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The match and mismatch between photosynthesis and land surface phenology of deciduous forests

Petra D'Odorico[a,*], Alemu Gonsamo[b], Christopher M. Gough[c], Gil Bohrer[d], James Morison[e], Matthew Wilkinson[e], Paul J. Hanson[f], Damiano Gianelle[g], Jose D. Fuentes[h], Nina Buchmann[a]

[a] Grassland Sciences Group, Institute of Agricultural Sciences, ETH Zurich, Universitätstrasse 2, CH-8092 Zurich, Switzerland
[b] Department of Geography and Program in Planning, University of Toronto, Toronto, ON M5S 3G3, Canada
[c] Department of Biology, Virginia Commonwealth University, Richmond, VA 23284-2012, United States
[d] Department of Civil, Environmental and Geodetic Engineering, The Ohio State University, Columbus, OH 43210, United States
[e] Centre for Sustainable Forestry and Climate Change, Forest Research, Farnham, Surrey GU10 4LH, United Kingdom
[f] Oak Ridge National Laboratory, 1 Bethel Valley Road, Oak Ridge, TN 37831, United States
[g] Sustainable Agro-ecosystems and Bioresources Department, IASMA Research and Innovation Centre, Fondazione Edmund Mach, 38010 San Michele all'Adige, TN, Italy
[h] Department of Meteorology, Pennsylvania State University, University Park, United States

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ABSTRACT

Plant phenology is a key indicator of the terrestrial biosphere's response to climate change, as well as a driver of global climate through changes in the carbon, energy and water cycles. Remote sensing observations of seasonal canopy greenness dynamics represent a valuable means to study land surface phenology (LSP) at scales relevant for comparison with regional climate information as well as ecosystem-level CO_2 fluxes. We explore relationships among key LSP dates at the start and end of the season captured by three remote sensing products (i.e., NDVI: Normalized Difference Vegetation Index; PI: Phenology Index; MODIS Land Cover Dynamics Product based on the Enhanced Vegetation Index, EVI) over 19 deciduous broadleaf and mixed forest sites in the northern hemisphere for 2000–2012, and compare these estimates to estimates of start and end of photosynthesis phenology extracted from gross primary productivity (GPP) from CO_2 flux measurements. To derive phenological transition dates, we use analytical solutions of various derivatives from the fitted logistic curves. LSP dates estimated by the three remote sensing products were not equivalent and differed in their sign and magnitude of lags with photosynthesis phenology dates. NDVI-derived phenology was characterized by shorter growing seasons, while EVI prolonged it by about two weeks compared to the photosynthesis phenology season length. PI start and end of season dates more closely matched the start ($r^2 = 0.84$, RMSE = 7.61) and end ($r^2 = 0.61$, RMSE = 8.57) of photosynthesis phenology as estimated by GPP time series. PI was also found agreeing best with LSP estimates from highly spatially resolved ground digital camera observations, available for about half of the investigated FLUXNET sites. Although there were strong relationships between remotely sensed LSP and photosynthesis phenology, the relationships were not consistent across deciduous forest ecosystems implying that the vegetative and photosynthetic timing do not always follow each other in the same direction.

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1. Introduction

Plant photosynthesis and transpiration are among the most important processes regulating the global carbon (C), water and energy cycles. For deciduous plant species, photosynthetic activity is tightly linked with the seasonal emergence and senescence of leaves. Thus, the study of plant phenology, the timing of recurring biological events in the plant world, the causes of their timing with regard to biotic and abiotic drivers, and the interrelation among phases of the same or different species (Lieth, 1974), is key in understanding changes in biogeochemical processes (especially C sequestration) and in surface energy and water balances (Peñuelas et al., 2009). Field and remote sensing evidence, predominantly for northern hemisphere regions, shows a warming climate has

* Corresponding author. Tel.: +41 446328515.
E-mail address: petra.dodorico@usys.ethz.ch (P. D'Odorico).

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advanced the biological spring and delayed the arrival of biological winter (Cleland et al., 2007; Delbart et al., 2008; Fitzjarrald et al., 2001; Myneni et al., 1997; Parmesan, 2007; Rosenzweig et al., 2008).

Phenology remains one of the most difficult processes to parameterize in dynamic vegetation and ecosystem process models, with most contemporary models employing simple functions derived from meteorological variables (Arora and Boer, 2005; Gonsamo et al., 2013b; Richardson et al., 2012). These functions model phenology as a contemporary climate-dependent process and do not reflect the changing climates (Migliavacca et al., 2012).

