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Seasonal patterns of canopy photosynthesis captured by remotely sensed sun-induced fluorescence and vegetation indexes in mid-to-high latitude forests: A cross-platform comparison

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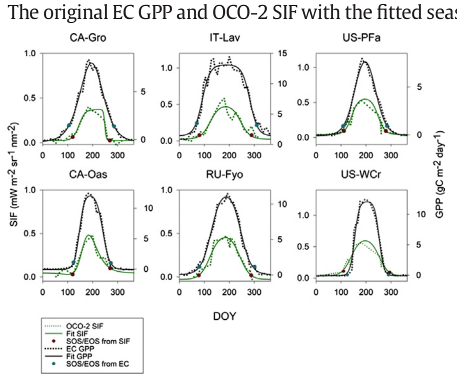
HIGHLIGHTS

- Phenological metrics from 2 SIF sets and 4 vegetation indexes were intercompared.
- Remotely sensed SIF were highly correlated with GPP in mid-to-high latitude forests.
- The SIF-GPP relationships can be generally considered linear at 16-day scale.
- PI and NDVI provided reliable predictions of start of seasons among MODIS indexes.
- Limitations remained for OCO-2 SIF to extract photosynthesis phenology at site-level.

GRAPHICAL ABSTRACT

The original EC GPP and OCO-2 SIF with the fitted seasonal cycles and predicted SOS and EOS at six forested sites.



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ABSTRACT

Characterized by the noticeable seasonal patterns of canopy photosynthesis, mid-to-high latitude forests are sensitive to climate change and crucial for understanding the global carbon cycle. To monitor the seasonal cycle of the canopy photosynthesis from space, several remotely sensed indexes, such as normalized difference vegetation index (NDVI), enhanced vegetation index (EVI), and leaf area index (LAI) have been implemented within the past decades. Recently, satellite-derived sun-induced fluorescence (SIF) has shown great potential of providing retrievals that are more related to photosynthesis process. However, the potentials of different canopy measurements have not been thoroughly assessed in the context of recent advances of new satellites and proposals of improved indexes. At 15 forested sites, we present a cross-platform intercomparison of one emerging remote sensing based index of phenology index (PI) and two SIF datasets against the conventional indexes such as NDVI, EVI, and LAI to capture the seasonal cycles of canopy photosynthesis. NDVI, EVI, LAI, and PI were calculated from Moderate Resolution Imaging Spectroradiometer (MODIS) measurements, while SIF were evaluated from Global Ozone Monitoring Experiment-2 (GOME-2) and Orbiting Carbon Observatory-2 (OCO-2) observations. Results indicated that GOME-2 SIF was highly correlated with gross primary production (GPP) and absorbed photosynthetically active radiation during the growing seasons. The SIF-GPP relationship can generally be considered linear at the 16-day scale. Key phenological metrics such as start of the seasons and end of the seasons captured

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by SIF from GOME-2 and OCO-2 matched closely with photosynthesis phenology as inferred by GPP. However, the applications of OCO-2 SIF for phenological studies may be limited only for a small range of sites (at site-level) due to a limited spatial sampling. Among the MODIS estimations, PI and NDVI provided most reliable predictions of start of growing seasons, while no indexes accurately captured the end of growing seasons.

1. Introduction

Terrestrial ecosystems play an important role in regulating regional and global climate (Burrows et al., 2011). Mid-to-high latitude forests, especially the boreal forests, are substantial contributors to carbon fluxes (Beer et al., 2010; Rolleston, 1996). As plants in these regions are expected to experience the greatest warming among forest biomes, they are deemed to react and respond sensitively to climate change and variability (Keenan et al., 2014). In recent years, with the developments of networks of flux measurements and advances of remote sensing based models, the monitoring of the physiological processes such as photosynthesis of mid-to-high latitudes has become generally possible.

Mid-to-high latitude forests are showing noticeable seasonal cycles of canopy photosynthesis. These life cycle events are sensitive indicators of the biosphere's response to climate changes through contributions to the global carbon, energy and water cycles (Buitenwerf et al., 2015; Peñuelas et al., 2009). Understanding the changes of these cycles as well as the underlying mechanisms are of significance for predicting future changes of climate and the global carbon cycle. Recent in-situ and remote sensing based studies have shown that the warming climate has triggered lengthier growing seasons in northern hemisphere regions (Cleland et al., 2007; Viña et al., 2016; Wang et al., 2015). Remote sensing based approaches to estimate phenological metrics (e.g., the start and end of growing seasons) were mainly based on reflectance-calculated vegetation indexes (VIs), such as normalized difference vegetation index (NDVI), enhanced vegetation index (EVI) and leaf area index (LAI) retrieved using these VIs (Helman, 2018). These indexes have been applied to regional and global studies, especially for the regions without long-term ground observations (Gonsamo and Chen, 2016). Fundamentally, yet, those VIs cannot provide us a direct understanding of physiological processes so that can be hard to be perfectly applied to modelling frameworks. At the same time, several recent studies found that performances of VIs are significantly hindered by snow cover and soil moisture in high-latitude regions (D'Odorico et al., 2015; Peng et al., 2017; Wu et al., 2017). Several improved indexes including phenology index (PI) that aimed at the match between remotely sensed and ground observed seasonal cycles of canopy photosynthesis have been proposed in recent years (Gonsamo et al., 2012a). The PI combines NDVI and Normalized Difference Infrared Index (NDII) aiming to decouple the seasonality of the green vegetation component from the background one because green-up co-occurs with snow melt (Delbart et al., 2005; Gonsamo et al., 2012a). Yet, the biological recovery and dormancy for evergreen forests are still extremely difficult to identify during the transition period when the greenness signal of the vegetation is weak or does not necessarily correspond with the shifts of photosynthesis (Wong and Gamon, 2015).

