Comparing carbon flux and high-resolution spring phenological measurements in a northern mixed forest

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ABSTRACT

Vegetative canopies play a crucial role in the energy balance and composition of the atmospheric boundary layer via biotic control over evapotranspiration and carbon sources/sinks. Accurately predicting the onset/increase of carbon uptake/transpiration during the spring leaf development period using coarse resolution tower-based and satellite-derived data alone is difficult. Thus, understanding stand-level spatial patterns of spring plant phenological development and the processes that drive them may be crucial for improving landscape level estimates of evapotranspiration and carbon accumulation.

In this study, high-resolution spatial and temporal tree phenology data were recorded in field campaigns over approximately 5 weeks during spring 2006 and 2007 (within a 625 m × 275 m area), and over similar periods during spring 2008, 2009, and 2010 (within two 625 m × 625 m areas) near the WLEF eddy covariance flux tower site near Park Falls in northern Wisconsin. Our findings demonstrate that phenological variations between individual trees in a specific microclimate can be adequately represented with a sample of 30 or more individuals. Further, visual phenological observations can be generally related to under-canopy light levels, and for spring phenology measurements in similar microclimates, a sampling interval of every 4 days minimizes data uncertainty and field work expenses. An analysis of the relationships among phenology, climate, and gross primary productivity (GPP) during the spring indicate that the phenology of the dominant tree species is responsible for an overall positive trend in carbon assimilation, but climate is the cause of day-to-day variation.

1. Introduction

Greater understanding of atmosphere-biosphere interactions is needed to improve models of Earth's physical systems. Detection of continental-scale biotic responses to climate change is limited both temporally and spatially, and rarely co-located with the detailed measurements available for the climate itself (Root et al., 2003; NEON Science Workshop 2004; Hijmans et al., 2005). This difference is primarily due to the existence of a dense and effective meteorological data network (many locations include over a century of information), and lack of a comparable biospheric network (Schwartz, 1999; van Vliet et al., 2003; Betancourt et al., 2005; Friend et al., 2007; Keller et al., 2008). Until recently, biospheric data existed only as simple land cover/land use types or sporadic observations for most areas, with detailed information (such as phenology) available for just a few sites (Willis et al., 2008; Morisette et al., 2009). The advent of satellite measures created

the opportunity to use empirical data for improved understanding of bioclimatic processes (Goward, 1989; Zhang et al., 2007). Satellite measures of vegetation activity are one of the key components of both downscaling climatic information and upscaling ground-based plant function measures (Jarvis, 1995; Sellers et al., 1997; Turner et al., 2003). However, the overall utility of coarse-resolution satellite data (e.g., Advanced Very High Resolution, AVHRR or Moderate Resolution Imaging Spectroradiometer, MODIS) for repeated continental-scale monitoring can be considerably enhanced when combined with higher temporal and spatial resolution ground-based (e.g., leaf development and microclimate) data and high spatial resolution satellite data (e.g., Quickbird or IKONOS) to facilitate scaling (Liang and Schwartz, 2009; Liang et al., 2011). Similarly, tower-based measurements of ecosystem carbon flux may also benefit from a detailed comparison with high-resolution phenology in order to better reveal the underlying biophysical driver of the seasonality of ecosystem exchange.

Vegetative canopies play a crucial role in the energy balance and composition of the atmospheric boundary layer via biotic control over evapotranspiration and carbon sources/sinks. Through the leaf stomata, plants regulate the rate of exchange of these

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gases between the land surface and the atmosphere. Consequently, canopy average stomatal conductance (G_S) is one of the most important variables needed to predict atmospheric, hydrologic, and biospheric dynamics in response to the integrated effects of multiple stressors (White et al., 2000; Ewers et al., 2001; Thornton et al., 2002; Bond-Lamberty et al., 2005) and has been used successfully to scale between stands and the landscape level during the height of the growing season (Mackay et al., 2002). However, being able to understand and model these interactions at the start of the growing season is of equal or even greater importance, given the large impact of spring onset variations on total seasonal evapotranspiration and carbon accumulation (Ricciuto et al., 2008). The leaf development phenomenon is of particular interest as a dynamic feature resulting from close atmosphere-biosphere interaction (Schwartz, 1998). In spring, increasing solar radiation allows vegetation to resume growth, but the appearance of foliage causes rapid increases in near-infrared reflectance and transpiration (Rosenberg, 1983; Kaufmann, 1984). These biospheric effects in turn feedback upon the lower atmosphere, through modification of the surface energy and moisture balances, resulting in detectable changes in surface daily maximum temperatures (Schwartz and Karl, 1990; Schwartz, 1992). Evidence suggests that due to these interactions, the onset of spring in the lower atmosphere is a modally abrupt, rather than gradual seasonal transition (Schwartz, 1996; Fitzjarrald et al., 2001).

