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Evaluation of seasonal variations of remotely sensed leaf area index over five evergreen coniferous forests

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ABSTRACT

Seasonal variations of leaf area index (LAI) have crucial controls on the interactions between the land surface and the atmosphere. Over the past decades, a number of remote sensing (RS) LAI products have been developed at both global and regional scales for various applications. These products are so far only validated using ground LAI data acquired mostly in the middle of the growing season. The accuracy of the seasonal LAI variation in these products remains unknown and there are few ground data available for this purpose. We performed regular LAI measurements over a whole year at five coniferous sites using two methods: (1) an optical method with LAI-2000 and TRAC; (2) a direct method through needle elongation monitoring and litterfall collection. We compared seasonal trajectory of LAI from remote sensing (RS LAI) with that from a direct method (direct LAI). RS LAI agrees very well with direct LAI from the onset of needle growth to the seasonal peak (R^2 = 0.94, RMSE = 0.44), whereas RS LAI declines earlier and faster than direct LAI from the seasonal peak to the completion of needle fall. To investigate the possible reasons for the discrepancy, the MERIS Terrestrial Chlorophyll Index (MTCI) was compared with RS LAI. Meanwhile, phenological metrics, i.e. the start of growing season (SOS) and the end of growing season (EOS), were extracted from direct LAI, RS LAI and MTCI time series. SOS from RS LAI is later than that from direct LAI by 9.3 ± 4.0 days but earlier than that from MTCI by 2.6 ± 1.9 days. On the contrary, for EOS, RS LAI is later than MTCI by 3.3 ± 8.4 days and much earlier than direct LAI by 30.8 ± 7.2 days. Our results suggest that the seasonal trajectory of RS LAI well captures canopy structural information from the onset of needle growth to the seasonal peak, but is greatly influenced by the decrease in leaf chlorophyll content, as indicated by MTCI, from the seasonal peak to the completion of needle fall. These findings have significant implications for improving existing RS LAI products and terrestrial productivity modeling.

1. Introduction

Leaf area index (LAI), defined as one half of the total (all sided) leaf area per unit ground surface area (Chen and Black, 1992), is an important canopy structural parameter that affects the exchanges of mass (e.g. CO_2 and water), energy and momentum between land ecosystems and the atmosphere (Kala et al., 2013; Puma et al., 2013; Sellers et al., 1997). In particular, these physical processes are closely correlated with seasonal variations of LAI (Barr et al., 2004; Bondeau et al., 1999; Chen et al., 2015; Gond et al., 1999; Guillevic et al., 2002; Muraoka et al., 2010; van den Hurk et al., 2003). For example, LAI seasonality exerts a major influence on carbon assimilation since the onset and cessation of photosynthesis strongly rely on the timing of budburst and leaf senescence (Liu et al., 2008). Seasonal changes in LAI may shift land surface energy balance and partitioning, leading to variations in land surface temperature (Slevin et al., 2014). LAI time series have been used as model inputs in order to advance current understanding of biosphere–atmosphere interactions (Buermann et al., 2001; Running et al., 1989; Sellers et al., 1997; Yan et al., 2012; Yuan et al., 2010) or assimilated into prognostic models to constrain unrealistic parameters for better predictions (Boussetta et al., 2015; Demarty et al., 2007; Liu et al., 2008; Rüdiger et al., 2010; Slevin et al., 2014; Stöckli et al., 2008).

In particular, LAI has been widely used in terrestrial primary production models, categorized mainly as canopy photosynthesis models (process-based models) and production efficiency models

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(PEM, also called light use efficiency models) (Bondeau et al., 1999; Ruimy et al., 1999). In process-based models, LAI is taken as one of the canopy structural parameters and plays two key roles. Firstly, from the leaf-level to the canopy-level photosynthetic rate, one of the commonly used upscaling approaches is the two-leaf method (Chen et al., 1999; Chen et al., 2012; Dai et al., 2004; Liu et al., 1997; Wang and Leuning, 1998), in which LAI is used to calculate the fraction of sunlit and shaded leaves. Secondly, LAI is also needed for the estimation of sunlit and shaded leaf irradiances, which determine both the photosynthetic rate and stomatal conductance. In PEM models, where the fraction of absorbed photosynthetically active radiation (fAPAR) needs to be known, LAI has been used to estimate fAPAR by the Beer's law (Daughtry et al., 1992; Turner et al., 2002). To calculate net primary productivity (NPP) in both process-based and PEM models, autotrophic respiration including growth respiration and maintenance respiration should be subtracted from gross primary productivity (GPP). Leaf maintenance respiration is proportional to leaf biomass which is calculated as the product of LAI and specific leaf weight (SLW) (Chen et al., 1999; Pan et al., 2014). Therefore, proper characterization of seasonal LAI variations may improve model accuracy or help to identify hidden errors in the model framework (Buermann et al., 2001; Lafont et al., 2012; Xiang et al., 2014).

