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Evaluation of land surface phenology from VIIRS data using time series of PhenoCam imagery

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ABSTRACT

Land surface phenology (LSP) has been widely retrieved from time series of various satellite instruments in order to monitor climate change and ecosystem dynamics. However, any evaluation of the quality of LSP data sets is quite challenging because the in situ observations on a limited number of individual trees, shrubs, or other plants are rarely representative of the landscape sampled in a single satellite pixel. Moreover, vegetation indices detecting biophysical features of vegetation seasonality are different from (but related to) the specific plant life history stages observed by humans at ground level. This study is the first comprehensive evaluation of the LSP product derived from Visible Infrared Imaging Radiometer Suite (VIIRS) data using both MODIS LSP products and observations from the PhenoCam network across the Contiguous United States during 2013 and 2014. PhenoCam observes vegetation canopy over a landscape at very high frequency, providing nearly continuous canopy status and enabling the estimate of discrete phenophase using vegetation indices that are conceptually similar to satellite data. Six phenological dates (greenup onset, mid-greenup phase, maturity onset, senescence onset, mid-senescence phase, and dormancy onset) were retrieved separately from daily VIIRS NDVI (normalized difference vegetative index) and EVI2 (two-band enhanced vegetation index) time series. Similarly, the six phenological dates were also extracted from the 30-min time series of PhenoCam data using GCC (green chromatic coordinate) and VCI (vegetation contrast index) separately. Phenological dates derived from VIIRS NDVI and EVI2 and PhenoCam GCC and VCI were generally comparable for the vegetation greenup phase, but differed considerably for the senescence phase. Although all indices captured green leaf development effectively, performance discrepancies arose due to their ability to track the mixture of senescing leaf colors. PhenoCam GCC and VCI phenological observations were in better agreement with the phenological dates from VIIRS EVI2 than from VIIRS NDVI. Further, the VIIRS EVI2 phenological metrics were more similar to those from PhenoCam VCI than from PhenoCam GCC time series. Overall, the average absolute difference between the VIIRS EVI2 and PhenoCam VCI phenological dates was 7–11 days in the greenup phase and 10–13 days in the senescence phase. The difference was smaller in forests, followed by grasslands and croplands, and then savannas. Finally, the phenological dates derived from VIIRS EVI2 were compared with MODIS detections, which showed a good agreement with an average absolute difference less than a week except for the senescence onset. These results for the first time demonstrate the upper boundary of uncertainty in VIIRS LSP detections and the continuity to MODIS LSP product.

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1. Introduction

Vegetation phenology plays an important role in understanding climate change due to the biophysical nature of the timing of leaf-on and leaf-off (Cleland et al., 2012; Ivits et al., 2012; Menzel et al., 2006; Morisette et al., 2009; Parmesan and Yohe, 2003). Ground-based direct visual observations and measurements have traditionally been used to record the timing of specific phenological events (e.g., flowering) for particular plant species, at small spatial extents (Abu-Asab et al., 2001; Ault et al., 2015; Morin et al., 2009; Richardson et al., 2006; Schwartz et al., 2006, 2013, 2002). Sensors onboard satellite observatories, such as the Advanced Very High Resolution Radiometer (AVHRR) and the MODerate resolution Imaging Spectroradiometer (MODIS), provide Earth observations at nearly global coverage every day. These data allow the seasonal dynamics of the vegetated land surface to be mapped and monitored at regional to global scales. As a result, a variety of land surface phenology (LSP) products have been developed for the study of climate change, ecosystem dynamics, biodiversity, and terrestrial carbon budget at multiple scales (Henebry and de Beurs, 2013). For example, the start and end of vegetation growth, as observed since 1981 at spatial resolutions of 8–16 km, have been extensively investigated using the normalized difference vegetation index (NDVI) data derived from the AVHRR GIMMS (Global Inventory Modeling and Mapping Studies) dataset at local, regional, and global scales (de Beurs and Henebry, 2010; de Jong et al., 2011; Myneni et al., 1997; Reed et al., 1994; White et al., 2009; Zhang et al., 2007). More recently, LSP products with spatial resolutions of 250–1000 m have been produced from MODIS NDVI and enhanced vegetation index (EVI) data, including the USGS EROS 250 m eMODIS LSP data (2001–2014) across the Contiguous United States (CONUS) (cf. Reed et al., 1994); the NASA NACP (North American Carbon Program) 250 m LSP data over North America (Tan et al., 2011); and the NASA 500 m Land Cover Dynamics Products (MCD12Q2) covering the entire globe (Ganguly et al., 2010; Zhang et al., 2006, 2003). Further, for continuity purposes, since the AVHRRs lack a separate blue channel needed to calculate the EVI, the two-band enhanced vegetation index (EVI2; Jiang et al., 2008), which is functionally equivalent to the EVI, has been used to detect long-term global land surface phenology from both AVHHR and MODIS at a spatial resolution of 0.05° (Zhang et al., 2014).