Fortunately, recent advances of atmospheric measurements has made it possible to retrieve an alternative indicator that is more related to the photosynthesis processes: sun-induced fluorescence (SIF). Chlorophyll pigments absorb photons to power photosynthesis, with some of the photons are re-emitted at longer wavelengths as chlorophyll fluorescence (Baker, 2008). The re-emitted SIF has been successfully related to downward carbon flux, i.e., carbon uptake by the vegetation. This provides a promising way in estimating photosynthesis through SIF. Global SIF datasets using space-borne spectroscopy from satellites became available past few years (Frankenberg et al., 2011; Frankenberg et al., 2014; Guanter et al., 2013; Guanter et al., 2014; Joiner et al., 2013; Joiner et al., 2016; Köhler et al., 2015). Despite the complex processes underlying the relationship between SIF and gross primary production (GPP), it has been reported the satellite-retrieved SIF was highly correlated with GPP estimated based on eddy covariance (EC) flux towers (van der Tol et al., 2014; Verma et al., 2017; Yang et al., 2017; Yang et al., 2015; Zhang et al., 2016b). Their relationship appears to reflect the level of absorbed photosynthetically active radiation (APAR) with additional information of light use efficiency (LUE). Based on >50 EC towers, Joiner et al. (2014) found that the Global Ozone Monitoring Experiment-2 (GOME-2) SIF retrieved phenological metrics matched closely with that of EC-based estimations, although the footprints of GOME-2 (40 km by 80 km) were significantly larger than most EC sites. Walther et al. (2016) found that GOME-2 SIF decoupled growing seasons can be up to 6 weeks longer than that captured by EVI. Jeong et al. (2017) evaluated remotely sensed SIF and NDVI of several platforms and proposed that the continued measurements of SIF and NDVI would help us to understand the seasonal variations of vegetation photosynthesis and greenness. However, the coarse spatial representativeness of previous atmospheric measurements (~40 km by 80 km or coarser) makes it difficult to compare with ground-based canopy measurements (Chen et al., 2012; Joiner et al., 2014; Zhang et al., 2016b). Very recently, Orbiting Carbon Observatory 2 (OCO-2) has shown renewed promises of provinding satellite-derived SIF with the improved spatial representativeness at around 1.3 km by 2.25 km (Frankenberg et al., 2014). The footprints of OCO-2 that match the spatial representativeness of most EC towers enables it to produce better results (Lu et al., 2018; Verma et al., 2017). The emerging observations from OCO-2, however, have rarely been applied in phenological studies (Köhler et al., 2018).

In most physiological models, VIs and/or LAI were used to decouple the seasonal cycles of processes such as photosynthesis (Wang et al., 2016). To constrain the uncertainties of current models regarding the estimations of productivity, the use of high-resolution and global retrieval of SIF might further improve the accuracy. In the context of extreme events including prolonged droughts in recent decades, it was vital to comprehensively investigate the usability of SIF in monitoring canopy photosynthesis, including the key phenological metrics, compared with conventional VIs and LAI (Dahlin et al., 2015; Melaas et al., 2016; Zipper et al., 2016). At the same time, although several models that can estimate GPP globally with VIs have been proposed, the advantages of SIF can potentially be exploited to improve their performances especially at high-latitude regions (Jeong et al., 2017; Luus et al., 2017; Luus and Lin, 2015). However, the advantages of SIF compared against conventional VIs have not been comprehensively accessed in the context that there are advances of new satellites capable of monitoring SIF at relatively high spatial resolutions and proposal of improved VIs with different theories (Sun et al., 2017). In this study, our primary objective was to evaluate and compare the seasonal cycles of several remotely sensed canopy measurements across mid-to-high latitude forests with a focus on evergreen needleleaf forests (ENF), deciduous broadleaf forests (DBF) and mixed forests (MF). An additional objective was to focus on phenological transition dates derived from different platforms, which are indicators directly related to the carbon budgets of terrestrial ecosystems.

2. Materials and methods

2.1. EC estimated canopy properties

We conducted this study at 15 EC sites in North America and Europe where relatively homogeneous landscapes exist around the flux towers.