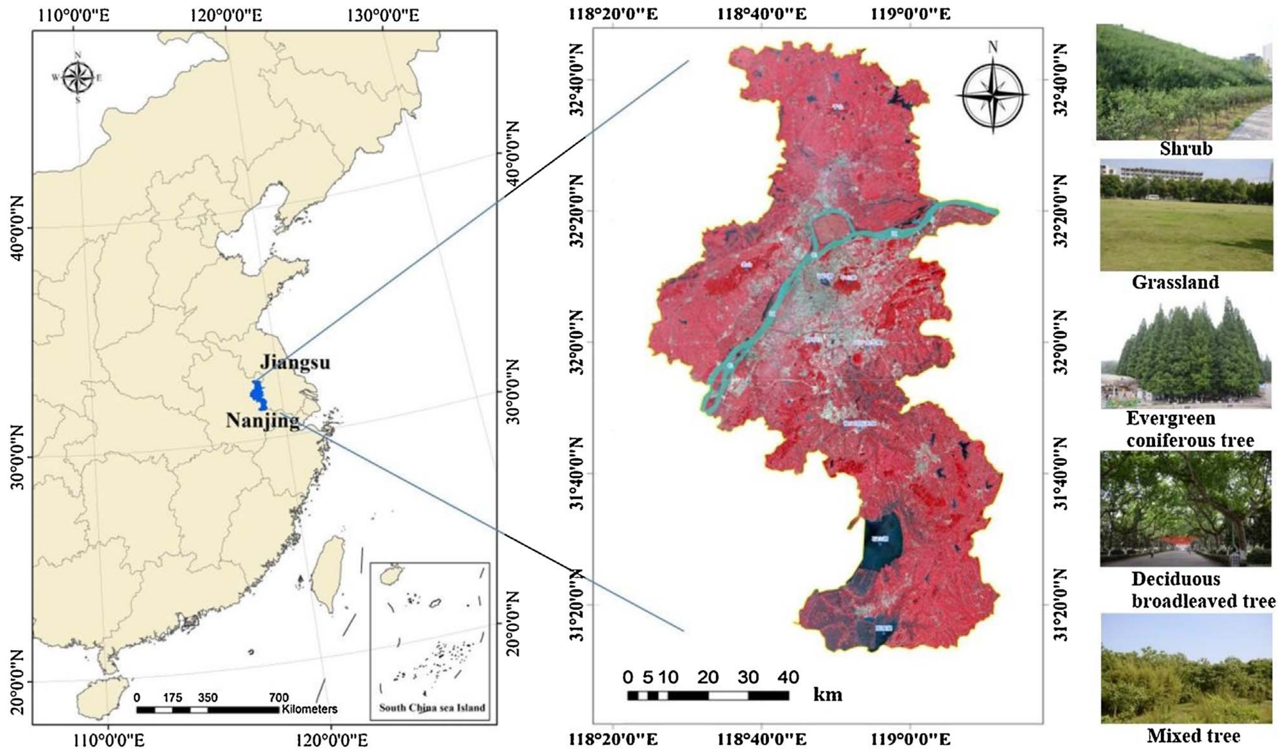

Fig. 1. Location of the study area and main types of urban vegetation.

application Landsat data to phenology study (Fisher et al., 2006; Vogelmann et al., 2012; Melaas et al., 2013).

Despite the great advance, few studies have been carried out in urban area. The main challenging is that the urban vegetation is different from the natural forest, which is smaller in spatial scale and more complex in spatial pattern. Phenological features of urban vegetation cannot be fully captured by aforementioned satellites (Pan et al., 2015). Fortunately, the new generation of satellite in a form of constellation, e.g. Europe's Sentinel-2, China's HJ-1A/B and GF-1/6, can provide more frequent observations (< 1 week) with a higher spatial resolution (< 30 m). The high spatio-temporal time-series NDVI products derived from these missions is expected to provide a great opportunity for urban applications.

Excepting the data set, the methodology for deriving vegetation phenology is also very important. Reed et al. (1994) proposed the autoregressive moving average method to measure phenological variability from satellite imagery, and the derived phenological metrics with this method have been proven to be consistent with the ground observed phenological events. And then, a curve fitting methodology was used to derive inter-annual phenologies from time series of satellite NDVI data (Bradley et al., 2007) and the method of high-order annual splines with roughness damping was employed to extract phenological signals from multiyear AVHRR NDVI time series (Hermance et al., 2007). More recently, Verbesselt et al. (2010b, 2012) proposed a Breaks For Additive Seasonal and Trend (BFAST) technique which is a very effective method to simulate long-term gradual phenological changes. Jamali et al. (2015) proposed one new user-program for analyzing vegetation time series named Detecting Breakpoints and Estimating Segments in Trend (DBEST) which is able to detect and characterize changes over large areas. Among these methods, BFAST is the most commonly used for deriving the vegetation phenology (Forkel et al., 2013).

As mentioned above, these studies investigated the vegetation phenology based on remote sensing data with relatively low spatial or temporal resolution. Therefore, for the scale of urban vegetation, some issues should be settled down including how to construct the high spatio-temporal resolution NDVI time series. In 2008, China launched the environmental and disaster monitoring and forecasting satellite A, B (HJ-1A/B satellite, hereafter referred to as HJ). The sensors capture ground features with 30 m pixel resolution at nadir angle, with four bands covering visible and near-infrared wavelength range (Ma et al., 2013a, 2013b). At present, most of researches based on HJ NDVI time series focus on large scale or homogeneous vegetation (Ma et al., 2013a, 2013b; Hao et al., 2014). Therefore, what are the optimal methods of deriving the urban vegetation phenology and what is the difference of urban vegetation phenology analysis using high spatio-temporal resolution NDVI time series and present NDVI time series products should be settled down. Related to these issues, in this study, we proposed the complete thinking for urban vegetation phenology researches including selecting the optimal filter, deriving phenology of urban vegetation, analyzing the spatial distribution patterns of urban vegetation phenology based on HJ NDVI time series, and then evaluating the advantage of the high spatio-temporal NDVI time series in urban vegetation phenology research. It is worth noting that the high spatio-temporal NDVI time series is necessary for urban vegetation phenology. The main contributions/purposes of this paper are as follows:

1) Forming the complete thinking for urban vegetation phenology study with the relative novel NDVI time-series product.
2) Addressing the importance of the high spatial resolution and temporal resolution for urban vegetation.

2. Study area, data source and image pre-processing

2.1. Study area

The city of Nanjing (118°46′ E , 32°03′N) is one of the metropolitan in China located in the largest economic zones of China, the Yangtze River Delta (Fig. 1), with an administrative area of 6598 km^2 of which 46.50% is covered by vegetation. Nanjing has a humid subtropical climate heavily influenced by the East Asia Monsoon, resulting in a hot rainy summer and cold dry winter. Specifically, the average annual

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