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An improved logistic method for detecting spring vegetation phenology in grasslands from MODIS EVI time-series data

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ABSTRACT

Satellite-derived greenness vegetation indices provide a valuable data source for characterizing spring vegetation phenology over regional or global scales. A logistic function has been widely used to fit time series of vegetation indices to estimate green-up date (GUD), which is currently being used for generating the global phenological product from the Enhanced Vegetation Index (EVI) time-series data provided by the Moderate Resolution Imaging Spectroradiometer (MODIS). In this study, we address a violation of the basic assumption of the logistic fitting method that arises from the fact that vegetation growth under natural conditions is controlled by multiple environmental factors and often does not follow a well-defined S-shaped logistic temporal profile. We developed the adaptive local iterative logistic fitting method (ALILF) to analyze the "local range" (i.e., the range of data points where the values in the time series begin to increase rapidly) in the MODIS EVI profile in which GUD is found. The new method adopts an iterative procedure and an adaptive temporal window to properly simulate the trajectory of EVI time series in the local range, and can determine GUD more accurately. GUD estimated by ALILF almost match the date of the onset of the greenness increase well while the traditional logistic fitting method shows errors of even more than 1 month in the same cases. ALILF is a more general form of the logistic fitting method that can estimate GUD both from well-defined S-shaped time series and from non-logistic ones. Besides, it is resistant to a range of noise levels added on the time-series data (Gaussian noise with a mean value of zero and standard deviations ranging from 0% to 15% of the EVI value). These advantages mean ALILF may be widely used for monitoring spring vegetation phenology from greenness vegetation indices.

1. Introduction

Spring vegetation phenology refers to the onset of photosynthetic activity, and is controlled by multiple environmental factors. Spring temperature has been widely accepted as the main factor driving spring phenology in temperate forests (Piao et al., 2006, Richardson et al., 2006), and spring precipitation is considered to be a main driver for deserts and temperate grasslands (Cong et al., 2012; Shen et al., 2011). Other less obvious factors such as photoperiod (Partanen et al., 1998) also affect spring phenology. Recent climate change, particularly spring warming, has greatly altered spring vegetation phenology (e.g., Menzel et al., 2006; Jeong et al., 2012). The changes in spring phenology are ecologically important because they strongly affect carbon cycling and energy balance in terrestrial ecosystems (Chapin et al., 2008; Jeong et al., 2009; Richardson et al., 2009). For instance, an earlier onset in spring was found to be one of the main factors to increase the carbon sink for northern hemisphere terrestrial ecosystems (Piao et al., 2008). It is thus very significant to monitor spring vegetation phenology to gain insights into linkage between phenology and climate at the large scale, which is a hot topic in global change research. Currently, monitoring spring phenology with wall-to-wall spatial coverage is only available based on satellite remotely sensed data.

Two main types of methods have been developed to determine the timing of spring phenology from time series of satellite-derived

Abbreviations: ALILF, adaptive local iterative logistic fitting method; AVHRR, advanced very high resolution radiometer; DOY, day of year; EVI, enhanced vegetation index; GUD, green-up date; MODIS, moderate resolution imaging spectroradiometer.

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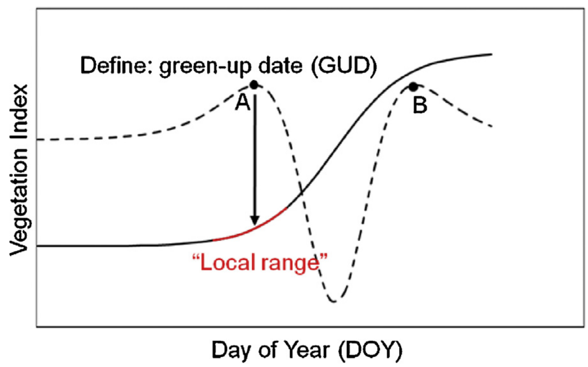

Fig. 1. A schematic diagram of how the vegetation green-up date (GUD) can be determined using the logistic fitting method, modified after Zhang et al. (2003). The solid line indicates the fitted logistic curve, and the dashed line is the rate of change in curvature of the fitted logistic curve. GUD is defined as the first local maximum of the dashed curve (i.e., point A), and the second local maximum (i.e., point B) is identified as the onset of vegetation maturity. The red line indicates the Local range (i.e., the range where the vegetation index begin to increase rapidly) in the time-series data in which GUD is found. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

vegetation indices. The first type is threshold-based, and defines spring phenology based on the date when a vegetation index reaches a predefined threshold (i.e., an absolute threshold; Lloyd, 1990) or a specific percentage (e.g., 20% or 50%) of its annual amplitude (i.e., a relative threshold; White et al., 1997; Yu et al., 2010). The second type of method commonly used focuses on changing characteristics in the time series. This group of methods assumes that vegetation growth follows a relatively well-defined temporal pattern and can be fitted by a predefined mathematical function, which is normally considered to be a sigmoid function. Spring phenological events can then be identified from the fitted curve (Fisher and Mustard, 2007; Zhang et al., 2003, 2006). For example, Zhang et al. (2003) used a four-parameter logistic model to simulate vegetation growth and defined spring phenology as the date when the rate of change in curvature for the fitted curve exhibits the first local maximum (Fig. 1).

