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Temporal disparity in leaf chlorophyll content and leaf area index across a growing season in a temperate deciduous forest

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ABSTRACT

Spatial and temporal variations in canopy structure and leaf biochemistry have considerable influence on fluxes of CO_2, water and energy and nutrient cycling in vegetation. Two vegetation indices (VI), NDVI and Macc01, were used to model the spatio-temporal variability of broadleaf chlorophyll content and leaf area index (LAI) across a growing season. Ground data including LAI, hyperspectral leaf reflectance factors (400–2500 nm) and leaf chlorophyll content were measured across the growing season and satellite-derived canopy reflectance data was acquired for 33 dates at 1200 m spatial resolution. Key phenological information was extracted using the TIMESAT software. Results showed that LAI and chlorophyll start of season (SOS) dates were at day of year (DOY) 130 and 157 respectively, and total season duration varied by 57 days. The spatial variability of chlorophyll and LAI phenology was also analyzed at the landscape scale to investigate phenological patterns over a larger spatial extent. Whilst a degree of spatial variability existed, results showed that chlorophyll SOS lagged approximately 20–35 days behind LAI SOS, and the end of season (EOS) LAI dates were predominantly between 20 and 30 days later than chlorophyll EOS. The large temporal differences between VI-derived chlorophyll content and LAI has important implications for biogeochemical models using NDVI or LAI to represent the fraction of photosynthetically active radiation absorbed by a canopy, in neglecting to account for delays in chlorophyll production and thus photosynthetic capacity.

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Introduction

Spatiotemporal variation in ecosystem properties such as canopy structure and leaf biochemistry has profound impacts on CO_2, water and energy fluxes and nutrient cycling (Churkina et al., 2005; Richardson et al., 2009b; Zhang et al., 2006). Leaf biochemistry is an important indicator of forest health, vegetation stress through disease or drought (Carter and Knapp, 2001) and is crucial to monitoring vegetation response to climate change (Morin et al., 2009) and for the inclusion within climate and ecological models (Morisette et al., 2009). Leaf area index (LAI), defined as one half the total (all-sided) green leaf area per unit ground surface area (Chen and Black, 1992), exhibits a major control on transpiration, CO_2 uptake and the interception of light and water by the canopy (Boegh et al., 2002; Houborg and Boegh, 2008). Ecological systems are highly complex and dynamic, with temporal variations in vegetation phenology and biophysical variables being far from uniform across space, both within and between species (Richardson et al., 2006, 2009a). However, many ecological studies use satellite-derived products to approximate vegetation 'greenness', as a composite of vegetation composition, structure and function (Pfeifer et al., 2012). Whilst this amalgam of canopy physical and biochemical properties implicitly assumes a correlation in time and space, research has shown that in addition to LAI, leaf structure and chemistry also vary across a growing season (Demarez et al., 1999; Kodani et al., 2002). Consequently, temporal and spatial variations in reflectance factors can be attributed to variations in vegetation properties at both canopy-level (LAI) and leaf-level (chlorophyll) (Croft et al., 2013; Zhang et al., 2006). Differences in the behavior of these physiological and biophysical variables (Croft et al., 2014b), as a result of varying dependency on different environmental drivers, may have large implications for the monitoring and parameterization of key terrestrial processes, including gross primary production (GPP).

Remote sensing techniques have tremendous potential to provide a cost-effective, spatially continuous means of monitoring the dynamic properties of tree biophysical variables at a range of different spatial and temporal scales. The estimation of vegetation

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characteristics from remotely-sensed reflectance data is often achieved through the development of statistical relationships between canopy or leaf variables and spectral vegetation indices (VI). This approach can be subject to error and uncertainty in spatially heterogeneous regions, but is less of a concern in closed broadleaf canopies, which essentially behave as a 'big leaf' (Gamon et al., 2010). In order to investigate the temporal behavior of LAI and chlorophyll over a growing season at a landscape scale, the biomass-sensitive, normalized difference vegetation index (NDVI) is used to represent LAI, and a red-edge vegetation index (Macc01) to represent leaf chlorophyll content. The widely used phenology software Timesat (Jonsson and Eklundh, 2002; Jönsson and Eklundh, 2004) is used to extract phenological metrics from the chlorophyll- and LAI-sensitive VIs, such as the start/end of growing season, in order to quantify differences in seasonal timings. The specific objectives of this study are to: (1) investigate the temporal variations of chlorophyll content and LAI across a growing season; (2) assess the impact of the selected VI on differences in retrieved key phenological metrics; (3) model spatial variations in chlorophyll content and LAI at the landscape scale.

Methods

Study site and data collection

Field sampling was conducted in 2004 in a mature sugar maple (*Acer saccharum* M.) stand located in Haliburton Forest, Ontario, Canada (45°14′16″N, 78°32′18″W). Haliburton forest falls within the Great-Lakes – St.-Lawrence region (Rowe, 1972) and is dominated by sugar maple but also contains beech (*Fagus grandifolia* Ehrh.), eastern hemlock (*Tsuga canadensis* (L.) Carr.), and yellow birch (*Betula alleghaniensis* Britt.) (Caspersen and Saprunoff, 2005). The upland hardwood forests experience an average annual precipitation of approximately 1050 mm and mean annual temperature of 5 °C (Gradowski and Thomas, 2006). The site is underlain by shallow brunisols or juvenile podzols, (pH 4.2–5.1); mainly silty sands from Precambrian Shield granite or granite-gneiss deposits (Gradowski and Thomas, 2006).

