Remote Sensing of Environment 199 (2017) 167–170

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

The relationship between threshold-based and inflexion-based approaches for extraction of land surface phenology

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ARTICLE INFO

Article history:
Received 23 November 2016
Received in revised form 11 July 2017
Accepted 17 July 2017
Available online xxxx

Keywords:
Land surface phenology
Vegetation growth trajectory
SOS
EOS
MODIS

ABSTRACT

The inflexion-based and threshold-based approaches are the two most popular approaches for extracting land surface phenology (LSP). The first approach uses inflexion point of the vegetation growth curve to determine the start-of-season (SOS) and end-of-season (EOS), while the second approach identifies SOS and EOS with a predefined percentage of vegetation growth amplitude. These two approaches have long been thought to be independent. In this letter, we investigated the relationship between the two approaches for extracting SOS. It was found that the thresholds at several key points in the inflexion-based approach are constant. The threshold at the inflexion point for SOS and EOS is 9.18% of vegetation growth amplitude. This threshold can link the SOS derived from the two approaches, which made it possible to determine the significant vegetation growth transitions for the threshold-based approach. Other thresholds for SOS retrieval, such as commonly-used 10% and 20% of vegetation growth amplitude, were also analyzed using a global reference NDVI. A high SOS difference between the two approaches indicates a slow vegetation growth.

1. Introduction

Phenology is critical for understanding the effect of climate change on vegetation (Ge et al., 2015). Satellite data provides the ability to extract land surface phenology (LSP) at regional and global scales. Two approaches are broadly used to determine the timing of the start-of-season (SOS) and end-of-season (EOS) from satellite data. The first determines SOS and EOS as a predefined percentage of the vegetation growth amplitude (Jonsson and Eklundh, 2004) (hereafter referred as the threshold-based approach), and the second identifies SOS and EOS by using the transitional characteristics of the vegetation growth curve (Zhang et al., 2003) (hereafter referred the inflexion-based approach).

The SOS for the two approaches was previously found to differ by up to ± 60 days (White et al., 2009). For example, the SOS from the threshold-based approach (50% of vegetation growth amplitude) occurs considerably later (>3 weeks) than that with the inflexion-based method in the eastern part of the United States (de Beurs and Henebry, 2010). The SOS acquired using the inflexion-based approach represents the vegetation growth transition from one approximately linear stage to another (Zhang et al., 2003). However, some vegetation growth trajectories cannot be fitted well with a logistic function (Cao et al., 2015), which prevents an inflexion point from being determined correctly. The threshold-based approach can extract SOS from a variety of vegetation growth trajectories. However, the threshold was arbitrarily set to extract SOS in terms of vegetation growth amplitude: 10% (Wu et al., 2014), 20% (Jonsson and Eklundh, 2004), 30% (Verger et al., 2016) or 50% (White et al., 1997).

This letter aimed to reveal the relationship of the two approaches for extracting SOS. The percentages (thresholds) of vegetation growth amplitude at several inflexion points in a logistic function were determined for extracting SOS. The spatial difference of the SOS between the two approaches for other thresholds was also demonstrated.

2. Methods and data

2.1. Theory analysis

The growth of deciduous vegetation tends to follow a specific temporal pattern: leaves appear, followed by rapid growth until a relatively stable period with maximum leaf area is reached (Zhang et al., 2003). This pattern can be modeled by a logistic function:

$$VI(t) = NDVI_{Min} + \frac{NDVI_{Max} - NDVI_{Min}}{1 + \exp(\text{ParaA} + \text{ParaB} * t)} \quad (1)$$

where $NDVI_{Max}$ is the maximum NDVI, $NDVI_{Min}$ is the minimum NDVI, t is the DOY, $VI(t)$ is the modeled NDVI value at t, and ParaA and ParaB are

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http://dx.doi.org/10.1016/j.rse.2017.07.020
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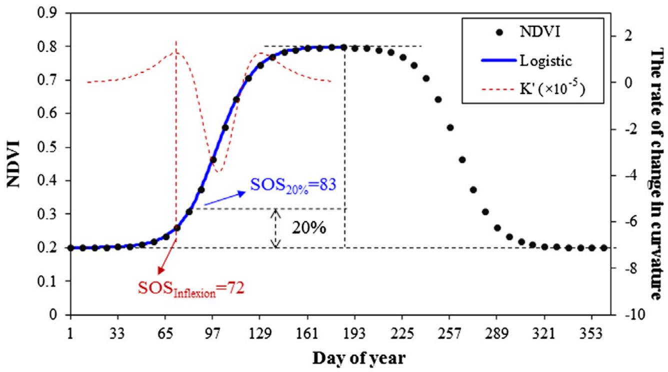

Fig. 1. The schematic diagram for extracting SOS from the two approaches, K′ is the rate of curvature change of the logistic function.

the fitting parameters. The absolute difference of the maximum and minimum NDVI is the vegetation growth amplitude (VGA).

The SOS from the inflexion-based approach is the maximum rate of change in curvature of the logistic function (hereafter referred as Zhang's inflexion point) (Zhang et al., 2003). The threshold-based approach determines SOS when the NDVI reaches a particular threshold (e.g., 20% of VGA). Fig. 1 is a schematic diagram for extraction of SOS with these two approaches. The SOS for the inflexion-based approach is DOY 72, and that for the threshold-based approach (with a threshold of 20%) is DOY 83.

