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Short communication

Continuous observation of leaf area index at Fluxnet-Canada sites

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ABSTRACT

Continuous observation of leaf area index (LAI) is needed in order to interpret and model carbon, water and energy fluxes measured at Fluxnet tower sites. Although remote sensing LAI products can be used in regional and global scale modelling with reasonable performance, the site level modelling of ecophysiological processes needs more accurate LAI time series than those provided by global LAI products. Here we present a semi-empirical approach using satellite measured modified soil-adjusted vegetation index (MSAVI) and sparsely sampled LAI time series measurements at 7 Canadian Carbon Program (CCP) flux tower sites to produce continuous observations of site level LAI. The results indicate that accurate and continuous observation of site level LAI time series is possible using a few ground measurements and remotely sensed MSAVI observations. In order for the semi-empirical model to work correctly, the ground LAI measurements should represent all seasons, preferably including extreme values in winter and the peak of growing season.

1. Introduction

Leaf area index (LAI), defined as one half the total leaf area per unit horizontal ground surface area (Chen and Black, 1992; Gonsamo and Pellikka, 2008; Jonckheere et al., 2004), is a key parameter for interpreting carbon, water and energy fluxes. It is also of a great interest to modellers who attempt to upscale the flux tower measurements and leaf level ecophysiological processes to canopy or ecosystem levels based on unit LAI (e.g., Chen et al., 1999). The global network of Fluxnet tower sites including the Canadian Carbon Program (CCP) encourages its participants to acquire accurate and consistent seasonal in situ LAI measurements. In situ LAI measurements are usually acquired using various indirect measurement techniques such as hemispherical photography, LAI-2000 (Li-Cor, Nebraska, USA), and TRAC (Third Wave Engineering, Ottawa, Canada) which have been tested and shown to have comparable estimates to that from labour-intensive direct (destructive) measurements (Breda, 2003; Chen and Cihlar, 1995; Chen et al., 2006, 1997; Gonsamo et al., 2011b; Gower et al., 1999; Jonckheere et al., 2004; Weiss et al., 2004). However, continuous indirect measurement of LAI is challenging because it involves several field visits which are not often attainable. Therefore, researchers who conduct in situ evaluation of different ecophysiological process models for carbon, water and energy flux simulations have often relied on satellite LAI products, in place of more accurate continuous ground based LAI measurements (Gonsamo et al., 2013). A recent study by Ryu et al. (2012) has shown that continuous observations of LAI using indirect methods (digital cameras) perform comparably with the direct LAI measurement. They have also demonstrated seasonal biases involved in a standard Moderate Resolution Imaging Spectroradiometer (MODIS) LAI product indicating the satellite-based LAI estimates cannot directly be used as a replacement of continuous in situ LAI observations. One possible solution for continuous LAI observation is to measure LAI in the growing season and develop an empirical relationship with satellite-based continuous measures of vegetation index (VI). However, this relationship is often linear since it is developed at the peak of the growing season when VIs are known to saturate to changing LAI. Therefore the summertime VI-LAI relationship cannot be used for LAI seasonal mapping. This short communication will address the use of VI-LAI semi-empirical formulations considering the non-linear VI-LAI relationships constrained with sparsely sampled in situ LAI time series at CCP Fluxnet sites.

2. Methods

We focus on 7 forest and grassland CO_2 flux tower sites from the Canadian Carbon Program (CCP) formerly known as Fluxnet-Canada Research Network (FCRN) which have in situ LAI measurements. The sites include 5 needleleaf forest, 1 deciduous

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Table 1
Site description.

