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Estimation of the directional and whole apparent clumping index (ACI) from indirect optical measurements

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ABSTRACT

Canopy clumping index (CI) indicates the non-random distribution of foliage components in space, and is an important structural parameter for better understanding the radiative transfer process in a canopy. The apparent clumping index (ACI), calculated using the logarithmic gap fraction averaging method, is reported by the LAI-2200 Plant Canopy Analyzer. While LAI-2200 calculates the gap fraction and ACI from different conical rings, calculation of ACI for other geometric units (e.g., an angular cell or an azimuth sector) and instruments has been lacked. Building upon the LAI-2200 ACI, this study compares the ACIs calculated for different geometric spaces from different optical instruments. The field data obtained from seasonal continuous measurements with LAI-2200, digital hemispheric photography (DHP), and AccuPAR at a paddy rice field in northeast China were used to calculate the directional ACIs at different levels—a directional cell ($\Omega_A(\theta, \phi)$), a concentric ring ($\Omega_A(\theta)$), an azimuth sector ($\Omega_A(\phi)$), and over the horizontal landscape ($\Omega_A(\nu)$). The whole ACIs were calculated from the directional ACIs with an angular integration method, a simple averaging method, a non-linear correction method, and a variance-to-mean ratio method. The directional ACIs for paddy rice generally follow the order of $\Omega_A(\theta, \phi) < \Omega_A(\theta)$ and $\Omega_A(\phi) < \Omega_A(\nu)$, displaying an increase of foliage randomness with the segment size. The $\Omega_A(\theta, \phi)$ estimated from DHP indicates canopy clumping at the finest level and is consistent with the CIs estimated from the logarithmic averaging method (Ω_{LX}) and the ratio method (the effective leaf area index (LAI_e) divided by the LAI). The ACI metrics expand the current CI metrics and can be obtained with different optical instruments. The expanded metrics can be applied in the canopy radiative transfer modeling and in the estimation of canopy biophysical parameters for other vegetation ecosystems.

1. Introduction

The spatial distribution of canopy foliage elements, generally described by a clumping index (CI), is important for proper understanding of canopy radiative transfer, precipitation interception, and the photosynthetic process (Wei and Fang, 2016). In theory, CI (Ω) is defined as the ratio of the effective leaf area index (LAI_e), usually obtained by optical sensors, to the true leaf area index (LAI) (Nilson, 1971; Fernandes et al., 2014)

$$\Omega = LAI_e/LAI \tag{1}$$

The value of CI is equal to 1.0 when leaves are randomly distributed, and less than 1.0 when leaves are aggregated. CI has been incorporated in several land surface models (LSMs) to characterize the radiation penetration and photosynthetic processes in clumped canopies (Chen et al., 2012; Haverd et al., 2012; Ni-Meister et al., 2010; Nouvellon et al., 2000; Pinty et al., 2006; Rambal et al., 2003; Yang et al., 2010). The gross primary productivity (GPP) and canopy evapotranspiration (ET) would be substantially underestimated if LAI_e is used without taking CI into consideration (Chen et al., 2016, 2012).

Global and regional scale CI products have been generated from POLDER, MODIS, and MISR satellite data, based on an empirical relationship with the normalized difference between hotspot and darkspot (NDHD) (Chen et al., 2005; Leblanc et al., 2005b). The monthly POLDER CI was generated at 6 km resolution from October 1996 to June 1997 and the minimum CI during the eight months was extracted as the final product (Chen et al., 2005). The global MODIS CI was estimated from NDHD at 500 m resolution, and the seasonal variability was explored at a regional scale (He et al., 2012; He et al., 2016). Moreover, the MISR CI was derived with a similar method at a regional scale in 275 m (Pisek et al., 2013).

