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Characterizing spatiotemporal dynamics in phenology of urban ecosystems based on Landsat data

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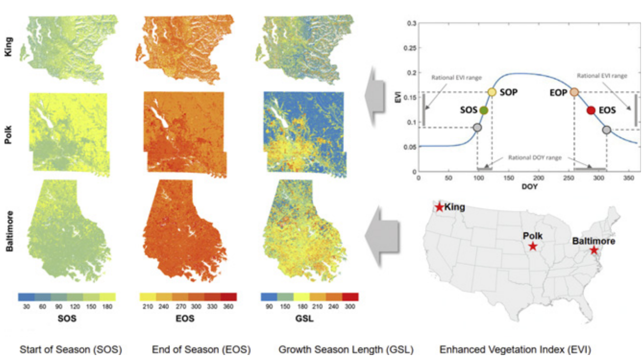
HIGHLIGHTS

- A self-adjusting double logistic model was used to derive vegetation phenology indicators (1982-2015) from Landsat
- The vegetation phenology in urban domains shows an earlier start-of-season (SOS) and a later end-of-season (EOS)
- The Landsat-derived phenology in urban domains can provide more spatial details compared to coarse-resolution products

GRAPHICAL ABSTRACT



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ABSTRACT

Seasonal phenology of vegetation plays an important role in global carbon cycle and ecosystem productivity. In urban environments, vegetation phenology is also important because of its influence on public health (e.g., allergies), and energy demand (e.g. cooling effects). In this study, we studied the potential use of remotely sensed observations (i.e. Landsat data) to derive some phenology indicators for vegetation embedded within the urban core domains in four distinctly different U.S. regions (Washington, D.C., King County in Washington, Polk County in Iowa, and Baltimore City and County in Maryland) during the past three decades. We used all available Landsat observations (circa 3000 scenes) from 1982 to 2015 and a self-adjusting double logistic model to detect and quantify the annual change of vegetation phenophases, i.e. indicators of seasonal changes in vegetation. The proposed model can capture and quantify not only phenophases of dense vegetation in rural areas, but also those of mixed vegetation in urban core domains. The derived phenology indicators show a good agreement with similar indicators derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) and in situ observations, suggesting that the phenology dynamic depicted by the proposed model is reliable. The vegetation phenology and its seasonal and interannual dynamics demonstrate a distinct spatial pattern in urban domains with an earlier (9–14 days) start-of-season (SOS) and a later (13–20 days) end-of-season (EOS), resulting in an extended (5–30 days) growing season length (GSL) when compared to the surrounding suburban and rural areas in the four study regions. There is a general long-term trend of decreasing SOS (−0.30 day per year), and increasing EOS and GSL (0.50 and 0.90 day per year, respectively) over past three decades for these study regions. The magnitude of these trends varies among the four urban systems due to their diverse local climate conditions, vegetation types, and different urban-rural settings. The Landsat derived phenology information for urban domains provides more details when compared to the coarse-resolution datasets such as MODIS, thus improves our understanding of human-natural systems interactions (or feedbacks) in urban domains. Such

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information is very valuable for urban planning in light of rapid urbanization and expansion of major metropolitans at the national and global levels.

1. Introduction

1.1. Background of urban vegetation phenology

Vegetation phenology and related indicators are widely used to assess the impact of ecological and environmental factors such as carbon emission, biodiversity, surface temperature change, land-use and land-cover changes on terrestrial ecosystems (Da Silva et al., 2015; Dahlin et al., 2015; Lu et al., 2006; Piao et al., 2008). The changes in vegetation phenology, for example, are affected by climate conditions and human activities, especially in urban systems (Brown et al., 2010; Luo et al., 2006; Schwartz, 1998). These factors in turn affect urban planning and design, energy consumption, and human health in rapidly expanding cities around the world. The population growth and economic development also contribute to rapid urbanization in most regions of the world and they in turn have significant impacts on surrounding natural ecosystems and their phenology (Liu et al., 2014; Solecki et al., 2013; Zhou et al., 2014b; Zhou et al., 2015; Zhou et al., 2010). Studies on urban vegetation phenology, an indicator of interactions between natural and human systems, is gaining increasing recognition (Jochner and Menzel, 2015; Wu, 2014). For example, a change in vegetation phenophases (i.e. stages of vegetation development) in the urban environment can alter the intensity of the urban heat island effect (Imhoff et al., 2010; Zhou et al., 2004), which is closely associated with the energy use in the urban system (Zhang et al., 2013; Zhou et al., 2014a). The change in vegetation phenophases also affects the amount and duration of pollens that have a major influence on the public health (e.g., allergies) in urban areas (Jochner and Menzel, 2015; Lu et al., 2006; Neil and Wu, 2006).