The challenge of representing phenology in process models can mainly be ascribed to the incomplete understanding of the mechanism behind plant phenological developments and their response to environmental drivers. To improve this understanding and to determine whether global patterns in phenology emerge across ecosystems, there exists the need for observational approaches to be broadly and systematically established at the ecosystem level and to be validated over long time scales. Remote sensing based approaches offer unprecedented means to capture vegetation dynamics at scales relevant for comparison with regional climate information and ecosystem level C flux measurements. The land surface phenology (LSP), defined as the study of the timing of recurring seasonal pattern of variation in vegetated land surfaces observed from synoptic sensors (Gonsamo et al., 2012b), aggregates over areas that can range from moderate (250 m) to coarse (25 km) spatial resolutions. Observed patterns integrate the response of multiple species, age classes and canopy structural layers within the ecosystem's vertical and horizontal profiles, thus the biological interpretation of such responses is far from trivial. Remote sensing based vegetation indices (VIs) provide an effective means of monitoring LSP developments by exploiting the visible light interaction with leaf pigments (mainly the absorption of red light by chlorophyll) and the high scattering of near infrared (NIR) energy by internal leaf and canopy structures. However, it is not well understood how the timing of biological events extracted from the remote sensing optical measurements matches the timing of changes in canopy functions, e.g., photosynthesis. A number of studies investigated which part of the vegetation phenological cycle is effectively captured by remote sensing measurements by comparing with ground observations of canopy developments (Fisher and Mustard, 2007; Hmimina et al., 2013; Klosterman et al., 2014), while less work has been devoted to establishing the link with distinct plant physiological and functional processes (Gonsamo et al., 2012a; Shen et al., 2014).

Eddy covariance (EC) measurements of carbon dioxide (CO_2) exchange between terrestrial ecosystems and the atmosphere for numerous sites offers a spatially and temporally broad perspective for extracting photosynthesis phenological dates through gross primary productivity (GPP) (Garrity et al., 2011; Gonsamo et al., 2013a, 2012a; Noormets et al., 2009; Richardson et al., 2010). The long-term availability of CO_2 flux measurements at EC tower sites now allows for comparison with remote sensing based LSP estimates over significant time periods and at a spatial footprint similar to coarse and medium resolution satellite pixels. As a complement to these measurements at EC tower sites, recent digital red–green–blue (RGB) camera installations, performing hourly to daily photographs of extended portions of the forest canopy, are now starting to provide optical ground LSP observations (Ahrends et al., 2008; Richardson et al., 2007; Sonnentag et al., 2012).

This study investigates potential matches (and lack thereof) in retrieved start (SOS) and end (EOS) of season dates, as well as start (SOP) and end (EOP) of growing season peak, between land-surface and photosynthesis phenology. Land surface phenology is captured by three remote sensing products: Normalized Difference Vegetation Index (NDVI); Phenology Index (PI); MODIS Land Cover Dynamics Product based on the Enhanced Vegetation Index (EVI), and by Green Fraction index (GF), derived from ground based digital cameras. Photosynthesis phenology is captured by GPP, derived from EC CO_2 flux measurements. We explore relationships among phenological transition dates for nineteen broadleaf and mixed forest sites located across temperate and boreal ecosystems in the northern hemisphere covering the period 2000–2012. Our first objective is to determine if the different satellite remote sensing products provide comparable estimates of LSP dates and if these agree with LSP dates derived from ground based digital cameras. Secondly, we aim at assessing the utility of remotely sensed LSP as a surrogate of canopy photosynthesis phenology, by determining the match and mismatch with dates estimated from ground based CO_2 flux measurements.

2. Data and methods

2.1. Site descriptions

We examined recent (2000–2012) trends in land surface phenology of 19 temperate and boreal deciduous broadleaf forest sites. A few sites include a fraction of conifers and were thus classified as mixed forests. The dominant deciduous genera include beech (*Fagus*), oak (*Quercus*), maple (*Acer*) and aspen (*Populus*). All sites are part of the FLUXNET network of micrometeorological tower sites, at which EC methods are used to measure the exchange of CO_2, water vapor, and energy fluxes between terrestrial ecosystems and the atmosphere (Baldocchi et al., 1988). Sites with at least three years of concurrent GPP and satellite data were included in this analysis. Fully evergreen sites were intentionally excluded from this study since confidence in optical data sources for the detection of seasonal trajectories and extraction of key phenological transition dates is not as high as for deciduous sites. Site descriptions and primary references are given in Table 1. The study site areas range from 36° N to 54° N in North America and from 42° N to 55° N in Europe (Fig. 1).

2.2. Photosynthesis phenology from CO_2 flux measurements

Daily total gross primary productivity (GPP, $gC\,m^{-2}\,d^{-1}$) was obtained as a gap-filled level-4 data product from the Ameriflux and the Euroflux Databases. Daily total GPP was calculated as the sum of observed daytime net ecosystem CO_2 exchange (NEE) and modeled ecosystem respiration (Re) inferred from night-time NEE. The partitioning algorithm extrapolates night-time values of ecosystem respiration into the daytime based on short-term temperature sensitivity of ecosystem respiration (Reichstein et al., 2005). When observations were not available, gap-filled data were generated using the Marginal Distribution Sampling (MDS) method, a moving look-up table technique that uses similar meteorological conditions (of a fixed margin) sampled in the temporal vicinity of the gap to be filled (Moffat et al., 2007). Fluxes estimates differ in their approach when calculating CO_2 storage below the tower height at which CO_2 is sampled. For this study, we chose the standardized approach (GPP_st), in which CO_2 sampled from a single discrete location is used to calculate CO_2 storage (Papale et al., 2006).

The comparability of the information derived from the EC flux footprint and the remote sensing pixel centered at the tower location depends on and increases with site homogeneity. Specifically for phenological research, it is key that the highest contribution to the measured flux comes from the main vegetation functional type also covered by the satellite pixel ground location. Footprint climatology analysis has shown that for many sites the EC footprint is comparable to the 500 m × 500 m satellite pixel (Chen et al., 2012).

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