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Evaluating the potential of MODIS satellite data to track temporal dynamics of autumn phenology in a temperate mixed forest

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ABSTRACT

Autumn phenology plays a critical role in regulating growing season duration and can be estimated from satellite remote sensing. However, to date, little work has been undertaken to evaluate the performance of remotely sensed autumn phenology, mainly due to a lack of spatiotemporally compatible field observations. To address this limitation, we conducted intensive ground observations of leaf coloration and leaf fall from 610 deciduous trees at two 625 × 625 m study areas within a mixed forest in northern Wisconsin, USA during 2010 and 2012. We derived landscape phenology (LP) indices by upscaling these plot-level observations to facilitate spatially compatible comparisons with coarse resolution satellite measures. The satellite-derived land surface phenology (LSP) was based on 250 m Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) data from both standard 16-day composite (MOD13Q1) and daily Nadir Bidirectional Reflectance Distribution Function (BRDF)-Adjusted Reflectance (NBAR) products. The results revealed that LSP dormancy onset differed from the observed date of full leaf coloration by 5.25 days on average (ranging from 0 to 12 days). Furthermore, progression of the autumn season as determined from LSP and LP showed close agreement as increasing LP leaf coloration corresponded to declining NDVI and EVI values. In addition, the end of the leaf coloring phase was marked by a simultaneous stabilizing of both NDVI and EVI time series whereas the timing of the end of the growing season (leaf fall) closely corresponded to minimum NDVI values. These findings clearly support the use of satellite measurements to effectively monitor temporal dynamics of autumn phenology in a temperate mixed forest.

1. Introduction

Plant phenology, the study of recurring life cycle events such as budburst and leaf senescence, is a sensitive bio-indicator of climate change (Ahl et al., 2006; Hughes, 2000; Liu et al., 2014; Richardson, Bailey, Denny, Martin, & O'Keefe, 2006; Schwartz, 1999). Phenological changes can be monitored using: 1) visual observations, 2) ground-based NDVI measurements (Hmimina et al., 2013; Soudani et al., 2012), 3) bioclimatic models (Kang et al., 2003; Schwartz, 1997; White, Thornton, & Running, 1997), 4) visible light digital camera imaging (Richardson, Friedl, Frolking, Pless, & Collaborators, 2011; Sonnentag et al., 2012), and 5) satellite remote sensing. Each of these techniques has advantages and disadvantages, and the choice of method often depends on the questions being addressed and corresponding scale of study. Among these techniques, satellite remote sensing is most useful for large-scale phenological research (Julien & Sobrino, 2009; Zhang, 2001; Zhang, Friedl, & Schaaf, 2006) because it offers global coverage with consistent temporal repeatability, which is not possible with any other data collection methods (Myneni, Keeling, Tucker, Asrar, & Nemani, 1997).

In acquiring accurate remote sensing phenology, considerable progress has been made to develop methods to reduce noise (e.g., cloud contamination) in satellite time series (Chen et al., 2004; Holben, 1986; Jönsson & Eklundh, 2002; Viovy, Arino, & Belward, 1992; Wolfe, Roy, & Vermote, 1998) and to derive and validate phenological markers (e.g., start of season and end of season; Hmimina et al., 2013; Kaduk & Heimann, 1996; Liang, Schwartz, & Fei, 2011; Schwartz, Reed, & White, 2002; Soudani et al., 2008; White et al., 1997; Zhang & Goldberg, 2011; Zhang et al., 2003). In addition to the quality of satellite data, the relevance of the remotely sensed phenology to ground biophysical processes also varies with vegetation type. For example, although phenology of deciduous forests characterized by pronounced seasonal variations can be readily detected by satellite sensors,

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evergreen forests show less seasonal variation in foliage color (Moulin, Kergoat, Viovy, & Dedieu, 1997).

To date, most satellite phenology studies have focused on the spring season, and in particular on deriving and validating the start of the growing season (Hamunyela, Verbesselt, Roerink, & Herold, 2013; Liang et al., 2011; Soudani et al., 2008; White et al., 2009). Although the end of the growing season has been estimated with similar methods used for the start of the growing season, the potential of satellite data for accurately monitoring autumn phenology (e.g., leaf coloration and leaf fall) has not been evaluated (Shuai et al., 2013; Zhang, 2001; Zhang & Goldberg, 2011), likely due to a lack of spatiotemporally compatible field data. Given that autumn phenology is important for determining the growing season length and it is also affected by climate warming (Dragoni & Rahman, 2012; Dragoni et al., 2011; Jeong, Ho, Gim, & Brown, 2011), it is important to assess the ability of satellite data to effectively track temporal dynamics of autumn phenology. Such information would permit a more accurate determination of variability in growing season length, which in turn will facilitate a more reliable measure of carbon dynamics in the modeling of vegetation–climate interactions.

Delayed leaf senescence in autumn (as a result of warmer temperatures) has contributed to extensions of the growing seasons in many regions (Donnelly, Salamin, & Jones, 2006; Dragoni et al., 2011; Jeong et al., 2011; Menzel, 2000). Piao, Friedlingstein, Ciais, Viovy, and Demarty (2007) showed that an increased growing season length in the Northern Hemisphere (1980–2002) was due to a combination of an earlier spring greenup and a later senescence in autumn. Similarly, Peñuelas, Filella, and Comas (2002) reported an extension to growing season length in the Mediterranean region over a fifty-year period (1952–2000), resulting from both an earlier starting and a later ending of the growing season. In addition, a number of studies suggested that delays in autumn phenology might have played a stronger role than spring phenology in extending the growing seasons for temperate vegetation over mid- and high latitudes in North America (1982–2006; Zhu et al., 2012), eastern China (1982–1993; Chen, Hu, & Yu, 2005) and over the entire Northern Hemisphere (1982–2008; Jeong et al., 2011).