Site	Code	Land cover	Overstorey	LAI measurement year (number of measurements)	Lat., Long.	Instrument	Sampling	$MSAVI_{\infty}$	k	LAI measurement reference
Alberta Grassland, Lethbridge, Alberta	AB-GRL	Grassland	Mixed Prairie Grass Spp.	2001(12), 2002(14), 2003(11), 2004(13), 2005(14), 2006(14)	49.7093, −112.940	LI-3100 Area Meter	Grid	0.332	0.435	Flanagan et al. (2002)
2000 Harvested Douglas Fir, Campbell River, B.C.	BC-DF00	Needleleaf forest	*P. menziesii*	2001(1), 2002(7), 2003(7), 2004(6), 2005(6)	49.871, −125.291	LAI-2000, Point quadrant, Hemispherical, LI-1300 C Area Meter photography	Transect, grid	0.497	2.179	Chen et al. (2006) and Humphreys et al. (2005)
1988 Harvested Douglas Fir, Campbell River, B.C.	BC-DF88	Needleleaf forest	*P. menziesii*	2002(8), 2003(11), 2004(7), 2005(5)	49.535, −124.900	LAI-2000, Hemispherical photography, LI-1300 C Area Meter	Transect	0.656	3.608	Chen et al. (2006) and Humphreys et al. (2005)
Old Mixed Wood, Timmins, Ontario	ON-OMW	Needleleaf forest	*Picea mariana*	2003(2), 2004(4)	48.217, −82.156	Hemispherical photography	Grid	0.604	1.911	Thomas et al. (2008)
Old Aspen, Prince Albert, Sask.	SK-OA	Broadleaf forest	*Populus tremuloides*	2002(5), 2003(1), 2004(2), 2005(1)	53.629, −106.1978	LAI-2000, TRAC	Transect	0.635	0.843	Chen et al. (2006)
Southern Old Black Spruce, Candle Lake, Sask.	SK-SOBS	Needleleaf forest	*P. mariana*	2001(3), 2004(3)	53.987, −105.118	LAI-2000, TRAC	Transect	0.311	1.637	Chen et al. (2006)
Southern Old Jack Pine, Candle Lake, Sask.	SK-OJP	Needleleaf forest	*P. banksiana*	2001(3), 2004 (3), 2005(1)	53.916, −104.692	LAI-2000, TRAC	Transect	0.292	1.152	Chen et al. (2006)

broadleaf forest, and 1 grassland. Most CCP sites that are included in this study are described in the literature (Chen et al., 2006; Coursolle et al., 2006; Humphreys et al., 2005; Peichl and Arain, 2006; Thomas et al., 2008) and the details of sites, measurements, and references are given in Table 1. The in situ LAI is measured following standard procedures (Chen, 1996; Chen and Cihlar, 1995; Chen et al., 2006, 2002; Leblanc et al., 2005; Zhang et al., 2005) using LI-3100 Area Meter (Li-Cor, Nebraska, USA), LAI-2000 (Li-Cor, Nebraska, USA), Point quadrant, hemispherical photography, and TRAC (Third Wave Engineering, Ottawa, Canada) (Table 1). All in situ LAI represent the green leaf area index corrected for clumping index, woody-to-total area ratio, and needle-to-shoot area ratio (Chen et al., 2006, 1997).

We used the red (620–670 nm), and near-infrared (NIR: 841–875 nm) surface reflectance product (MOD09A1) from the MODIS satellite based sensor. In the production of MOD09A1, atmospheric corrections for Rayleigh, ozone, stratospheric aerosols, and water vapor effects are implemented (Vermote and Vermeulen, 1999). The MOD09A1 product is produced in 8-day "maximum quality" composites in 500 m pixels, choosing observations with minimal cloud cover, and near-nadir views. We acquired the MOD09A1 surface reflectance product in a form of ASCII subsets for selected CO_2 flux tower sites from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) (http://daac.ornl.gov/MODIS/). We have extracted the red and NIR reflectances and the exact acquisition date for a 3×3 500 m pixels at each flux tower site for period spanning from January 1, 2001 to December 31, 2012.

