Remote Sensing of Environment 215 (2018) 1–6

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Data synergy between leaf area index and clumping index Earth Observation products using photon recollision probability theory

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ARTICLE INFO

Keywords:
Photon recollision probability
Foliage clumping index
Leaf area index
Multi-angle remote sensing

ABSTRACT

Clumping index (CI) is a measure of foliage aggregation relative to a random distribution of leaves in space. The CI can help with estimating fractions of sunlit and shaded leaves for a given leaf area index (LAI) value. Both the CI and LAI can be obtained from global Earth Observation data from sensors such as the Moderate Resolution Imaging Spectrometer (MODIS). Here, the synergy between a MODIS-based CI and a MODIS LAI product is examined using the theory of spectral invariants, also referred to as photon recollision probability ('*p*-theory'), along with raw LAI-2000/2200 Plant Canopy Analyzer data from 75 sites distributed across a range of plant functional types. The *p*-theory describes the probability (*p*-value) that a photon, having intercepted an element in the canopy, will recollide with another canopy element rather than escape the canopy. We show that empirically-based CI maps can be integrated with the MODIS LAI product. Our results indicate that it is feasible to derive approximate *p*-values for any location solely from Earth Observation data. This approximation is relevant for future applications of the photon recollision probability concept for global and local monitoring of vegetation using Earth Observation data.

1. Introduction

Clumping index (CI) is a measure of foliage aggregation relative to a random distribution of leaves in space (Nilson, 1971; Chen and Black, 1992). The CI is an important factor for the correct quantification of true leaf area index (LAI). The CI is also needed for estimating fractions of sunlit and shaded leaves in the canopy (Norman, 1982) - an effective way for upscaling from leaf to canopy for modeling vegetation photosynthesis (Bonan et al., 2014; He et al., 2017; Jiang and Ryu, 2016). Global and regional scale CI maps have been generated from various multi-angle sensors (e.g. He et al., 2012; Pisek et al., 2010, 2013a; Wei and Fang, 2016) based on an empirical relationship with the normalized difference between hotspot and darkspot (NDHD) index (Chen et al., 2005). Ryu et al. (2011) suggested that the adequate representation of canopy radiative transfer, important for the simulation of gross primary productivity and evapotranspiration (Baldocchi and Harley, 1995), is possible by integrating CI with incoming solar irradiance and LAI from Moderate Resolution Imaging Spectrometer (MODIS) land and atmosphere products. It should be noted that the MODIS LAI/FPAR product (MOD15A2H) uses internal a set of non-

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https://doi.org/10.1016/j.rse.2018.05.026
Received 14 December 2017; Received in revised form 24 May 2018; Accepted 25 May 2018

empirical, stochastic equations for the parameterization of foliage clumping (Shabanov et al., 2003). Our objective is to find out if the MODIS LAI product with its non-empirical, stochastic clumping parameterization can be used together with empirically-based CI maps, e.g. for the calculation of sunlit/shaded fractions of LAI.

Here, we assess the synergy between a MODIS-based CI (He et al., 2012) and a MODIS LAI product (Yan et al., 2016a, 2016b) using the theory of spectral invariants or '*p*-theory' (Knyazikhin et al., 1998) along with raw LAI-2000/2200 Plant Canopy Analyzer (PCA; LI-COR Biosciences, Lincoln, NE, USA) data from 75 sites surveyed across a range of plant functional types (PFTs). The *p*-theory predicts that the amount of radiation scattered (reflected or transmitted) within a canopy depends only on the wavelength and the spectrally invariant canopy structural parameter *p*. It can be interpreted as the probability of a photon, having intercepted an element in the canopy, to recollide with another canopy element rather than escape the canopy (Smolander and Stenberg, 2005). The parameter *p* is linked to the foliage clumping (Stenberg et al., 2016). Simulation studies by Mõttus et al. (2007) and Smolander and Stenberg (2005) showed the recollision probability is closely related to LAI, with *p*-LAI relationships varying with the degree of clumping in the spatial distribution of leaf (needle) area. At a fixed LAI, *p*-value is larger the more aggregated the leaves in a canopy, or the smaller the canopy CI. The *p*-theory is intuitive and connected to the radiative transfer theory through the eigenvalues of the radiative transfer equation (Knyazikhin et al., 1998). Stenberg et al. (2016) provide an excellent review of the photon recollision probability concept in modeling the radiation regime of canopies.

2. Materials and methods

2.1. Method

Stenberg (2007) proposed to approximate a photon recollision probability for a canopy (*p*-value) from the Plant Canopy Analyzer (PCA) as:

$$p = 1 - (i_0/\mathrm{LAI}_{true}) \quad (1)$$

where *p* is photon recollision probability, LAI_{true} is true leaf area index, and i_0 is canopy interceptance (the portion of the incoming radiation (photons) that is intercepted by the leaves), which can be expressed as:

$$i_0 = 1 - t_0 \quad (2)$$

where i_0 and t_0 are canopy interceptance and transmittance under diffuse, isotropic illumination conditions with constant directional intensity (Stenberg, 2007). Both i_0 and t_0 describe first interactions (with the canopy or the ground) only, and do not include photons which escape or interact again after being scattered from a leaf or the ground (Stenberg, pers. comm). Stenberg (2007) and Smolander and Stenberg (2005) further assume the canopy to have spherical leaf/shoot orientation and to be bounded underneath by a non-reflecting surface. t_0 is obtained as:

$$t_0 = 2\int_0^{\frac{\pi}{2}} \overline{cgf}(\theta)\sin(\theta)\cos(\theta)d\theta \quad (3)$$

where $\overline{cgf}$ is the canopy gap fraction at zenith angle θ (averaged over azimuth angle and horizontal area). Eqs. (1) and (2) can be combined to give:

$$p = 1 - \frac{1 - 2\int_0^{\frac{\pi}{2}} \overline{cgf}(\theta)\sin(\theta)\cos(\theta)d\theta}{\mathrm{LAI}_{true}} \quad (4)$$

