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Multisite analysis of land surface phenology in North American temperate and boreal deciduous forests from Landsat

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ABSTRACT

Forests play important roles in the Earth's climate system and global carbon cycle. Therefore, a critical need exists to improve our understanding of how the growing seasons of forests are changing, and by extension, how the composition and function of forests will respond to future climate change. Coarse spatial resolution satellite remote sensing has been widely used to monitor and map the phenology of terrestrial ecosystems at regional to global scales, and despite widespread agreement that the growing season of Northern Hemisphere forests is changing, the spatial resolution of these data sources imposes significant limitations on the character and quality of inferences that can be drawn from them. In particular, the spatial resolution afforded by instruments such as MODIS does not resolve ecologically important landscape-scale patterns in phenology. With this issue in mind, here we evaluate the ability of a newly developed Landsat phenology algorithm (LPA) to reconstruct a 32-year time series for the start and end of the growing season in North American temperate and boreal forests. We focus on 13 "sidelap" regions located between overlapping Landsat scenes that span a large geographic range of temperate and boreal forests, and evaluate the quality and character of LPA-derived start and end of growing season (SOS and EOS) dates using several independent data sources. On average, SOS and EOS dates were detected for about two-thirds of the 32 years included in our analysis, with the remaining one-third missing due to cloud cover. Moreover, there was generally better agreement between ground observations and LPA-derived estimates of SOS dates than for EOS across the 13 sites included in our study. Our results demonstrate that, despite the presence of time series gaps, LPA provides a robust basis for retrospective analysis of long-term changes in spring and autumn deciduous forest phenology over the last three decades. Finally, our results support the potential for monitoring land surface phenology at 30 m spatial resolution in near real-time by combining time series from multiple sensors such as the Landsat Operational Land Imager and the Sentinel 2 MultiSpectral Instrument.

1. Introduction

Forests play an important role in the Earth's climate system and global carbon cycle (Bonan, 2008). They influence planetary albedo and energy partitioning, and are an important sink for atmospheric carbon dioxide (Betts, 2000; Eugster et al., 2000; Pan et al., 2011). They also provide critical ecosystem services to society (Bennett et al., 2009). Over the last 30 years, most Northern Hemisphere forests have experienced warming, and evidence from both ground and satellite observations suggests that the timing and duration of growing seasons in many Northern Hemisphere forests is changing (Soja et al., 2007; Pudas et al., 2007; Beaubien & Freeland, 2000; Friedl et al., 2014; Keenan et al., 2014a; Gill et al., 2015). For all these reasons, a critical need exists to improve understanding of how the phenology of Northern Hemisphere forests is changing, and by extension, how the composition and function of these forests will respond to future climate change.

Satellite remote sensing has been widely used to monitor and map the phenology of terrestrial ecosystems at regional to global scales (Justice et al., 1985; Reed et al., 1994; Zhang et al., 2003). In particular, seasonal variation in spectral vegetation indices such as the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI) has been shown to be correlated with seasonal dynamics in photosynthetically active leaf area (Myneni & Hall, 1995; Huete et al., 2002). Exploiting this, numerous studies have used coarse spatial resolution instruments such as the Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) to characterize large-scale trends and variability in vegetation phenology (e.g., Myneni et al., 1997; Myneni et al., 1998; Zhou et al.,

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2003; Slayback et al., 2003; Jeong et al., 2011; Keenan et al., 2014a). These studies have identified changes in the growing season of terrestrial ecosystems across the Northern Hemisphere that are generally consistent with results from ground studies (Richardson et al., 2013). Specifically, results from both remote sensing and ground-based studies indicate that leaf emergence is happening earlier and leaf senescence is happening later in many ecosystems, leading to longer growing seasons.

Despite widespread agreement that the growing season of Northern Hemisphere forests is changing, the nature of remote sensing datasets used for these studies imposes significant limitations on the character and quality of inferences that can be drawn from them. In particular, results from AVHRR NDVI time series are limited by their coarse spatial resolution and uncertainties in sensor radiometry, geolocation, cloud screening and atmospheric correction (Goward et al., 1991; Huete et al., 2002). In regions where seasonal snow cover is common, detection and correction or removal of NDVI values contaminated by snow is challenging, even in MODIS data (Studer et al., 2007; Jönsson et al., 2010; Eklundh et al., 2011). Alternative vegetation indices (e.g., the Normalized Difference Wetness Index (Delbart et al., 2005) and Plant Phenology Index (Jin & Eklundh, 2014)) and heuristic approaches (e.g., Beck et al., 2006; Zhang et al., 2006) show promise for resolving this issue, but further testing of these methods is needed. Perhaps most importantly, disturbance regimes (fires, insects, humans), topography, and variation in edaphic, climate, and moisture controls produce landscapes in many forested ecosystems that are heterogeneous at scales well below the resolution of AVHRR or MODIS (Ahl et al., 2006; Serbin et al., 2013; Hogg et al., 2008). As a result, analyses based on coarse spatial resolution data are not able to resolve important modes and sources of variation in the growing season of terrestrial ecosystems (Badeck et al., 2004; Klosterman et al., 2014).