A semi-empirical relationship was developed to relate a vegetation index (VI) to the vertical gap fraction P_0. Nilson (1971) demonstrated from theoretical considerations that the gap fraction in canopies could be expressed as a simple exponential function of LAI:

$$P_0 = e^{-kLAI} \tag{1}$$

where extinction coefficient k depends on leaf and solar zenith angles. In the same way, theoretical considerations (Baret et al., 1995; Baret and Guyot, 1991; Clevers, 1989) confirmed by some experimental observations (Gonsamo, 2010; Gonsamo et al., 2011a; Sprintsin et al., 2007; Xiao and Moody, 2005) showed that most VIs can be related to vegetation fractional cover and can be approximated as a simple exponential function of LAI for given sun and view directions:

$$\mathrm{VI} = \mathrm{VI}_\infty + (\mathrm{VI}_s - \mathrm{VI}_\infty)\mathrm{e}^{-k\mathrm{LAI}} \tag{2}$$

where VI_s and VI_∞ are, respectively, the VI values for the soil (LAI = 0) and for infinite LAI (asymptotic value). The combination of Eqs. (1) and (2) by replacing $\mathrm{e}^{-k\mathrm{LAI}}$ in Eq. (2) with P_0 from Eq. (1) leads to the following generic semi-empirical relationship between the vertical P_0 and a VI:

$$P_0 = \frac{(\mathrm{VI} - \mathrm{VI}_\infty)}{(\mathrm{VI}_s - \mathrm{VI}_\infty)} \tag{3}$$

Experimental studies comparing several VIs have found modified soil-adjusted vegetation index (MSAVI) to be a good candidate to estimate LAI without the knowledge of VI values for the soil (i.e., VI_s) while performing best among several candidate VIs (Baret et al., 1995; Gonsamo, 2010). Therefore, the combination of Eqs. (1)and (3), without VI_s yields:

$$\mathrm{LAI} = -\frac{\ln P_0}{k} = -\frac{\ln\left((\mathrm{VI} - \mathrm{VI}_\infty)/ - \mathrm{VI}_\infty\right)}{k} = -\frac{\ln\left(\left(1 - \mathrm{VI}/\mathrm{VI}_\infty\right)\right)}{k} = -\frac{\ln\left(\left(1 - \mathrm{MSAVI}/\mathrm{MSAVI}_\infty\right)\right)}{k}. \tag{4}$$

k is dependent on leaf, sun and view zenith angles. P_0 to VI relationship is also affected by leaf optical properties through radiation absorption and scattering processes. It follows that k, and P_0 to VI relationship are functions of (i) structural variables such as LAI, leaf angle, leaf size and dispersion, (ii) view and sun angles, and (iii) optical properties of the leaves where leaf optical properties depend obviously on leaf biochemical composition. In order to account for all of these factors, we replace k with VI specific term, i.e., k(MSAVI) which is directly applied on the remotely sensed P_0:

$$\mathrm{LAI} = -\ln\left(\left(1 - \frac{\mathrm{MSAVI}}{\mathrm{MSAVI}_\infty}\right)^{k(\mathrm{MSAVI})}\right) \tag{5}$$

In Eq. (5), $k = 1/k$(MSAVI) based on logarithmic power rule. In Eq. (5) two constants (i.e., k(MSAVI) and MSAVI_∞) are required to estimate LAI from measured MSAVI. We assume that these constants vary with plant functional types (PFTs) showing the differences in canopy architecture and leaf optical properties.

In this study, the MSAVI_∞ is obtained as a maximum value for each CCP flux site from MODIS measurements obtained between January 2001 and December 2012. The parameter k(MSAVI) is estimated using a simple linear minimization algorithm between measured in situ LAI and satellite measured MSAVI and MSAVI_∞. Results of k(MSAVI) and MSAVI_∞ are presented in Table 1. The relationship between P_0 and MSAVI is linear when the k(MSAVI) equals unity. MSAVI is calculated from the red and NIR surface reflectances of MODIS data as follows:

$$\mathrm{MSAVI} = \frac{((2\mathrm{NIR} + 1 - \sqrt{(2\mathrm{NIR} + 1)^2 - 8(\mathrm{NIR} - R)}}{2} \tag{6}$$

