



## Exploration of scaling effects on coarse resolution land surface phenology



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## ARTICLE INFO

## Article history:

Received 2 April 2016

Received in revised form 22 December 2016

Accepted 7 January 2017

Available online 13 January 2017

## Keywords:

Land Surface Phenology

Scaling Effects

Spatial Heterogeneity

VIIRS

OLI

## ABSTRACT

Numerous land surface phenology (LSP) datasets have been produced from various coarse resolution satellite data and different detection algorithms from regional to global scales. In contrast to field-observed phenological events that are defined by clearly evident organismal changes with biophysical meaning, current approaches to detecting transitions in LSP only determine the timing of variations in remotely sensed observations of surface greenness. Since activities to bridge LSP and field observations are challenging and limited, our understanding of the biophysical characteristics of LSP transitions is poor. Therefore, we set out to explore the scaling effects on LSP transitions at the nominal start of growing season (SOS) by comparing detections from coarse resolution data with those from finer resolution imagery. Specifically, using a hybrid piecewise-logistic-model-based LSP detection algorithm, we detected SOS in the agricultural core of the United States—central Iowa—at two scales: first, at a finer scale (30 m) using reflectance generated by fusing MODIS data with Landsat 8 OLI data (OLI SOS) and, second, at a coarser resolution of 500 m using Visible Infrared Imaging Radiometer Suite (VIIRS) observations. The VIIRS SOS data were compared with OLI SOS that had been aggregated using a percentile approach at various degrees of heterogeneity. The results revealed the complexities of SOS detections and the scaling effects that are latent at the coarser resolution. Specifically, OLI SOS variation defined using standard deviation (SD) was as large as 40 days within a highly spatially heterogeneous VIIRS pixel; whereas, SD could be <10 days for a more homogeneous set of pixels. Furthermore, the VIIRS SOS detections equaled the OLI SOS (with an absolute difference less than one day) in >60% of OLI pixels within a homogeneous VIIRS pixel, but in <20% of OLI pixels within a spatially heterogeneous VIIRS pixel. Moreover, the SOS detections in a coarser resolution pixel reflected the timing at which vegetation greenup onset occurred in 30% of area, despite variation in SOS heterogeneities. This result suggests that (1) the SOS detections at coarser resolution are controlled more by the earlier SOS pixels at the finer resolution rather than by the later SOS pixels, and (2) it should be possible to well simulate the coarser SOS value by selecting the timing at 30th percentile SOS at the finer resolution. Finally, it was demonstrated that in homogeneous areas the VIIRS SOS was comparable with OLI SOS with an overall difference of <5 days.

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## 1. Introduction

Remote sensing has been widely used to characterize seasonal vegetation dynamics at continental and global scales during the last three decades, because it can provide frequent and consistent measurements that are spatially exhaustive. Due to the coarse spatial resolution (>500 m) of synoptic sensors, remote sensing monitors seasonal

dynamics of the vegetated land surface that often includes multiple types of vegetation mixed with other scene objects, such as soil, water, and human structures. Land surface phenology (LSP) is the term used to distinguish the object of remote sensing from traditional notions of species-specific organismal phenology observed at ground level (de Beurs and Henebry, 2004; Henebry and de Beurs, 2013). The most commonly used satellite data for LSP characterization have been from the Advanced Very High Resolution Radiometer (AVHRR) instruments at a spatial resolution from 5 km–8 km (White et al., 2009; Zhang et al., 2007, 2014; de Jong et al., 2011; Julien and Sobrino, 2009; Zhou et al., 2001), because they boast the longest and densest time

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series available at a global coverage. With the availability of the Moderate-resolution Imaging Spectroradiometer (MODIS) data since 2000, which substantially improved radiometric and geometric properties, atmospheric correction, and cloud screening of the time series, it has been possible to characterize a more reliable and consistent LSP at spatial resolutions from 250 m to 1000 m (Ganguly et al., 2010; Tan et al., 2011; Zhang et al., 2006). Recently, Landsat data at a spatial resolution of 30 m has also been applied to retrieve LSP (Fisher et al., 2006; Krehbiel et al., 2015; Melaas et al., 2013; Walker et al., 2012); however, Landsat's relatively long period for repeat observations (~16 days) have made it impractical to consistently produce annual time series at a regional scale for most parts of the planet.

A number of approaches have been developed to detect LSP, particularly, the start of growing season (SOS), based on the time series of satellite observations. Most approaches first smooth and gap-fill time series of vegetation indices using one or more of the methods that include asymmetric Gaussians (Jonsson and Eklundh, 2002), piecewise logistic function (Zhang et al., 2003), Savitzky-Golay filter (Chen et al., 2004), best index slope extraction algorithm (BISE) (Viovy et al., 1992), moving average (Reed et al., 1994), moving median, iterative interpolation (Julien and Sobrino, 2010), Fourier fitting (Moody and Johnson, 2001; Wagenseil and Samimi, 2006), polynomial curve fitting (Bradley et al., 2007), or the convex quadratic model based on thermal time (de Beurs and Henebry, 2004; Henebry and de Beurs, 2013). The timings of phenophase transitions during the vegetation growing season are then extracted based on either predefined absolute or relative thresholds of vegetation indices (Jonsson and Eklundh, 2002; Lloyd, 1990; Reed et al., 1994; White et al., 1997), or features of the fitted curves such as the inflection points (de Beurs and Henebry, 2010; Tan et al., 2011; Zhang et al., 2003).