Remote sensing data from moderate resolution (0.5–1 km) optical sensors have the advantage of large area coverage and short revisit time (7–10 days), and thus have tremendous potential to monitor seasonal dynamics of land ecosystems and to retrieve ecosystem parameters, e.g. LAI and chlorophyll, as inputs for ecosystem models. To utilize this potential, a number of LAI products have been developed and under continuous improvement, such as MODIS Collection 5 (Myneni et al., 2002), GLASS (Xiao et al., 2014), U of T LAI Version 2 (Deng et al., 2006; Gonsamo and Chen, 2014), and GEOV1 (Baret et al., 2013). Understanding the uncertainties associated with these LAI products is one crucial step before their proper use in ecosystem models (Morisette et al., 2006). The global LAI validation and intercomparison initiative has been established by the Land Product Validation (LPV) subgroup of the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) and a four-stage validation hierarchy (Fernandes et al., 2014). The uncertainties can be evaluated through direct validation against ground reference data and indirect validation through intercomparison of different LAI products. Indirect validation can be performed without actual ground measurements, and therefore has been adopted in a number of validation initiatives (Fang et al., 2013; Garrigues et al., 2008; Li et al., 2015; Weiss et al., 2007). Unlike indirect validation which provides information on the relative performance of different products, direct validation allows for the estimation of the absolute accuracy of a given product (Justice et al., 2000). A number of validation site networks have been established, such as BIGFOOT (Running et al., 1999), EOS core sites (Morisette et al., 2002), Validation of LAnd European Remote sensing Instruments (VALERI) (http://w3.avignon.inra.fr/valeri/), FP7 ImagineS (Camacho et al., 2014) and CEOS-Benchmark Land Multisite Analysis and Intercomparison of Products (BELMANIP2) (Baret et al., 2006) which has been incorporated into the On Line Interactive Validation Exercise (OLIVE) (Weiss et al., 2014). However, measuring LAI at the site level over large areas is time consuming, even with optical instruments such as the LAI-2000 plant canopy analyzer (LI-COR, Lincoln, Nebraska) and the TRAC (Tracing Radiation and Architecture of Canopies) rather than traditional destructive sampling. In addition, acquisition of seasonal trajectories of LAI requires multiple visits to study sites over the season. Therefore, existing validation datasets usually contain only one ground truth LAI measured close to the peak time of plant growth and are not representative for the spatial and temporal variations of vegetation (Baret et al., 2006). The inadequacy of seasonal site-level measurements makes it challenging to validate RS LAI at other times of the year. As a result, the validity of the LAI time series from RS remains unclear, and this has largely limited its application in land surface models.

Over the past decade, there are only a handful of studies specifically focusing on the evaluation of seasonal RS LAI (Heiskanen et al., 2012; Kobayashi et al., 2010; Rautiainen et al., 2012; Wang et al., 2005). One interesting thing to notice is that both Wang et al. (2005) and Rautiainen et al. (2012) observed an earlier decline of MODIS LAI during leaf senescence than in-situ reference LAI, and in both studies this discrepancy was attributed to changes in leaf pigments which can be barely detected by in-situ measurements. Moreover, by analyzing the data at the same site as in (Rautiainen et al., 2012), Heiskanen et al. (2012) stated that this early decline could be intensified by the cloud appearance. Similar discrepancy in the timing of decline in three seasonal RS LAI products has been reported by Kobayashi et al. (2010) who believed that this is because the three products are based on different reflectance bands that respond to leaf chlorophyll and water content distinctively. This is supported by Rautiainen et al. (2009) who concluded that other than the main driving factor of the reflectance seasonality, i.e. LAI, seasonal variations of leaf chlorophyll and water content can marginally influence the surface reflectance.

To address the issue of inadequate ground measurements that hinders evaluation of seasonal RS LAI, we measured LAI periodically for a whole year at five evergreen coniferous sites using the following two methods: (1) an optical method combining LAI-2000 and TRAC, and (2) a direct method, by quantifying needle growth and fall through regular needle elongation measurements and litterfall collection. The optical method has previously been tested for boreal forest stands (Chen et al., 1997). The direct method has been successfully applied at four mixed evergreen-deciduous forests and proven comparable to the optical method (Liu et al., 2015). Comparisons were then conducted among the optical, direct and RS LAI seasonal trajectories. Since both leaf area and leaf chlorophyll content are the factors that can influence surface reflectance and ultimately the RS LAI, in order to estimate the extent of this influence from leaf chlorophyll, we also extracted remotely sensed time series of chlorophyll index and compare them to RS LAI. Our specific objectives are : (1) to assess the level of agreement between the direct and optical methods for estimating in-situ LAI; (2) to evaluate the seasonal trajectory of RS LAI with ground measurements using these two methods; and (3) to investigate the information content of RS LAI seasonal trajectory for its potential impacts on ecosystem modeling.

2. Methods and materials

2.1. Study sites

Since it is time consuming to perform in-situ LAI measurements using optical instruments on a regular basis, and it is even more labor-intensive to make measurements that are required by the direct method; study sites with seasonal LAI estimated by both methods are rare. After years of data collection, we find five sites that meet this criteria, two in Canada and three in China (Fig. 1).

Two Fluxnet-Canada sites located near Turkey Point at the north-western shore of Lake Erie, Ontario, are: TP39 and TP74, both eastern white pine forests (*Pinus Strobus*) planted in 1939 and 1974 on cleared oak-savannah land, respectively. The region has a temperate climate with a mean annual temperature of 7.8 °C and an annual precipitation of 1010 mm based on 30-year observations by Environment Canada from 1971 to 2000 (Peichl and Arain, 2006; Peichl et al., 2010). Data collection, including optical LAI