Finally, the estimated LAI using the aforementioned semi-empirical model is presented for each of the 7 CCP flux tower sites for the January 2001–December 2012 period. The parameters, k(MSAVI)and MSAVI_∞ presented in Table 1 can be further used to estimate LAI for the CCP flux sites. In order to estimate LAI using Eq. (5), we used smoothed MSAVI based on the Savitzky–Golay filter to smooth out noise in MSAVI time series, which is caused primarily by cloud contamination and atmospheric variability. The half-width of the smoothing window was set to 4. The coefficients of a Savitzky–Golay filter can be obtained directly from Steinier et al. (1972). The parameters MSAVI_∞ and k(MSAVI) in Table 1 and the estimated LAI from year 2001 to 2012 were obtained from smoothed MSAVI data. Finally the estimated LAI were compared with collection 5 MODIS/Terra 8-day 1 km LAI product (MOD15A2).

Since both the measured and estimated LAI are not without error, we apply robust regression and correlation approaches. For analysis of the relationships between estimated and measured LAI, we use Spearman's correlation coefficient and type II regression (i.e., geometric mean regression). When we explore the relationship between variable y and x, for example, we first regress y on x and obtain a slope (β_{yx}). Secondly, we regress x on y to obtain the inverse slope (β_{xy}). The final slope between y and x for this type II regression was calculated as:

$$\beta = [\mathrm{sign}(R)]\sqrt{\frac{\beta_{xy}}{\beta_{yx}}} \tag{7}$$

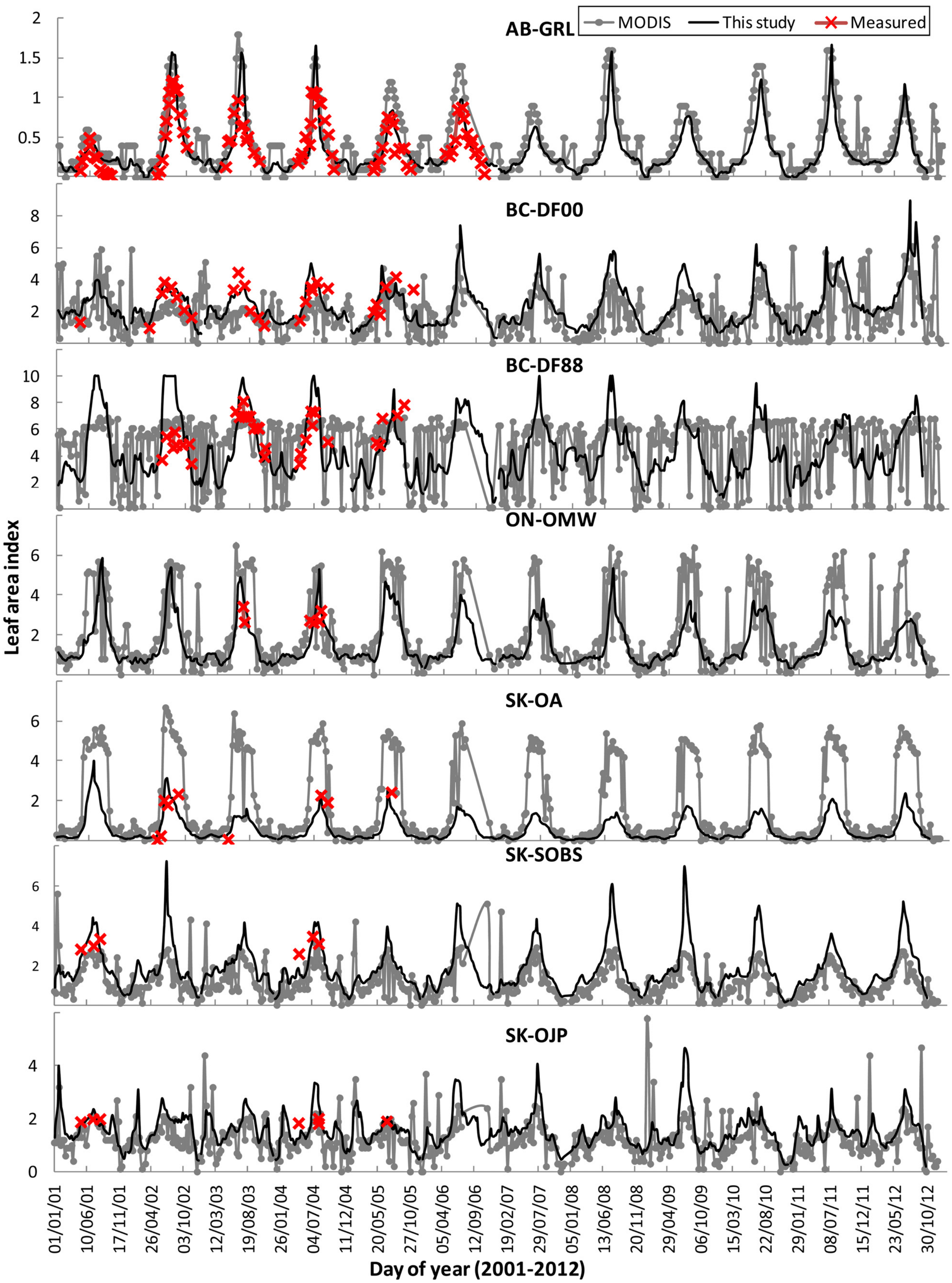

Fig. 1. Temporal evolution of estimated and measured leaf area index at Fluxnet-Canada sites.

where [sign(R)] is the sign (±) of the correlation coefficient. With this new slope, we can then calculate the new intercept (α) as:

$$\alpha = \hat{y} - \beta\hat{x} \quad (8)$$

where $\hat{y}$ and $\hat{x}$ are mean values of y and x, respectively. All regression and correlation analyses reported in this study are based on type II regression and Spearman's correlation coefficient, respectively.

3. Results and discussion

We note that the estimates of parameters k(MSAVI) and MSAVI_∞ are different among the studied CCP flux sites. The difference concerns mainly the curvature of the relationship characterized by the k(MSAVI) exponent in Eq. (5), which counterbalances the small variations in MSAVI_∞. The MSAVI_∞ corresponding to the asymptotic LAI values vary across plant functional types ranging from 0.292 to 0.656 (Table 1). The boreal needleleaf forest sites (Black Spruce and Jack Pine) resulted in the lowest MSAVI_∞ values. The highest MSAVI_∞ are associated with the temperate needleleaf (Douglas Fir and White Pine) and boreal broadleaf (Aspen) forest sites. Grass has an intermediate MSAVI_∞ value. The exponent k(MSAVI)also varies across the plant functional types showing the differences in canopy architecture and leaf optical properties (Table 1). The k(MSAVI) which is inversely proportional to the extinction coefficient of the classical Beer's law, describes the relative variation of absorption to a diffuse medium's transmission when its optical thickness (i.e., LAI) is submitted to an elementary increase, controlling the slope of the MSAVI–LAI relationship. The higher the k(MSAVI) value, the higher the MSAVI–LAI slope, meaning the MSAVI reaches asymptotic (saturation) value faster. The higher the MSAVI_∞ value for the same LAI across plant functional types, the higher the absorption in photosynthetically active region (PAR) and/or the higher the scattering in NIR region. One should note that the interaction of MSAVI_∞ and k may compensate the magnitude of each other. For example, the grass tower site has a higher MSAVI_∞ compared to the actual LAI values showing that grasslands compared to forest sites have relatively higher VI for the same LAI, a common phenomenon.