Our ability to accurately predict the onset and increase of carbon uptake and transpiration during the spring leaf development period (the time from bud burst to maximum photosynthetic and transpiration rates) using satellite-derived data alone is limited (Turner et al., 2003; White et al., 2009). Accurate representation of these dynamics at regional to global scales requires an ability to obtain spatially extensive G_S and leaf level photosynthetic estimates over relatively short timescales (sub-daily to weekly). Measures of the timing of specific levels of plant leaf development (phenological events) have proven to be effective general proxies for transpiration and other plant growth-driven processes during spring (Fitzjarrald et al., 2001; Schwartz and Crawford, 2001). Annual variation in surface phenology models (Spring Indices, Schwartz and Reiter, 2000, determined from micrometeorological temperature data recorded near the Chequamegon Ecosystem-Atmosphere Study [ChEAS] tall tower site near Park Falls, WI from 1998 to 2005) show a 19–21 days range in the onset of spring, implying 34–52 days variability on the century time scale (when compared to nearby long-term temperature stations). Such quantification of temporal variability still leaves a knowledge gap in the simultaneous spatial variability which precludes rigorous upscaling in this heterogeneous landscape. Thus, understanding stand-level spatial patterns of spring plant phenological development and the processes that drive them may be the key knowledge needed to improve landscape level estimates of evapotranspiration and carbon accumulation derived from flux towers and coarse resolution remote sensing data.

In this study, high-resolution spatial and temporal tree phenology data were recorded in field campaigns over approximately 5 weeks during spring 2006 and 2007 (within an initial 625 m × 275 m area), and over similar periods during spring 2008, 2009, and 2010 (within two expanded 625 m × 625 m areas) near the Chequamegon Ecosystem-Atmosphere Study (ChEAS) WLEF tall tower site in northern Wisconsin (an EOS Land Validation Core Site). We assess/model the characteristics of these data, link them to environmental measurements and flux tower estimates of gross primary production (GPP) during the spring, and lay the foundations for explicit connections of all these measures to leaf function and G_S during the crucial spring leaf development period. The results of these analyses demonstrate whether micrometeorological measurements and visual phenology observations with high spatial and temporal resolutions can be scaled up to accurately model GPP during the spring. Further, we test the effects of decreases in the temporal sampling frequency and number of sampled individuals on overall measurement error. Thus, this work is intended to provide valuable methodological and logistical guidance for future studies in similar environments.

2. Materials and methods

2.1. Overall development of study areas

Spatial phenological variability was quantified in two sampling blocks representing two different types of vegetation boundary conditions in the mixed forest of northern Wisconsin, within the Chequamegon-Nicolet National Forest, a composite of northern temperate, sub-boreal, and boreal species (Fig. 1). Because this forest type is representative of large areas that change from carbon sources to sinks based on age and species type (Davis et al., 2003; Denning et al., 2003; Desai et al., 2005) and sources of seasonal evapotranspiration (Ewers et al., 2002, 2008; Mackay et al., 2002) such areas are important for global change research. This forest consists of monoculture and mixed stands of deciduous broadleaf and conifer needle-leaf species in upland and wetland conditions. The region around the WLEF AmeriFlux tall tower now has a 17-year tower flux record (since 1995), and many supporting measures for shorter time periods (Mackay et al., 2002; Burrows et al., 2002, 2003; Cook et al., 2004; Ewers et al., 2007; Loranty et al., 2008).

The study site lies within a broadly forested 200 km × 200 km region, near Park Falls in northern Wisconsin. The focal point is the WLEF-TV AmeriFlux tower, located at 45.946°N, 90.272°W. Within the footprint of this unusually tall (447 m) eddy covariance tower lie the field blocks. The two phenology sampling blocks in this project are distributed across major species and landform gradients necessary for scaling to the WLEF tower (Mackay et al., 2002). The study area is covered approximately 30% by coniferous species and 70% by deciduous species in four major cover types (Ewers et al., 2002; Mackay et al., 2002): (1) aspen uplands consisting mostly of *Populus tremoloides*-trembling aspen and *Abies balsamea*-balsam fir; (2) northern hardwoods, primarily *Acer saccharum*-sugar maple; (3) conifer groves dominated by *Pinus resinosa*-red pine; and (4) forested wetlands with mixtures of *Alnus rugosa*-speckled alder, *Thuja occidentalis*-white cedar, *Acer rubrum*, and *A. balsamea*.

2.2. Initial area

During summer 2005, the three largest dominant species trees were identified, tagged, and measured for diameter at breast height (DBH) at each of 72 plots (arranged following a 25 m grid 3/7 cyclic sampling design, Burrows et al., 2002) in an initial 625 m × 275 m area near the WLEF tower (northern half of the southern 625 m × 625 m sampling block, which contains a transition from aspen upland to forested wetland, Fig. 1). Our cyclic sampling took 3 of 7 evenly spaced potential plots (spaced at 25 m intervals) so that the selected plots from multiple cycles were separated by a full range of spatial intervals (e.g., 25, 50, 75, and 100 m). These 216 trees were observed in phenological monitoring campaigns in spring 2006 and spring 2007 to test the sampling methodology.

2.3. Expanded areas

Subsequently, during summer 2007, using the same sampling design described above, the plots were expanded to two 625 m × 625 m areas (Fig. 1). One was a southward extension of the initial "south" study area, and the other a new "north" area containing a transition from northern hardwoods to conifer groves. Each area contained 3 trees at each of the 144 plots, for a total of