Commercial optical instruments, e.g., digital camera (Ryu et al., 2012), digital hemispheric photography (DHP) (Fang et al., 2014; Leblanc et al., 2005a; van Gardingen et al., 1999), LAI-2200 (Fang

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et al., 2014, 2018), and TRAC (Chen and Cihlar, 1995), have been frequently used to take indirect CI estimates when making field LAI measurements. The choice of a specific method varies for different biome types and ground conditions (Demarez et al., 2008; Gonsamo and Pellikka, 2009; Pisek et al., 2011). In theory, CI is generally derived in the estimation of LAI_e with the Beer-Lambert equation (Nilson, 1971)

$$P(\theta) = e^{-G(\theta)\cdot LAI_e(\theta)/\cos(\theta)} = e^{-G(\theta)\cdot\Omega(\theta)\cdot LAI/\cos(\theta)} \tag{2}$$

where θ is the solar zenith angle, $P(\theta)$ is the canopy gap fraction in direction θ, and $G(\theta)$ is the foliage projection function. Miller (1967) proposed a theorem for the inverse estimation of LAI_e that does not require a prior knowledge of $G(\theta)$.

$$LAI_e = 2\int_0^{\pi/2} -\ln P(\theta)\cos\theta\sin\theta d\theta \tag{3}$$

When multiple observations of $P(\theta)$ are available, there are two averaging methods ($\ln\overline{P(\theta)}$ vs. $\overline{\ln P(\theta)}$) and Eq. (3) can be expressed as:

$$L_1 = 2\int_0^{\pi/2} -\ln\overline{P(\theta)}\cos\theta\sin\theta d\theta \tag{4}$$

or

$$L_2 = 2\int_0^{\pi/2} -\overline{\ln P(\theta)}\cos\theta\sin\theta d\theta \tag{5}$$

CI can be derived as a ratio of the above two equations:

$$\Omega = L_1/L_2 = \frac{\int_0^{\pi/2} -\ln\overline{P(\theta)}\cos\theta\sin\theta d\theta}{\int_0^{\pi/2} -\overline{\ln P(\theta)}\cos\theta\sin\theta d\theta} \tag{6}$$

Eq. (6) can be expressed in a simple numerical form:

$$\Omega = \frac{\ln\overline{P}}{\overline{\ln P}} \tag{7}$$

The logarithmic averaging equation (Eq. (7)), i.e., the LX method, is calculated over different segments (Lang and Xiang, 1986) and thus the size of segments significantly affect the CI values estimated using this method (Demarez et al., 2008; Pisek et al., 2011). The segment size should be large enough so that the statistics of the gap fraction are meaningful, and small enough for the assumption of leaf distribution randomness within a cell to hold. Demarez et al. (2008) experimented with different segment sizes and found that 10° × 16° is optimal for corn fields. Pisek et al. (2011) suggested a 15° DHP interval to be compatible with the TRAC measurement. Theoretically, the most appropriate gap fraction sampling size is related to pixel size and angular units (Gonsamo et al., 2010). However, the determination of the optimal sampling resolution for various canopy types is not trivial. A theoretical analysis of this problem suggests that a segment of at least 10 times the width of a leaf should be used (Lang, 1986; Leblanc et al., 2005a).

For the commonly used instruments, the observational configuration and the segment size cannot be directly compared, and problems arise in the interpretation of CIs obtained from different optical instruments (Fang et al., 2014; Ryu et al., 2010b). DHP provides a fine sampling of segments that can be used to derive CI at different levels. The LAI-2200 gap fractions are derived from the transmittance observations at different rings. Without a view cap restriction, it is impossible to mimic the DHP cells because LAI-2200 provides an azimuthally integrated transmittance for each ring. In an entirely different manner, AccuPAR and other ceptometers make photosynthetically active radiation (PAR) observations over a whole hemisphere (Decagon Devices, 2004).

Ryu et al. (2010a) coined an apparent clumping index (ACI) for LAI-2200, calculated in the form of Eq. (6), where $P(\theta)$ is calculated for each ring. The purpose of ACI is to compensate for the clumping factor inherent in LAI-2200 rings and to properly calculate the true LAI (LI-COR, 2010; Ryu et al., 2010a).