The temporal evolution of estimated and measured LAI is shown in Fig. 1. The estimated seasonal LAI variations show expected trends with broadleaf and grass sites showing 0 or close to 0 LAI values in winter seasons, whereas the needleleaf sites maintain their LAI values in winter and in early and late growing seasons. However, the standard MODIS LAI product gives LAI values of 0 or close to 0 for all sites in winter and early and late growing seasons even though the needleleaf sites are evergreen forests (Fig. 1). Three needleleaf flux sites: BC-DF00, ON-OMW and SK-SOBS also show pronounced seasonal variations of estimated LAI. BC-DF00 had been clearcut harvested in winter 1999/2000 and planted with 1-year-old seedlings which were 93% Douglas Fir and 7% Western Redcedar (*Thuja plicata*), at a density of 1600 stems ha^{-1} in March 2000 (Humphreys et al., 2005) and can still accommodate considerable amount of deciduous understorey common to the temperate region of British Columbia, Canada. ON-OMW principally includes trembling Aspen (Populus tremuloides Michx), Black Spruce (*Picea mariana* (Mill.) BSP), White Spruce (*Picea glauca* (Moench) Voss), White Birch (*Betula papyrifera* Marsh), Balsam Fir (*Abies balsamea* (L.) Mill), herbaceous species and mosses (Sun et al., 2008) which give distinct seasonal climatology of LAI. The SK-SOBS tower is located in the centre of a lowland Black Spruce stand with approximately 10% Tamarack (*Larix laricina* (Du Roi) K. Koch) and occasional Jack Pine and Balsam Poplar (*Populus balsamifera* L.) with a sparse understory of shrubs (e.g., *Ledum groenlandicum*, *Vaccinium vitis-idaea*, *Salix* spp.), mixed tall herb community (e.g., *Mertensia paniculata*, *Geum aleppicum*, *Equisetum sylvaticum*), and occasional dwarf shrubs (e.g., *V. vitis-idaea*). Therefore, these three sites show substantial seasonal LAI variation due to their composition of deciduous trees and understorey vegetation. The remaining needleleaf sites (BC-DF88 and SK-OJP) show less seasonal variability. Generally speaking, the estimated LAI follows the measured value for all flux tower sites (Fig. 1).

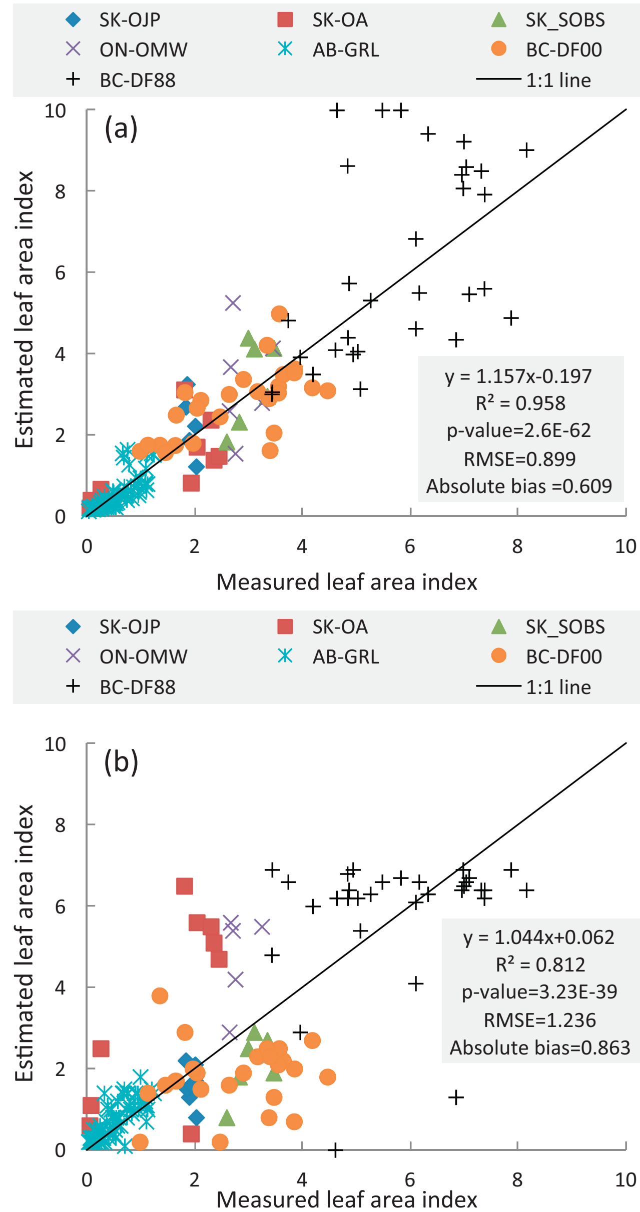

Fig. 2. Comparison of estimated and measured leaf area index (LAI). (a) Estimated LAI from this study, and (b) estimated LAI from MODIS standard product.

