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Application of satellite solar-induced chlorophyll fluorescence to understanding large-scale variations in vegetation phenology and function over northern high latitude forests

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ABSTRACT

This study evaluates the large-scale seasonal phenology and physiology of vegetation over northern high latitude forests (40°–55°N) during spring and fall by using remote sensing of solar-induced chlorophyll fluorescence (SIF), normalized difference vegetation index (NDVI) and observation-based estimate of gross primary productivity (GPP) from 2009 to 2011. Based on GPP phenology estimation in GPP, the growing season determined by SIF time-series is shorter in length than the growing season length determined solely using NDVI. This is mainly due to the extended period of high NDVI values, as compared to SIF, by about 46 days (±11 days), indicating a large-scale seasonal decoupling of physiological activity and changes in greenness in the fall. In addition to phenological timing, mean seasonal NDVI and SIF have different responses to temperature changes throughout the growing season. We observed that both NDVI and SIF linearly increased with temperature increases throughout the spring. However, in the fall, although NDVI linearly responded to temperature increases, SIF and GPP did not linearly increase with temperature increases, implying a seasonal hysteresis of SIF and GPP in response to temperature changes across boreal ecosystems throughout their growing season. Seasonal hysteresis of vegetation at large-scales is consistent with the known phenomena that light limits boreal forest ecosystem productivity in the fall. Our results suggest that continuing measurements from satellite remote sensing of both SIF and NDVI can help to understand the differences between, and information carried by, seasonal variations vegetation structure and greenness and physiology at large-scales across the critical boreal regions.

1. Introduction

Over northern temperate and boreal forests, vegetation has a clear seasonal cycle in its annual growth (Myneni et al., 1997). Seasonal processes, including spring green-up and fall senescence, control growing season length and therefore have a significant influence on photosynthetic CO_2 uptake from the atmosphere. In the Northern Hemisphere, seasonal activity of vegetation controls the observed seasonal cycle of atmospheric CO_2 (Keeling et al., 1996). Increases in temperature over cold temperate and boreal forests have the potential to influence atmospheric CO_2 seasonality globally (Denning et al., 1995; Graven et al., 2013). Therefore, understanding the seasonal dynamics of boreal zone vegetation is a key step in comprehending the seasonal response of atmospheric CO_2 to global and/or regional warming.

In characterizing the seasonal dynamics of vegetation, many researchers have focused on the timing of specific events (phenology) such as spring flowering, budburst, fall leaf coloring, and leaf drop (see review by Richardson et al., 2013). Many studies from various ground measurements with different species found dominant changes in spring phenology in response to temperature and/or precipitation variability over mid- to high-latitude forests (Ho et al., 2006; Menzel et al., 2006; Schwartz et al., 2006; Wolkovich et al., 2012; Fu et al., 2015; Piao et al., 2015). Although limited studies have focused on fall phenology, apparent variations in the timing of leaf coloring and drop in relation to temperature variations have been reported (Lee et al., 2003; Delpierre et al., 2009; Archetti et al., 2013; Jeong & Medvigy, 2014). It is expected that global and/or regional climate change will

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lead to an increase in growing season length through earlier spring onset or delayed fall senescence (e.g., Morin et al., 2009; Jeong et al., 2013).

Satellite remote sensing of vegetation has the potential to greatly improve our understanding of northern latitude forests, particularly their seasonal productivity, reflectance-based indices such as the normalized difference vegetation index (NDVI) has been widely used to understand the phenology and vegetation growing season from regional to the global scales (de Beurs & Henebry, 2005; Piao et al., 2006; White et al., 2009; Jeong et al., 2011; Barichivich et al., 2013; De Jong et al., 2013; Melaas, Friedl, & Zhu, 2013). NDVI-based studies also showed clear changes in spring and fall phenology related to temperature or precipitation changes (Fu et al., 2014; Shen et al., 2015). For example, increasing winter and spring temperatures can lead to earlier green-onset or increase in summer, and fall temperature delays the timing of leaf drop and reductions in greenness over the Northern Hemisphere (Jeong et al., 2011). Satellite remote sensing of NDVI is a widely used tool to understand the continuous temporal trajectory of vegetation growth and decay over the entire globe (Tucker et al., 1986; Xu et al., 2013; Buitenwerf et al., 2015; Park et al., 2015).

As a benefit of temporal and spatial coverage, satellite NDVI-based phenology is used to understand the relationships between vegetation growing season and vegetation carbon assimilation, or gross primary productivity (GPP) (e.g., Jeong et al., 2013; Keenan et al., 2014). Particularly in regions with minimal ground measurements, satellite-based phenology has tremendous potential to provide insights and monitoring capabilities for vegetation seasonal growth and productivity. However, previous studies which compare satellite NDVI data with tower-measured CO_2 flux data from FLUXNET (GPP and net ecosystem exchange (NEE)) (Churkina et al., 2005; Gonsamo et al., 2012) have found that the NDVI-based growing season is longer than the duration of flux measurements, suggesting a discrepancy in seasonality between vegetation greenness and function (Churkina et al., 2005). These discrepancies could be due to the differences in the scales between satellite and tower measurements, rather than actual offsets in time between greenness (or structure) and function (Cescatti et al., 2012), and so additional observations are required to help resolve these issues.