While a great number of LSP data have been produced from various satellite datasets and approaches, the biophysical meaning and scaling effects of these phenological data have rarely been investigated. Relative to the large number of LSP datasets produced, the validation activities have been surprisingly limited and simple. Validation efforts have been typically conducted in one or more of the following ways.

First, the extracted LSP transition or phenometrics have been indirectly compared with model outputs or other variables observed at ground level. For example, the LSP SOS calculated from 8 km 15-day composite AVHRR NDVI data was linked to phenological timings from empirical or bioclimatic models, such as the climate data-driven phenology (Schaber and Badeck, 2003; Schwartz and Reed, 1999), and associated with ground-based records from cryospheric and hydrological networks (White et al., 2009). These comparisons have generally shown poor correlations, such as no significant relationship between LSP SOS and the modeled phenology (Schwartz and Hanes, 2010), or differences between AVHRR SOS and ground observations that could exceed two months (White et al., 2009).

Second, pixel-based LSP has also been compared with phenological observations of vegetation communities within field plots. For example, the MODIS SOS in a 1 km<sup>2</sup> footprint exhibited a root mean square error (RMSE) of 20.5 days and a bias of 17 days compared with in-situ observations of 36 trees in a 0.5 ha (0.005 km<sup>2</sup>) plot in France (Soudani et al., 2008). Satellite derived green-up timing had a RMSE of about 15 days as compared with leaf-out dates of four woody species observed from the PlantWatch citizen science project across Canada (Delbart et al., 2015).

Third, LSP SOS dates have also been compared with landscape scale observations. By aggregating individual plants to population, community, and landscape scales within homogeneous regions consisting of deciduous and conifer plants, indices of landscape phenology — a concept distinct from land surface phenology (Liang and Schwartz, 2009) — were derived and compared with MODIS SOS dates (Liang et al., 2011). The results indicated the LSP SOS dates matched well with full bud burst in deciduous forests, but not so well in conifer forests, which lagged LSP SOS dates by about 10 days.

Fourth, LSP SOS dates have recently been compared to PhenoCam observations. PhenoCam provides consistent and continuous monitoring of vegetation canopy conditions using tower-mounted webcams that collect images multiple times a day (Hufkens et al., 2012; Richardson et al., 2009; Richardson et al., 2007; Sonnentag et al., 2012). It has provided important information for validating and understanding satellite-derived LSP. However, PhenoCam analyses rely on vegetation indices derived from visible wavelengths, introducing some differences from satellite vegetation indices that are derived from both red and near infrared reflectance. Moreover, a mismatch of camera field of view angle and its large variation with the view angle of satellite pixel-coverage may cause major uncertainties (Elmore et al., 2012; Graham et al., 2010; Hufkens et al., 2012; Keenan et al., 2014).

Validation efforts have shown a discrepancy of >10 days between LSP and other phenological observations. This discrepancy arises in part from the arguably erroneous assumptions that (1) field observations are obtained from large homogeneous sites, and (2) LSP measurements should be consistently equivalent to the field observations despite the scaling differences. Homogeneous SOS values within a moderate or coarse satellite footprint are rarely observed because the timing of phenophase transitions vary greatly among different species and even within the same species due to ecotypic variation or local site conditions. Indeed, woody understory plants often leaf out more than three weeks earlier than the forest canopy (Augspurger et al., 2005). Budburst dates for coexisting tree species in temperate forests can vary by three weeks or more (Lechowicz, 1984). Similarly, budburst dates among woody species within an area of locally homogeneous forests can even vary by roughly six weeks (Richardson and O'Keefe, 2009). Even in relatively homogeneous deciduous forests (with similar composition, age, and structure), leaf out timing in a same species can vary more than two weeks spatially within a 500 m area (Fisher et al., 2006).

These findings indicate that simple comparisons of LSP with field observations may only illuminate their differences rather than provide meaningful validation. This situation arises mainly because the scaling effects on the coarse resolution LSP are poorly understood. Field phenological measurements have sharply defined life cycle events, such as the appearance of first bloom, first leaf unfolding, and first leaf coloration. In contrast, "events" in LSP are not sharply defined, but rather are transitions within fitted curves of remotely sensed "greenness" that has equivocal biophysical meaning. This study, therefore, aims to explore the question: what kinds of SOS occurrences at the field scale translate into coarser resolution LSP "events"?

Our hypothesis is that SOS at coarser resolution becomes detectable once the vegetation starts to greenup in a certain proportion of finer resolution pixels. A corollary to this hypothesis is that coarser resolution SOS is driven by the portion of earlier SOS pixels at the finer resolution rather than the later SOS pixels. To explore this hypothesis, we made the assumptions that (1) vegetation phenology, environmental conditions, and microclimate within the 30 m scale are relatively homogenous, and (2) the SOS derived at the finer scale could well represent the start of surface vegetation leaf seasonality. Thus, we first detected LSP at finer scale (30 m) using the reflectance data from the fusion of MODIS data with Landsat 8 OLI observations, and then at the coarser resolution (500 m) using Visible Infrared Imaging Radiometer Suite (VIIRS) observations during 2013 and 2014. The scaling effect on SOS at coarser resolution was then investigated by linking to the SOS observations at the finer scale. Our study area is central Iowa in the United States (US), where agricultural lands dominate in the northern part of the State and forests and grasslands occur in the south. The timing of phenological events spans a wide range in central Iowa from low spatiotemporal heterogeneity within crop fields, to moderate spatiotemporal heterogeneity between different crop types, to high spatiotemporal heterogeneity in mixtures of croplands and natural vegetation.

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