The percentage of VGA at Zhang's inflexion point for SOS can be deduced mathematically below. The curvature (K) of a logistic curve (y) can be expressed as:

$$K = \frac{y''}{\left(1+(y')^2\right)^{3/2}} \quad (2)$$

where y' and y'' are the first-order and second-order derivatives, respectively. For the logistic function, $y' \ll 1$, so, $K \approx y''$. Therefore, the rate of change in curvature (K′) is approximately the third-order derivative of y. The SOS (t_{SOS}) and its percentage of VGA ($Percent_{SOS}$) can be acquired mathematically (details are given in Supplementary information):

$$t_{SOS} = \frac{\log_e\left(5+2\sqrt{6}\right) - ParaA}{ParaB} \quad (3)$$

$$Percent_{SOS} = \frac{NDVI_{SOS} - NDVI_{Min}}{NDVI_{Max} - NDVI_{Min}} \times 100\% = \frac{3-\sqrt{6}}{6} \times 100\% \approx 9.18\% \quad (4)$$

where t_{SOS} is the SOS, and $NDVI_{SOS}$ is its corresponding NDVI value. Eq. (4) shows that the percentage of VGA at Zhang's inflexion point for SOS is constant at 9.18%, which is independent of the fitting parameters. Similarly, the percentage of VGA at EOS is also 9.18%. Further, the percentage of VGA at maximum curvature is 21.13%, and that at the maximum growth rate is 50%. All these thresholds are constant and independent of the ParaA and ParaB.

2.2. Comparison of the two approaches at the global scale

The SOS extracted from the threshold-based approach with other thresholds such as commonly-used 10% and 20% were globally compared with those from the inflexion-based approach. The logistics function was fitted to the reference NDVI (described below) pixel-by-pixel and the SOS difference between the two approaches was calculated. To assure the logistics function can represent the real vegetation trajectory, those pixels with the absolute fitting bias larger than 0.06 were discarded. The low vegetated pixels with the annual maximum NDVI < 0.3 and the evergreen vegetation pixels with the VGA < 0.15 were excluded.

2.3. Examples using relationship between the two approaches

Two examples were presented the threshold of 9.18% can retrieve of SOS and EOS indicating transitional status of vegetation from some complicated vegetation growth trajectories. Firstly, the gaps in NDVI series were filled using the locally adjusted cubic-spline capping (LACC) approach (Chen et al., 2006), and then the SOS and EOS were retrieved by threshold of 9.18%. The results were compared with those from the adaptive local iterative logistic fitting method (ALILF) (Cao et al.,

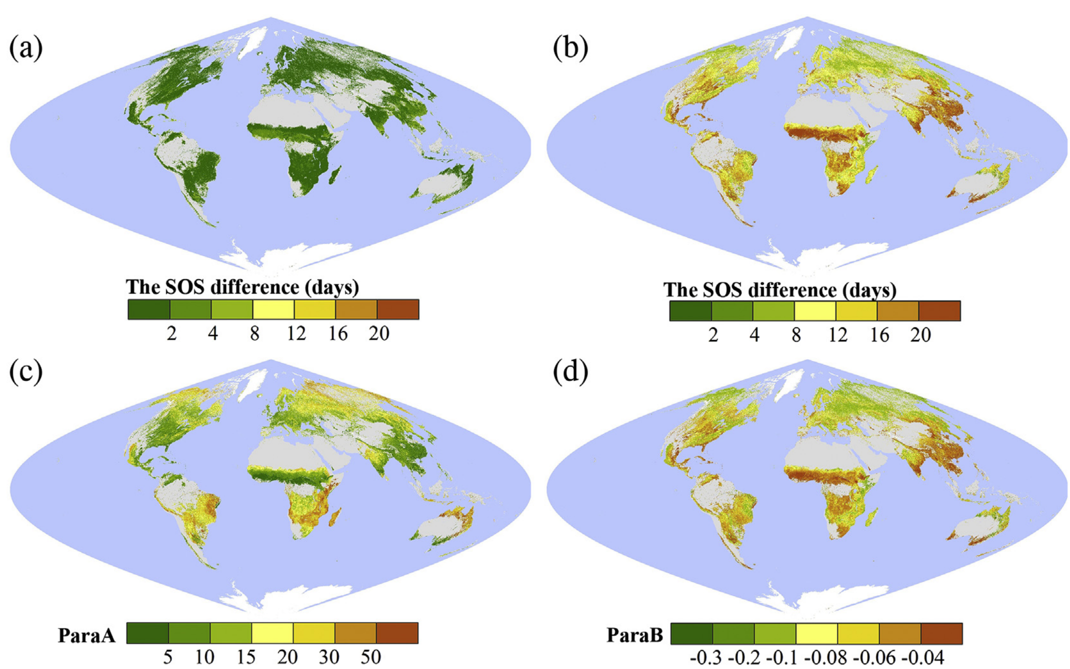

Fig. 2. The global distribution of the SOS differences between the inflexion-based approach and threshold-based approach with thresholds of 10% (a) and 20% (b), and the global distribution for the fitting parameter ParaA (c) and ParaB (d).