



A comparison of multiple phenology data sources for estimating seasonal transitions in deciduous forest carbon exchange

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ABSTRACT

There are currently numerous data sources available for estimating the timing of recurrent plant phenology transitions. We compared measurements from several phenology data sources to understand the relationship between phenology metrics derived from these data sources and the timing of seasonal transitions in net ecosystem exchange (NEE). We identified the timing of start, peak, end and the duration of the carbon uptake season, as well as the timing of the transitions from sink to source and source to sink using 11 years of NEE data from the University of Michigan Biological Station (UMBS). Using fitted logistic functions we identified proxy metrics for phenological transitions from the time series of Albedo, fraction of absorbed photosynthetically active radiation (fPAR), Plant Area Index (PAI), and MODIS normalized difference vegetation index (NDVI), enhanced vegetation index (EVI), and leaf area index (LAI) products of various spatial representations. We found that no single source of phenological data was able to accurately describe annual patterns of flux phenology. However, for each transition in NEE (e.g., start of season, transition to net sink), the metrics from one or more data sources were significantly ($p < 0.05$) correlated with the timing of these recurring events. A marginally significant trend toward a longer NEE carbon uptake period over 11 years was not detected by any of the metrics, primarily because none of the metrics were available for the full duration of the NEE data, and NEE did not show significant and consistent trends during the sub-sets of the time when proxy data were available. The results of our study highlight the relative strengths and weaknesses of each phenology data source for directly estimating seasonal transitions and interannual trends in carbon flux phenology of a deciduous forest.

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1. Introduction

The timing, location, and magnitude of plant canopy phenological events is a vital component of the temporal and spatial variability of ecosystem-atmosphere fluxes of mass and energy (e.g., Huttyra et al., 2007; Richardson et al., 2009a; Cadule et al., 2010; Richardson et al., 2010). Plasticity in the timing of phenological transitions allows plants to account for changes in abiotic conditions, such as local weather conditions (Forrest and Miller-Rushing, 2010; Matesanz et al., 2010). Thus, observing phenological transitions is important for understanding the climatic drivers of interannual variability in their timing and for understanding how

plant communities and terrestrial ecosystems respond to global change (Chmielewski and Rötzer, 2001; Sparks and Menzel, 2002; Menzel et al., 2006; Schwartz et al., 2006; Cleland et al., 2007; Walther, 2010). Such understanding contributes to the development of retrospective and prognostic models that are used for elucidating the consequences of climate change on biogeochemical cycling (e.g., Kaduk and Heimann, 1996; Richardson et al., 2006; Ibanez et al., 2010; Rammig et al., 2010). Improving our ability to accurately describe the timing of phenological transitions and associate those transitions with changes in ecosystem function will advance our understanding of climate–ecosystem linkages and feedbacks under current and future climate conditions.

Phenological dynamics play a role in driving biogeochemical fluxes of carbon dioxide (CO₂). Many studies have demonstrated that the timing of leaf emergence, development, and senescence in deciduous ecosystems is correlated with seasonal transitions in fluxes of CO₂ (e.g., Goulden et al., 1996; Barr et al., 2007; Ahrends et al., 2009; Richardson et al., 2009a, 2010). Phenology-dependent

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feedbacks between climate change and ecosystem productivity are expected to affect future ecosystem functions. For example, broad scale warming patterns have been shown to lengthen growing seasons (Parmesan and Yohe, 2003; Menzel et al., 2006; Vitasse et al., 2009). However, uncertainties still remain regarding the impact of climate-driven shifts in phenological timing on net ecosystem productivity due to the balance between respiration and photosynthesis (Piao et al., 2008; Richardson et al., 2010). Studies that investigate the linkages between shifts in the timing of phenology transitions and ecosystem metabolism will help reduce these uncertainties.

Remote sensing studies have shown that optical data from satellites (Jönsson and Eklundh, 2002; Zhang et al., 2006; Reed, 2006; Fisher and Mustard, 2007; Soudani et al., 2008; Julien and Sobrino, 2009; Richardson et al., 2010) and webcams (Richardson et al., 2007, 2009b; Ahrends et al., 2009; Ide and Oguma, 2010) can be used to estimate several phases of the annual cycle of vegetation development, with one study demonstrating that up to 12 annually recurring phenological metrics could be derived from a single data source (Reed et al., 1994). One recent study demonstrated that the four inflection points obtained from sigmoidal curves fitted to annual Moderate Resolution Imaging Spectrometer (MODIS) (see Table 1 for a list of acronyms and definitions used in this paper) enhanced vegetation index (EVI) measurements were significantly correlated with the timing of several transitions in CO₂ fluxes, including spring and fall source–sink transition dates and the dates on which gross ecosystem productivity crossed established thresholds (Richardson et al., 2010). Thus, remote sensing and similar continuously measured phenology data can provide spatially and temporally rich datasets that can be used to investigate patterns of phenology dynamics across a range of spatial and temporal scales.