Recently, large-scale satellite remote sensing of solar-induced chlorophyll fluorescence (SIF) has become available (Meroni et al., 2009; Frankenberg et al., 2011; Joiner et al., 2011). SIF is the re-emission of a small fraction of absorbed radiation, at longer wavelengths that extend into the near infrared. SIF has been theoretically related to photosynthetic activity by way of complex mechanisms of energy dissipation (Krause and Weis, 1991; Zhang et al., 2014). Several studies have shown an almost linear relationship between SIF and GPP (Van der Tol et al., 2009, Zarco-Tejada et al., 2013) In general, about 1% of the solar energy captured by plants is reemitted by chlorophyll as fluorescence. This relatively small amount of radiation is detectable from space with current high spectral resolution sensors, essentially providing a distinctive “glow” of photosynthetically active vegetation at wavelengths between approximately 640 nm and 820 nm. New spectrometers with high spectral resolution, in combination with advances in retrieval methodology based on the exploitation of Fraunhofer lines, now enable global SIF retrievals from platforms such as the Global Ozone Monitoring Instrument-2 (GOME-2) (Joiner et al., 2011), Greenhouse gases Observing SATellite (GOSAT) (Frankenberg et al., 2011), and Orbiting Carbon Observatory (OCO2) (Frankenberg et al., 2014). At canopy- and ecosystem-scale, compared to reflectance-based vegetation indices, changes in SIF provide insight into plant physiological functioning. Thus, satellite-based SIF observations offer an alternative view of vegetation function based on physiology, as opposed to the information on structure and greenness offered by traditional reflectance indices.

Studies on SIF from leaf to canopy-scale show a positive relationship between SIF and photosynthesis (Van der Tol et al., 2009, Zarco-Tejada et al., 2013; Guanter et al., 2014; Damm et al., 2015). Remote sensing of SIF also correlated well with ground-based SIF measurements and GPP from flux-towers over temperate and boreal forests (Joiner et al., 2014; Yang et al., 2015). In addition, Lee et al. (2013) show that SIF can capture a decline in photosynthesis in a drought-stressed forest even as leaf area remained constant, confirming that the passive measurements of SIF can be used to track changes in physiological activity at large scales in the absence of changes in greenness or structure. Several ground-based studies of SIF have also shown a positive correlation between SIF and water stress (Flexas et al., 2002; Daumard et al., 2010).

The applicability of satellite SIF to provide insights or a monitoring capability for seasonal changes in vegetation function is not yet well developed, particularly at large scales from region to the globe. Because of the highly non-linear characteristics of terrestrial ecosystem dynamics across scale (Heffernan et al., 2014), it has the potential to modify local-scale observations of positive relationships between SIF and GPP seasonality. In this study we examine the potential of SIF to provide unique information on the seasonal dynamics of northern latitude forests, by comparing satellite remote sensing of SIF, NDVI, and a validated data-driven model of GPP. We focus on two different characteristics of the seasonal dynamics of vegetation: structural phenology and physiology. A recent study comparing the temperature responses of NEE and GPP to across the growing season revealed a hysteresis in NEE response to temperature between spring and fall in northern latitude forests (Niu et al., 2013). This difference was primarily attributed to the different responses of GPP to temperature changes rather than those of ecosystem respiration. Here, we build on this result to examine the value of satellite-based SIF observations to characterize boreal forest physiological activity over the northern latitude growing season, with a particular focus on responses to seasonal temperature variations.

2. Data and methods

In this study, we used satellite remote sensing of NDVI and SIF from two different sources. For NDVI, we used the new Global Inventory Modeling and Mapping Studies (GIMMS) NDVI3g data from the Advanced Very High Resolution Radiometer (AVHRR) sensor (Pinzon and Tucker, 2014) that has been widely used for evaluating ecosystem changes (e.g., Bhatt et al., 2013; De Jong et al., 2013; Zhu et al., 2013; Dardel et al., 2014). In addition, we used Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI data (MOD13C2), which samples with narrower spectral bands. Compared to the AVHRR, the MODIS NDVI is based on spectral bands specifically designed for vegetation monitoring and includes improved radiometric sensitivity, atmospheric corrections, and reduced geometric distortions (Huete et al., 2002).

We used two different SIF datasets from the Global Ozone Monitoring Instrument - 2 (GOME-2) (Joiner et al., 2011) and the Greenhouse gases Observing SATellite (GOSAT) (Frankenberg et al., 2011). GOME-2 is a nadir-viewing grating spectrometer that measures backscattered sunlight at wavelengths between 270 and 800 nm on board the MetOp-A platform, which was launched in October 2006 in a sun-synchronous orbit with an equator crossing time of 09:30 AM. The nadir Earth footprint size is 40 × 80 km, and the normal swath is 1920 km. GOME-2 SIF primarily comes from the filling-in of solar Fraunhofer lines near the 740 nm far-red fluorescence emission peak as shown in Joiner et al. (2013). The GOME-2 SIF retrieval method uses principal component analysis with a simplified radiative transfer model to disentangle the spectral signatures of atmospheric absorption, surface reflectance, and fluorescence emission. All data has been cloud filtered and eliminated with solar zenith angle >70. In this study, we used Level 3 global-scale grid averaged (0.5° × 0.5°) data (Joiner et al., 2013).

In case of GOSAT SIF, high-resolution spectra are recorded by the thermal and near infrared sensor for carbon observation (TANSO) Fourier transform spectrometer (FTS) on board the Japanese GOSAT satellite, which was launched in January 2009 into a sun-synchronous orbit with a local overpass time of 13:00 PM. Approximately 10,000 soundings with circular spatial footprint (10 km diameter) are recorded