Both autumn phenology and spring phenology are important for regulating plant growth and biomass accumulation, although with only limited utility to represent the net ecosystem productivity (NEP; Richardson et al., 2010). In addition to the well-recognized importance of spring phenology, several recent studies have emphasized the role of autumn phenology over spring phenology in determining intra- and inter-annual NEP variations of forests (Wu, Chen, et al., 2013; Wu, Gough, et al., 2013). In addition, Taylor et al. (2008) reported that rising atmospheric CO_2 could lead to delayed autumnal leaf coloration and leaf fall for *Populus* sp., highlighting the need for a better understanding of fall phenology for tracking ecosystem responses to climate change. These studies suggest the need to more accurately monitor fall phenology with remote sensing, for which purpose validation using field data is essential.

The performance of MODIS based land surface phenology (LSP) has been mainly limited by the available spatial (250–500 m) and temporal (reduced from daily due to clouds) resolutions (Liang et al., 2011; Schwartz & Reed, 1999; Zhang et al., 2003). To validate LSP, species-specific ground phenology measurements are ideal given their explicit biophysical meaning (Ganguly, Friedl, Tan, Zhang, & Verma, 2010; Schwartz et al., 2002). However, the scale mismatch between traditional phenological observations and satellite pixels makes the direct comparison suffer from considerable uncertainty. Many recent studies have focused on addressing this limitation. For example, Melaas, Friedl, and Zhu (2013) and White, Pontius, and Schaberg (2014) demonstrated the utility of moderate resolution Landsat data as an intermediary to bridge this gap. Networked digital camera measurements also have contributed to this effort by offering economical, objective, and high temporal frequency records of canopy phenology that can be used for validating LSP (Hufkens et al., 2012; Sonnentag et al., 2012). Our previous work used high density visual observations and a landscape upscaling approach to reconcile the scale mismatch while retaining the biophysical meaning of plant phenology for validating LSP (Liang et al., 2011).

As a follow-up effort, the current study is aimed at evaluating MODIS-based autumn phenology using a similar high density in situ data set supported landscape phenology approach (Liang & Schwartz, 2009; Liang et al., 2011). In addition to evaluating the standard 16-day composite vegetation indices (MOD13Q1), the current work also adopted vegetation indices from the daily Nadir Bidirectional Reflectance Distribution Function (BRDF)-Adjusted Reflectance (NBAR). With the high density field data, we intend to evaluate the potential of MODIS data to monitor both the transitional dates and the overall dynamics of fall season forest phenology.

2. Study area and data

2.1. Study area

Our field observation covered two 625 × 625 m study areas (north and south) located near an AmeriFlux eddy covariance tower (Park Falls/WLEF, 45.946°N, 90.272°W) within the Chequamegon National Forest in northern Wisconsin, USA (Fig. 1). This study site is listed as a National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) Land Validation Core Site (Morisette, Privette, & Justice, 2002). The forest in which the study areas are situated, is composed of approximately 30% evergreen and 70% deciduous species with four dominant vegetation types as follows (Burrows et al., 2002; Ewers et al., 2002): (1) upland conifers dominated by red pine (*Pinus resinosa*) and jack pine (*Pinus banksiana*); (2) northern hardwoods consisting mostly of sugar maple (*Acer saccharum*) and other deciduous species such as red maple (*Acer rubrum*), white ash (*Fraxinus americana*), yellow birch (*Betula alleghaniensis*), and basswood (*Tilia americana*); (3) aspen/fir forest, composed primarily of quaking aspen (*Populus tremuloides*) and balsam fir (*Abies balsamea*), and other tree species such as white birch (*Betula papyrifera*) and bigtooth aspen (*Populus grandidentata*); and (4) forested wetlands with white cedar (*Thuja occidentalis*), balsam fir (*A. balsamea*), and speckled alder (*Alnus incana*) being the dominant species. Our two study areas covered these primary vegetation types and included most of the dominant tree species found in the region. In addition, this mixed forest has undergone a transition from carbon source to carbon sink with changes in species composition and forest age (Davis et al., 2003; Denning et al., 2003; Desai, Bolstad, Cook, Davis, & Carey, 2005), therefore providing potential opportunities to relate phenological measurements to carbon flux studies.

2.2. Phenological observation procedures and protocols

We sampled a total of 888 trees (635 deciduous trees – all broadleaf except for eleven *Larix laricina* [tamarack], a needle-leaf species – and 253 evergreen trees) across the two study areas. To facilitate identifying the presence of spatial autocorrelations, we used a 3/7 cyclic sampling scheme (Burrows et al., 2002; Clayton & Hudelson, 1995) along both the latitudinal and longitudinal directions of the transects within each study area (Fig. 1). This sampling scheme optimizes the field work efficiency by using only 3 out of 7 evenly spaced (25 m sampling interval) potential plots to capture consecutive increments of spacing between plots (i.e., 25 m, 50 m, 100 m…). The three largest trees, with preference for dominant species, were identified and tagged at each plot, yielding a total of 864 trees. An additional group of twenty-four *T. americana* (basswood) trees was included in the north study area for comparison with ongoing observations of this species in a small woodlot on the University of Wisconsin-Milwaukee campus (43.081°N, 87.881°W). 25 deciduous trees died during the time of observation, so we focused on the remaining 610 deciduous trees for this study. The evergreen trees

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