All these methods, in general, adopt different rules to define the area-averaged greenness onset in spring, and thus remotely-sensed spring phenology estimated by different methods could differ considerably (White et al., 2009). Zhang's logistic method actually captures the timing when vegetation greenness begins to increase rapidly, which is represented by the green-up date (GUD) in Fig. 1. This method has been widely used in regional and global phenology research (e.g., Shen et al., 2012; Zhang et al., 2004, 2006; Zhu et al., 2012), and is currently being used for generating the global phenological product based on the time series of the Enhanced Vegetation Index (EVI) data provided by the Moderate Resolution Imaging Spectroradiometer (MODIS; Friedl et al., 2010; Ganguly et al., 2010; MCD12Q2 User Guide; Zhang et al., 2003, 2006).

The effectiveness of logistic methods is dependent on the basic assumption that vegetation growth follows a well-defined S-shaped temporal profile. In this study, we hypothesized that determining GUD from time series of a greenness vegetation index, especially in grasslands, would suffer from uncertainties in logistic curve fitting due to the fact that the time series from spring to summer does not necessarily follow an ideal sigmoid curve, and sometimes may deviate greatly from this curve. Violation from the ideal S-shaped growth curve occurs quite often, because natural vegetation does not grow under ideal conditions, but is instead affected by a range of environmental stresses (e.g., climate, insects or diseases) at various times. In temperate grasslands, for example, grass growth can be greatly interfered by drought events, because herbaceous plants usually have underdeveloped root system

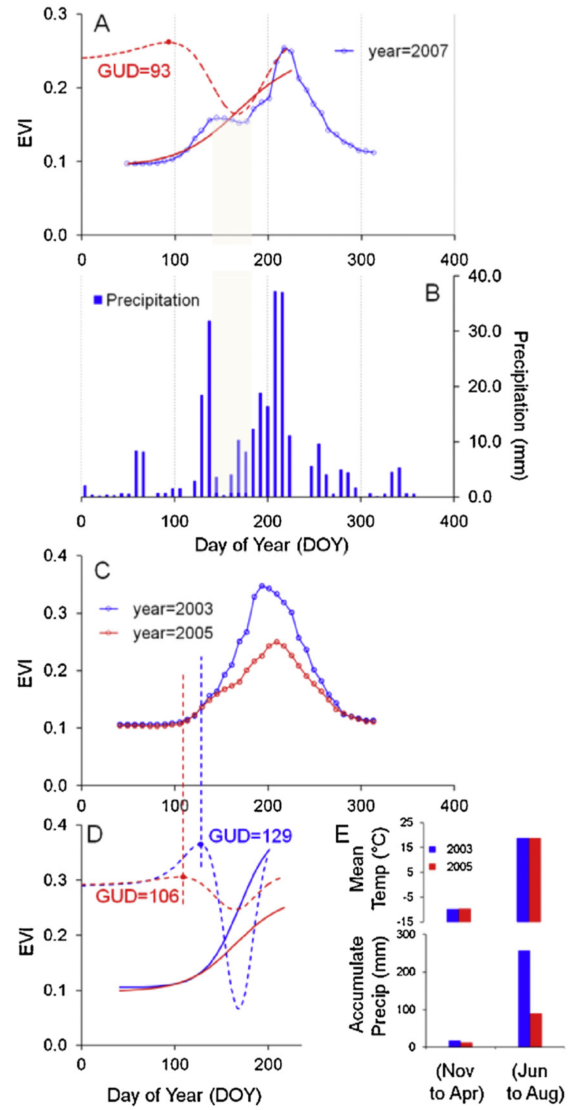

Fig. 2. Time series for MODIS enhanced vegetation index (EVI) and the determined GUD (the first local maximum in the rate of change in curvature) in 2007 (A) and the corresponding temporal precipitation in 2007 (B). The MODIS EVI time series in 2003 and 2005 (C), and the fitted logistic curve (solid line) and the determined GUD in 2003 and 2005 (D). Panel (E) shows the mean air temperature and cumulative precipitation during the growing season (from June to August) and in the preseason period (from November of the previous year through April of the current year) for 2003 and 2005. *Note*: All data represent spatially average data for 100 × 100 MODIS pixels around the Xilinhot weather station, Xilin Gol, Inner Mongolia (43.57°N, 116.07°E), which is indicated as the dashed line box in Fig. 5. Source of climate data: China Meteorological Data Sharing Service System (CMDSSS, http://cdc.cma.gov.cn).

compared with shrubs and forests and are less resistant to the lack of available soil water (Liu et al., 2013; Zhou et al., 2013). Fig. 2A illustrates this problem: MODIS EVI time-series data collected in the Xilin Gol grassland exhibited an obvious two-stage greenness increase in the spring of 2007. Vegetation growth stalled in the middle of this season (from approximately day of year (DOY) 140 to DOY 180) due to a lack of precipitation during this period (Fig. 2B). Fitting this time series by Zhang's logistic method (hereafter referred to as the traditional logistic fitting) only tends to model the overall growth pattern but miss the "local range" (i.e., the range of data points that occur around the onset of EVI increase) in the time series (Fig. 2A). Effects of non-ideal logistic vegetation growth on GUD determination are further illustrated in Fig. 2C and D, in which the difference in the determined GUD is as much as 23 d between 2003 and 2005. For the two years, an almost identical trajectory