Leaves were sampled from the upper canopy of representative trees using a mobile canopy lift 8 times throughout the growing season from May 27th to September 30th (Zhang et al., 2007), within a 50 m × 30 m area. On each date, three trees were sampled, from which three branches were selected and three leaves sampled from each branch, giving a total of 27 leaf samples per sampling date. The sampled branches were tagged to ensure repeatable measurements through the growing season. Leaf samples were sealed in plastic bags and kept at a temperature of 0 °C for subsequent biochemical analysis to extract leaf chlorophyll content ($\mu g/cm^2$) (Zhang et al., 2007). Leaf area index and canopy structural parameters were measured 10 times across the growing season, along a 100 m transect. Effective LAI (*Le*) was measured by the LAI-2000 plant canopy analyser (Li-Cor, Lincoln, NE, USA), using the methods of Chen et al. (1997). The element clumping index was measured using the TRAC (Tracing Radiation and Architecture of Canopies) instrument (Chen and Cihlar, 1995).

Satellite data acquisition and processing

The MEdium Resolution Imaging Spectrometer (MERIS) on board the ENVISAT platform measures surface reflectance in fifteen spectral bands from 415 to 885 nm, with a temporal revisit time of 2–3 days. Thirty-three MERIS Reduced Resolution (RR) Level 2 (1200 m) images were used in this study, spanning the growing season from 28th March to 30th November, 2004. The L2 products contain geolocated geophysical parameters in addition to surface reflectance, including terrain height, geometric information, solar and viewing geometry, meteorological data and several flags addressing image quality (Canisius et al., 2010). MERIS L2 products were radiometrically and atmospherically corrected to account for Rayleigh scattering, ozone, water vapor absorption and aerosol content. The MERIS images were reprojected to WGS 84 and coordinate system (UTM 18) and resampled using nearest neighbor interpolation using the BEAM VISAT software application (European Space Agency). The images were also co-registered and geometrically corrected using a grid of tie points, which contained geo-location coordinates and were distributed evenly throughout the image.

Vegetation index selection

A large number of vegetation indices have been developed and tested over a range of species and physiological conditions, using empirical and simulated data (Blackburn, 2007). This study uses the Macc01 vegetation index (Maccioni et al., 2001), calculated as:

$$\text{Macc01} = \frac{\text{R780} - \text{R710}}{\text{R780} - \text{R680}} \quad (1)$$

based on the findings of a recent study (Croft et al., 2014a), which tested the relationship between 60 vegetation indices and chlorophyll content at leaf and canopy scales. Macc01 displayed a very strong relationship with chlorophyll content at the canopy scale ($R^2 = 0.93$; RMSE = 1.68 $\mu m/cm^2$) and is one of several vegetation indices based on reflectance from wavelengths along the red-edge spectral region (Dash and Curran, 2004; Gitelson and Merzlyak, 1994; Vogelmann et al., 1993; Zarco-Tejada et al., 2001). Research has shown that the red edge region is sensitive to a wider range of chlorophyll content than chlorophyll absorption bands (680 nm), which are more likely to saturate under high chlorophyll conditions (Sims and Gamon, 2002).

Whilst interactions of chlorophyll with radiation are largely limited to optical wavelengths, ranging from 400 nm to 725 nm, LAI impacts occur in the NIR, due to canopy structure and multiple scattering which is particularly important at NIR wavelengths as little radiation is absorbed (Asner, 1998). NDVI (Eq. (2)) has been extensively used to estimate LAI, along with $\text{FAPAR}_{\text{canopy}}$ and gross primary production (Potter, 1993; Running et al., 2004).

$$\text{NDVI} = \frac{\text{NIR} - \text{red}}{\text{NIR} + \text{Red}} \quad (2)$$

NDVI has a very long time record of data usage, dating from early 1980s, and is very widely used and well documented in the literature (Xiao et al., 2009). Some care has to be taken using NDVI in regions of high LAI due to saturation and reduced sensitivity. Nevertheless, Soudani et al. (2012) found a very close agreement between NDVI measured using a network of ground-based sensors and physical measurements of LAI in a number of different ecosystems, which they used to monitor temporal dynamics in phenology and canopy structure.

The relationships of NDVI and Macc01 derived from satellite reflectance data with measured LAI and leaf chlorophyll content respectively, are shown in Fig. 1. Where ground sampling dates did not exactly coincide with remotely-sensed image dates, the values of spectral indices were temporally linearly interpolated to give results for the same ground date.

Fig. 1 demonstrates that both vegetation indices show a strong relationship with their respective vegetation parameter (LAI: $R^2 = 0.67$; Chlorophyll: $R^2 = 0.97$). Despite NDVI being prone to saturation at high LAI values, Fig. 1a displays a linear relationship, with the lower LAI values corresponding to the start and end of the season clearly identifiable and the NDVI values toward the middle of the growing season relatively consistent, with little variation in LAI

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