Fig. 2(b) shows that the MODIS LAI saturates for the measured LAI values >2. This is why except for the AB-GRL and BC-DF00 sites, MODIS LAI product show little or no interannual variability of LAI compared to both the ground measurements and the LAI estimates from this study (Fig. 1). The MODIS LAI product is known for performing poorly in capturing the interannual variability in dense canopies (e.g., Sanches et al., 2008). MODIS also consistently overestimates the broadleaf forest SK-OA site LAI compared to both the ground measurements and the LAI estimates from this study (Fig. 1). This is due to biome misclassification as half of the MODIS pixels for the SK-OA site are classified as deciduous needleleaf forest and the remaining half as mixed forest. The remaining differences between the MODIS and the LAI estimates from this study can be explained by the fact that majority of summer time LAI from MODIS are from back-up algorithm or main algorithm with saturation.

The analysis of the agreement between the estimated and measured LAI have resulted in a lower absolute bias and root mean square error (RMSE), and higher correlation compared to the MODIS LAI product (Fig. 2). The high deviation between estimated and measured LAI values in Fig. 2 for high LAI (>6) mainly comes from the BC-DF88 flux tower site. This site is characterised by dense forest where both the estimated and measured LAI values can be affected by saturations of VIs and gap fractions. In addition to this, three field instruments were used to collect the in situ LAI at different times at this site possibly introducing instrument dependent biases. In such cases, it is important to measure both extremes of LAI values in order to derive reliable $MSAVI_{\infty}$ and k(MSAVI) parameters for the semi-empirical model developed in this study. One of the remarkable attributes of MSAVI for semi-empirical modelling of LAI is that it can be applied without the knowledge of background MSAVI values corresponding to soil. Other studies which use normalized difference vegetation index (NDVI), perpendicular vegetation index (PVI), soil adjusted vegetation index (SAW), and transformed soil adjusted vegetation index (TSAVI) show that there is a need for background VI values corresponding to soil to be incorporated into Eq. (5) (Baret et al., 1995; Carlson and Ripley, 1997; Gonsamo, 2010; Gonsamo et al., 2011a). However, the results presented in Fig. 1 even for sites without winter LAI measurements to calibrate $MSAVI_{\infty}$ and k(MSAVI) parameters show expected seasonal variability across the plant functional types.

There can be several reasons for the unexplained variation of measured LAI by the estimated LAI using the new method presented in this study. One of the sources of errors can be in the ground measurements as summarized in Chen et al. (2006) for the *in situ* data used in this paper. These errors could be from saturation of measurable gaps as most of the CCP fluxnet sites are characterized by dense forest canopies. At high LAI, optical *in situ* instruments are known to perform poorly. The total error of ground measurements could be in range of 35% for the CCP fluxnet forest sites: 10% error coming from woody-to-total area ratio, 5% error in effective LAI, 5% in needle- to-shoot error ratio, and 5% in element clumping index above shoot level and upto 10% error from very dense tree crowns, such as the black spruce stands of CCP fluxnet sites (Chen et al., 2006).

4. Conclusions

Our results demonstrate the capability of the MSAVI based semi-empirical LAI retrieval method for estimating continuous LAI time series on flux tower sites using occasionally sampled in situ LAI time series. This will reduce the extensive cost and effort needed to continuously measure LAI in order to use it as an in situ reference time series. This approach is a better alternative to the global LAI products and the much needed continuous LAI observation in order to be used in site-level evaluations of ecophysiclocal model structural errors together with measured water, carbon and energy fluxes. In order to successfully use the presented semi-empirical LAI estimation approach, LAI time series should be measured for all seasons preferably including extreme values in winter and peak of growing season. The MSAVI time series should be temporally smoothed in order to remove the effect of poor quality remote sensing observations from atmospheric and cloud contaminations.

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