It is challenging to evaluate and validate LSP with in-situ measurements due to vast differences in scale and the different kinds of phenomena being observed. Consequently, the quality of satellite-derived LSP products and their relation to biological events in plants have been poorly characterized. Previous studies evaluated LSP using phenological timing from empirical or bioclimatic models (Schaber and Badeck, 2003; Schwartz, 1999), ground-based cryosphere and hydrology network records (White et al., 2009), phenological measurements from long-term ecological research networks (Ganguly et al., 2010; Soudani et al., 2008; Zhang et al., 2006), gross primary productivity from flux towers (Sakamoto et al., 2010; Xiao et al., 2013), observations of specific species in a phenology network (Delbart et al., 2015; Liang et al., 2014), and landscape phenology indices aggregated from individual plants (Liang et al., 2011). The samples from these assessments are not intrinsically comparable to satellite-derived LSP because different biophysical properties were being measured and the data are available only at very few locations and a limited number of ecosystem types. Thus, these approaches are ineffective for the direct evaluation and validation of LSP data at satellite pixels.

Recently, near-surface remote sensing has been used to provide diurnal monitoring of vegetation developments at canopy to landscape scales without significant impacts from atmospheric scattering or obscuring clouds (Richardson et al., 2009a). The PhenoCam network captures digital images from tower-mounted web cameras, thus providing consistent and continuous monitoring of vegetation canopy conditions at locations throughout the United States (Hufkens et al., 2012; Richardson et al., 2009b, 2007; Sonnentag et al., 2012). The digital repeat photography generated by PhenoCam protocol contains high spatial and temporal resolution imagery composed of red, green, and blue color planes. These images allow for the characterization of seasonal dynamics via image processing approaches similar to those applied to satellite imagery. They also provide the opportunity for visual interpretation of vegetation development, because they appear like ordinary photographs at a familiar resolution. Combining visual interpretation and image processing of PhenoCam time series enables a generalized phenology of the observed vegetation canopies to be characterized. The PhenoCam system and protocols are not able to replace direct high-quality field observations (e.g., date of first leaf, date of flowering, etc.). Thus, time series of PhenoCam observations have been used to monitor vegetation phenology at the local and regional scales (Sonnentag et al., 2012; Toomey et al., 2015). PhenoCam data have also been shown to be a robust tool to evaluate phenological transition dates derived from satellite remote sensing (Keenan and Richardson, 2015; Klosterman et al., 2014; Rodriguez-Galiano et al., 2015).

A well-validated long-term LSP product is critical for investigating the phenological shifts induced by climate change and land disturbance as well as the phenological impacts on ecosystem function, biodiversity, and carbon budgets. For this purpose, MODIS LSP product (MCD12Q2) has been operationally produced in NASA from time series of MODIS observations since 2000 (Ganguly et al., 2010; Zhang et al., 2006, 2003). Because the MODIS sensors are aging and nearing the end of their duty cycles, the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor, onboard the Suomi National Polar-orbiting Partnership (NPP) satellite (launched October 28, 2011), is intended to provide continuity with the MODIS data record (Justice et al., 2013; Roman et al., 2011). During the next few decades, VIIRS on the Joint Polar Satellite System (JPSS) series, which is planned to launch in late 2017 (JPSS-1) and late 2021 (JPSS-2) (Goldberg et al., 2013), will continue to provide the capability to monitor LSP. Thus, the MODIS phenology product (MCD12Q2) will be replaced using LSP retrievals from VIIRS data, which makes it critical now to understand the capabilities of VIIRS observations for LSP detections.

This study is the first comprehensive evaluation of the VIIRS phenology product that will become the operational standard to continue the MODIS phenology record. The three goals of this study are (1) to investigate the differences between NDVI and EVI2 for LSP detections so that the better vegetation index may be selected for VIIRS LSP product generation; (2) to evaluate the accuracy and uncertainty of VIIRS LSP detections by direct comparison against phenological transition dates derived from two indices calculated from PhenoCam data; and (3) to verify that VIIRS will provide continuity with MODIS by directly comparing the VIIRS LSP detections at PhenoCam sites with the corresponding MODIS retrievals.

2. Data and methods

2.1. Land cover and land surface temperature data

To define the land cover types of the VIIRS pixels that the PhenoCams were viewing, we used the International Geosphere-Biosphere Programme (IGBP) scheme in the MODIS land cover product (MCD12Q1) in 2013 (Friedl et al., 2010).

MODIS land surface temperature (LST) product (MOD11A1, V006) at a spatial resolution of 1 km was used from July 2012 to June 2015. The LST data were rescaled to 500 m using a nearest neighbor method to match the spatial resolution of the VIIRS data. These LST time series determined the winter period in the processing of VIIRS time series (cf. Section 2.4). Note that the VIIRS LST product, which is currently under development for operational production by NASA, will eventually replace the MODIS LST after the MODIS sensors reach their end of their duty cycles, by approximately 2021 or sooner.