It should be noted that *p* as defined by Stenberg (2007) is a canopy structural characteristic which is independent of the above canopy radiation conditions. The PCA-based LAI estimate ($\mathrm{LAI}_{\mathrm{PCA}}$) is calculated here as the mean of the logarithms of the gap fraction values with clumping effects partially considered (Ryu et al., 2010):

$$\mathrm{LAI}_{\mathrm{PCA}} = -2\int_0^{\frac{\pi}{2}} \overline{\ln(cgf(\theta))}\sin(\theta)\cos(\theta)d\theta \quad (5)$$

For the coniferous sites, the PCA estimate ($\mathrm{LAI}_{\mathrm{PCA}}$) is further converted to true LAI using a shoot-scale grouping correction factor γ_E ($\mathrm{LAI}_{true} = \mathrm{LAI}_{\mathrm{PCA}} * \gamma_E$) before calculating *p* (Rautiainen et al., 2009).

Alternatively, t_0 can be also estimated for an effective zenith angle θ as a function of LAI, mean projection of unit foliage area (G) (Ross, 1981), and clumping index (CI) (Chen et al., 2005):

$$t_0(\theta) = \exp[-G(\theta)\mathrm{CI}\ \mathrm{LAI}_{true}/\cos\theta] \quad (6)$$

Combining Eqs. (1) and (2) with (6), photon recollision probability *p* can then be calculated with CI and LAI estimated from Earth Observation data as:

$$p = 1 - (1 - \exp[-G(\theta)\mathrm{CI}\ \mathrm{LAI}_{true}/\cos\theta])/\mathrm{LAI}_{true} \quad (7)$$

with G(θ) = 0.5 and θ set as 57.3° to minimize the uncertainty about leaf angle orientation information (Pisek et al., 2013b) and assuming that t_0 in Eq. (2) for the upper hemisphere can be approximated by t_0 (57.3°). Eqs. (4) and (7) provide a simple way to evaluate the synergy of MODIS LAI (Yan et al., 2016a) and CI (He et al., 2012) products with independent PCA estimates. In case of needleleaf forests, Eq. (7) needs to be further modified when used in combination with the MODIS LAI product ($\mathrm{LAI}_{\mathrm{MODIS}}$):

$$p = 1 - (1 - \exp[-G(\theta)\ \mathrm{CI}\ \gamma_E \mathrm{LAI}_{\mathrm{MODIS}}/\cos\theta])/(\mathrm{LAI}_{\mathrm{MODIS}}\gamma_E) \quad (8)$$

as vegetation clumping is not accounted for at the shoot scale in the original MODIS LAI product (Yan et al., 2016b).

2.2. MODIS LAI data

The current version of the MODIS LAI/FPAR product (MOD15A2H) is Collection 6 (C6) (Yan et al., 2016a). The main algorithm is based on look-up tables (LUTs) simulated from a three-dimensional radiative transfer (3D RT) model (Knyazikhin et al., 1999; Myneni et al., 2002). The algorithm finds the best LAI and FPAR estimates with biome-specific LUTs using daily land surface Bi-directional Reflectance Factors (BRFs) along with their uncertainties. A back-up empirical method utilizes relationships between the Normalized Difference Vegetation Index and LAI/FPAR to produce lower quality LAI estimates. The LAI value corresponding to the maximum FPAR is selected over the compositing period of four or eight days. Vegetation clumping in the 3D RT is accounted for at plant and canopy scales.

The most important improvement in MOD15A2H C6 compared to previous versions is the increase from 1 km to 500 m spatial resolution. In addition, a new version of MODIS surface reflectances (MOD09GA C6) is used to replace the previous 1 km intermediate dataset (MODAGAGG). In C6 the 1 km static land cover input is replaced with new multi-year MODIS land cover product (MCD12Q1) at 500 m resolution.

Only MODIS LAI retrievals produced with the main RT algorithm closest to the date of PCA measurements (see Section 2.4) were used in this study.

2.3. MODIS CI data

He et al. (2012) derived a global CI map at 500 m spatial resolution using the red band (620–670 nm) from the MODIS BRDF Model Parameters product (MCD43A1; Schaaf et al., 2002). Since MODIS does not observe near the hotspot and the angular kernels used to construct the MODIS BRDF product do not include the complete hotspot physics and consistently underestimate the hotspot, He et al. (2012) developed an approach to correct the MODIS hotspot magnitude with synchronous co-registered POLDER-3 data. After the MODIS hotspot correction, CI is derived using two coefficients calculated from the second-order polynomial fit of the tabulated relationship between CI and NDHD by Chen et al. (2005). He et al. (2012) assigned a single annual CI value, the