1.2. Remote sensing of vegetation phenology in urban domains

A wide range of studies have used remotely sensed observation to study changes in vegetation phenology and point out the advantage of such observations for continuous monitoring of urban ecosystems (Cong et al., 2013; Dong et al., 2016; Gonsamo and Chen, 2016; Neil and Wu, 2006; White et al., 2002; Zhou et al., 2016). For example, the MODIS (Moderate Resolution Imaging Spectroradiometer) observations provide near daily observations for such a purpose, over the entire globe (Ganguly et al., 2010; White et al., 2014; White et al., 1997; Zhang et al., 2003). Hence, they have been successfully used for regional-to-global phenology studies. However, results derived from these relatively coarse spatial resolution (e.g., 500 m) datasets are less suitable for studying urban ecology and environment, due to the highly heterogeneous land surfaces in urban-dominated regions with relatively sparse vegetation cover (Sohl et al., 2007; Yu et al., 2014). As a result, limited attention has been paid to the phenology in urban domain, particularly in urban core areas. This is probably due to the sparse and highly mixed vegetation coverage in urban domains that cannot be captured properly with medium to coarse spatial resolution observations by sensors such as MODIS.

Landsat-based observations potentially offer the ability to capture more detailed phenology characteristics of highly urbanized areas, since they have a finer spatial resolution (30 m) and cover a longer observational period, i.e. since 1970s (Li and Gong, 2016; Li et al., 2015; Roy et al., 2014; Woodcock et al., 2008). The Landsat data offer a combination of required temporal and spatial attributes that are needed to develop time series of good quality vegetation indices (VI), in absence of cloud contamination, to capture the vegetation phenology dynamics on a seasonal, annual, and decadal time scales. Currently, the use of Landsat-based time series of observations for phenology detection can be divided into two branches. The first branch is making full use of the long-term (e.g., more than 30 years) temporal information to reveal the mean phenology pattern of urban ecosystems. For example, Fisher et al. (2006) successfully rebuilt the phenology pattern of deciduous forests in the U.S. Southern New England region with 57 Landsat scenes for the 1984–2002 period. They estimated the inter-annual variability of phenology of these ecosystems based on the shifted pattern of VI in a specific year relative the long-term mean. This approach has been also used in other studies, with more observations (Melaas et al., 2013), or in comparison with other approaches (Fisher and Mustard, 2007). The second branch is based on the blending of MODIS and Landsat data as a fused product to take advantage of better spatial and temporal resolutions offered by Landsat and MODIS, respectively, for detecting the dynamics of vegetation phenology for specific periods. For example, Walker et al. (2012) adopted the spatial and temporal adaptive reflectance fusion model (STARFM) to combine 30 m Landsat and 500 m MODIS data for phenology studies in dry-land regions (i.e., Arizona, U.S.). However, the uncertainties introduced by the heterogeneous land covers below the spatial resolution of MODIS make it difficult to retrieve accurate phenology information based on this approach (Melaas et al., 2013). Overall, Landsat-based vegetation phenology products provide substantial information (i.e., both in space and time) in comparison with MODIS-derived products, especially for highly urbanized areas and heterogeneous ecosystems (Ganguly et al., 2010; Zhang et al., 2003).

1.3. Challenges and proposed research

Although Landsat-based phenology studies have been successfully conducted for natural forests (Fisher and Mustard, 2007; Fisher et al., 2006; Melaas et al., 2013; Walker et al., 2014) and other ecosystems, fewer attempts have been made for urban ecosystems and urban dominated areas, particularly in highly urbanized regions. Differing from natural ecosystem and rural areas, the vegetation phenology in urban domains is highly influenced by human activities (Jochner and Menzel, 2015). Melaas et al. (2016) used the smoothing spline technique to map the phenology pattern in the Boston metropolitan region based on long-term Landsat observations; however, they excluded the vegetation phenology for high intensity urban areas because of relatively lower vegetation coverage. Zipper et al. (2016) used the Landsat time series to explore the relationship between vegetation phenology and the urban heat island for city of Madison, Wisconsin. However, they only focused on a short period (i.e., 2012–2014), and a limited area in the urban-rural fringe. Given that the response of phenology to urbanization varies among different regions (Li et al., 2016b), due to a combination of climate, vegetation types and urbanization extent and rate, limited number of studies have been carried out in urban-dominated regions, particularly inside the urbanized regions. Consequently, this offers an opportunity to further explore the spatial pattern and temporal dynamics of vegetation phenology in urban core regions to advance our scientific understanding and knowledge in such regions.

For this purpose, we further developed and used a Landsat-based phenology detection algorithm initially reported by Fisher and Mustard (2007), to study four U.S. urban areas with distinctly different urbanization patterns. Because of the complexity of vegetation phenology in urban areas, which is influenced by a number of factors such as climate and emissions, new capabilities are needed in phenology detecting methods. Our approach with such new capabilities is unique as