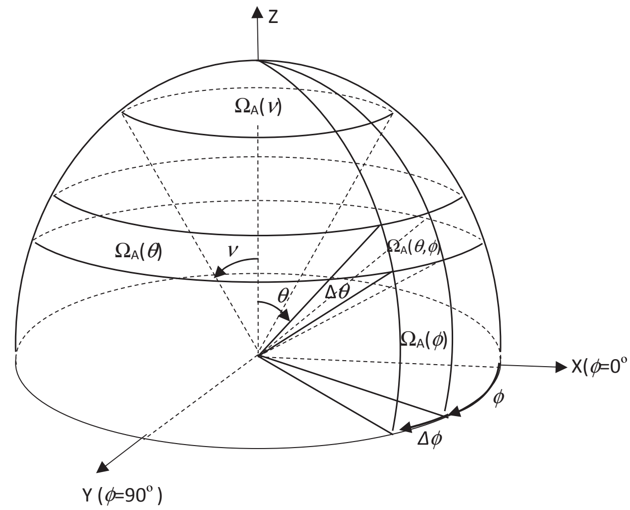

Fig. 1. Schematic illustration of different ACI metrics for different geometric units over the upper hemisphere. $\Omega_A(\theta, \phi)$ represents canopy clumping at direction (θ, ϕ). $\Omega_A(\theta)$ and $\Omega_A(\phi)$ are for a certain annulus or an azimuth sector, and $\Omega_A(\nu)$ over a solid angle ν.

$$LAI = \frac{LAI_e \times ACI}{\Omega} \tag{8}$$

where Ω is an independently determined clumping index, for example, from a gap size distribution measurement (Chen and Cihlar, 1995). Currently, LAI-2200 is the only instrument that reports ACI. Nevertheless, the ACI reported in LAI-2200 has rarely been investigated by the community.

Over the space, LAI-2200 calculates the gap fraction $P(\theta)$ and ACI ($\Omega_A(\theta)$) for five concentric conical rings only (Fig. 1). Other optical instruments provide more diversified spacial sampling and can be used to calculate various ACIs to describe the enhanced foliage distribution information. For example, DHP samples the field with a high angular resolution that can be used to calculate the gap fraction at an angular cell $P(\theta, \phi)$, an azimuth sector $P(\phi)$, or a solid angle $P(\nu)$ (Fig. 1). These instruments would enhance our existing knowledge about ACI and expand the conventional CI concept.

This paper aims to expand the ACI concept to other geometric units and instruments. We examined the variation of the directional CI at the cell level and the zenith and azimuth distribution of the ACI. The study addresses two crucial questions: (1) what are the zenith and azimuth distributions of the directional CI, and (2) what are the characteristics of the whole ACI estimated from different optical instruments. We address these questions through theoretical derivation and an experiment conducted in the paddy rice fields in northeast China.

2. Methods and material

2.1. Comparison of CI at the cell level

Generally, it is assumed that the leaf orientation is randomly distributed along the azimuth angle (ϕ) and CI is independent of ϕ. This assumption might not be true for row crops because of the large gaps between rows (Drouet and Moulia, 1997; Sinoquet and Andrieu, 1993). In this case, $P(\theta, \phi)$ needs to be calculated for a particular viewing cell, specified by the angular increment ($\Delta\theta$, $\Delta\phi$) (Fig. 1). Similar to Eq. (7), a directional ACI is defined for (θ, ϕ) (Lang and Xiang, 1986):

$$\Omega_A(\theta, \phi) = \frac{\ln\overline{P(\theta,\ \phi)}}{\overline{\ln P(\theta,\ \phi)}} \tag{9}$$

where $\Omega_A(\theta, \phi)$ describes the non-random distribution of foliage at a particular angular location (θ, ϕ) and size ($\Delta\theta$, $\Delta\phi$). Among the common indirect methods, DHP has very fine view zenith and azimuth