With these issues in mind, the goal of this paper is to evaluate the quality and utility of Landsat image time series for characterizing and quantifying long-term changes in North American temperate and boreal forest phenology over broad geographic scales. With over three decades of observations available at 30 m spatial resolution, the Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) instruments provide time series of stable and well-calibrated remote sensing observations that are well-suited for landscape-scale reconstruction and analysis of land surface phenology over the last 30 years. To perform our analysis, we exploit a newly developed Landsat phenology algorithm (LPA; Melaas et al., 2013a; Nijland et al., 2016), which uses all available images to estimate the timing of leaf emergence and fall senescence for pixels with well-defined deciduous phenology. In previous work, Melaas et al. (2013a) demonstrated that the LPA worked well at a single forested site in New England. In this paper, we use a larger and more diverse set of *in situ* observations to assess and interpret the nature and quality of Landsat-based estimates of deciduous temperate and boreal forest phenology. More specifically, we explore not only the agreement between traditional and Landsat-based measurements of phenology, but also examine a suite of complementary *in situ* data sources that provide a more comprehensive and critical assessment of the ecological meaning and utility of phenological information obtained from the LPA.

2. Methods

2.1. Landsat data and phenology algorithm

We used the Landsat phenology algorithm (LPA) described by Melaas et al. (2013a) to estimate the long-term average and annual day of year (DOY) associated with leaf emergence (start of growing season: SOS) and autumn senescence (end of growing season: EOS) at 30 m spatial resolution from time series of Landsat 4, 5, and 7 imagery. The original LPA described by Melaas et al. used all available images to model the phenology of observed Landsat EVI as a function of DOY based on separate logistic functions for spring and autumn. Long-term average SOS and EOS were estimated at each pixel based on the day of year when the spring and autumn logistic functions reached 50% of their amplitude. Observations during stable portions of each curve (e.g., the green and orange dots in Fig. 1c–d) were then used to estimate interannual anomalies in SOS and EOS, where spring and autumn anomalies were calculated as the difference between the date of each observation and the date on which the logistic curve reached the corresponding EVI value (Fig. 1e). Annual SOS and EOS dates were then estimated based on the retrieved anomalies in Spring (Autumn) and the long-term mean SOS (EOS) dates.

Because the LPA was originally developed at a relatively uniform and undisturbed temperate deciduous forest site, we implemented several revisions to the algorithm that allowed us to estimate SOS and EOS in forested landscapes that encompass more spatial heterogeneity in land cover and plant functional types. First, instead of using logistic functions fit to time series of EVI, we used cubic splines to model the mean annual phenology of EVI at each pixel. We find that cubic splines provide a more flexible basis for modeling mean annual phenology and reduce bias in estimated SOS and EOS dates that can be caused by asymmetric growth or decay in EVI, which is both common and not captured by logistic functions (Verma et al., 2016).

Second, the LPA assumes that EVI time series at each pixel follow a relatively consistent seasonal pattern from one year to the next. Hence, disturbance events that introduce large changes to the seasonal profile of EVI (e.g., wildfires, clear-cuts, or insect outbreaks) need to be identified and removed from further analysis. To do this, we used the Continuous Change Detection and Classification algorithm (Zhu & Woodcock, 2014), and excluded from our analysis pixels that experienced disturbance before 1999 or pixels that had more than two disturbance events during the entire record. For pixels with disturbance events that occurred after 1998, we estimated phenology dates using EVI observations acquired prior to the detected disturbance date. Thus, results from the LPA were only generated over extended undisturbed periods at each pixel. Third, to account for possible changes in peak-summer maximum greenness at each pixel (e.g., Goetz et al., 2005) that can introduce spurious trends in the timing of EOS and SOS estimated from the LPA, we normalized the Landsat time series using the 10th and 90th percentiles of EVI at each pixel within sequential three-year windows. After applying this normalization, both the range and the amplitude of seasonal EVI were consistent for each year over the time series at each pixel, and any biases in estimated SOS and EOS dates resulting from trends in greenness, either positive or negative, were eliminated. Finally, to account for radiometric differences between the TM and ETM+ sensors, we calibrated ETM+ EVI observations using the following linear correction derived by Sulla-Menashe et al. (2016):

$$EVI_{corr.} = (EVI_{obs.} - 0.019)/1.038$$

where $EVI_{corr.}$ and $EVI_{obs.}$ are corrected and observed ETM+ EVI values, respectively.

Our analysis used all available Landsat TM/ETM+ images at each of our study sites (see below) from 1982 to 2013 that had less than 90% cloud cover. Images were atmospherically corrected using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) atmosphere correction tool (Vermote et al., 1997; Masek et al., 2008), and clouds, cloud shadows, and snow were screened using the Fmask algorithm described by Zhu & Woodcock, (2012). Landsat images were clipped at each site to exclude pixels that were not located in sidelap regions between adjacent scenes (thereby doubling the number of images available for analysis), and were reprojected to the same Universal Transverse Mercator (UTM) Zone, as necessary.

2.2. Deciduous forest stratification

In Melaas et al. (2013a), the LPA was only applied to pixels that were identified as having strong deciduous phenology. Specifically, Melaas et