As data from both satellite- and ground-based instruments are increasingly relied upon to provide phenology data for studies that investigate the impact of global change on ecosystem function, a fundamental challenge will be to link metrics derived from leaf and canopy phenology data with seasonal transitions and interannual variability in fluxes of CO₂. It is recognized that linkages between canopy phenology and carbon flux are not always clearly defined (Piao et al., 2007). For example, physiological parameters important for describing photosynthesis, such as carboxylation rate, electron transport rate, and maximum photosynthetic potential typically scale with variables such as leaf nitrogen content, leaf mass, leaf area, and leaf age (Niinemets, 1999; Reich et al., 1999; Doughty and Goulden, 2008; Marino et al., 2010; Ma et al., 2011). However, time lags between morphological and physiological development can alter relationships between canopy phenological development and ecosystem carbon flux (e.g., Morecroft et al., 2003; Richardson et al., 2010). Even more so, respiration, which represents close to half of the gross carbon flux, follows seasonal transitions, but in a large part is not directly driven by plant phenology. Nonetheless, leaf and canopy structural development are readily observable from ground- and satellite-based instruments, and have relatively predictable trajectories associated with phenological development of plant canopies. However, to answer the question whether a warmer globe increases or decreases terrestrial carbon storage, we first need to determine whether warmer spring or fall temperatures lead to extended periods of ecosystem carbon sink, and how the timing of the peak carbon sink may change in response to growing season conditions. As a precondition to answer this, we need to determine when, during each year, these and other events that mark a regime change in carbon flux occur (hereafter referred to as carbon flux phenology (CFP)). The importance of such research questions was highlighted by White and Nemani (2003), who found that the carbon uptake period (i.e., the time period between ecosystem sink and source of CO₂) and not duration of canopy coverage (as might be estimated from SOS and EOS) was correlated with annual carbon

storage for deciduous forests. Therefore, studies that investigate the linkages between canopy phenology and CFP are necessary in order to improve the effectiveness of phenology measurements in studies of global change effects on fluxes of CO₂.

One challenge facing attempts to link phenology measurements with CFP is choosing from the large number of data sources from which phenology metrics can be obtained (White et al., 2009; Schwartz and Hanes, 2010). Although the majority of these measurements rely on optical properties of vegetation, the biophysical quantity that is measured (i.e., transmitted radiation, canopy gap fraction, canopy 'greenness') generally differs among methods. Furthermore, the spatial and temporal resolution of these measurements can vary greatly from one data source to another. Spatial resolutions can range from a few meters for point measurements to hundreds and thousands of meters for satellite-based measurements. Sampling frequencies of ground-based methods vary from seconds to days and return intervals of satellite data can range from days to weeks. Therefore, comparisons between phenology data sources and CO₂ fluxes are necessary for selecting the appropriate data source to use for estimating specific transitions in annual patterns of CFP.

The objective of this study is to determine the efficacy of measurements from several different phenology data sources for estimating seasonal transitions in CFP. Phenology measurements are often compared with direct observations of physical changes in canopy structure. Our approach differs in that we compare phenology measurements directly to measurements of CO₂ flux. We compared phenology metrics derived from numerous data sources with 11 years of Net Ecosystem Exchange (NEE)-derived CFP measured at a northern mixed hardwood forest. We used satellite- and ground-based data sources that are commonly available at flux monitoring sites, such as the Ameriflux network across North America, CarboEurope in Europe, and others worldwide (Baldocchi, 2008). The results of our study provide an evaluation of the performance of these data sources for estimating several recurring phenology related transitions in annual carbon flux in a deciduous forest ecosystem.

2. Methods

2.1. Study area

This study was conducted at the University of Michigan Biological Station (UMBS), which is located in the northern portion of Michigan's lower peninsula (45°33'35"N, 84°42'49"W). The UMBS study site is located in a northern mixed deciduous forest. According to the most recent MODIS International Geosphere-Biosphere Program (IGBP) land cover classification (MOD12Q1, available from <http://www.daac.ornl.gov>), within a 49 km² area around the flux tower, the predominant land cover types are mixed forest (38%) and deciduous broadleaf forest (35%). Remaining land cover types include grassland (13%), open water (9%), evergreen needleleaf forest (1.5%), wetland (1%), and cropland (0.5%). Within a 60 m radius plot surrounding the flux tower, dominant overstory tree species include (in order of decreasing frequency) *Populus grandidentata* Michx. (bigtooth aspen), *Acer rubrum* L. (red maple), *Populus tremuloides* Michx. (quaking aspen), *Betula papyrifera* Marsh. (paper birch), *Quercus rubra* L. (red oak), *Fagus grandifolia* Ehrh. (American beech), and *Pinus strobus* L. (eastern white pine). In a typical year, bud burst and leaf unfolding occur first in paper birch followed by red maple, red oak, and American beech. Bigtooth and trembling aspen are typically the last species to develop leaves. Species specific fall phenology (i.e., leaf senescence, leaf drop) has not been observed at this site. The mean canopy height surrounding the flux tower is roughly 18 m and the mean peak leaf area index

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