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# On the correct estimation of effective leaf area index: Does it reveal information on clumping effects?

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ABSTRACT

Effective leaf area index is routinely quantified with optical instruments that measure gap fraction through the probability of beam penetration of sunlight through the vegetation. However, there have been few efforts to obtain theoretically consistent effective leaf area indices from those measurements. To apply the Beer–Lambert law, multiple gap fraction measurements may be averaged in two ways: (1) by taking the mean of the logarithms of the individual gap fraction values or (2) by taking the logarithm of the mean gap fraction. Based on a theoretical model and gap fraction measurements from 41 sites, we report that effective leaf area index must be quantified using the second approach. The first approach implemented in the LAI-2000 instrument considers clumping effects at scales larger than shoots. Thus, the combination of the first approach with an independent clumping index overestimates leaf area index up to 30% at the investigated sites. Clumping effects accounted for by the LAI-2000 instrument, called the "apparent" clumping index, were dependent on canopy cover, crown shape, and canopy height. A forest gap fraction model showed that short canopy height, vertically prolonged crown shape and higher canopy cover are associated with the lowest apparent clumping indices. We show that the apparent clumping index is a useful quantity to constrain the true clumping index and to investigate spatial and temporal variation of clumping effects. Such information would be useful to evaluate a coarse global clumping index map and improve land surface models.



## 1. Introduction

Effective leaf area index ($L_e$) is defined as the product of the clumping index ($\Omega$) (Nilson, 1971) and the leaf area index ($L$) (Black et al., 1991). Thus, $L_e$ assumes no foliage clumping given the gap fraction ($P_o$) relating to the probability of beam penetration through the canopies. This definition is straightforward for one sample, but it is unclear for multiple samples across a heterogeneous and clumped canopy. So far, there has been little attention on the consistent use of $L_e$ in spite of its importance to obtain $L$ adequately.

Miller's theorem (Miller, 1967) has traditionally been used to quantify $L_e$ (Chason et al., 1991; Welles and Norman, 1991). The theorem integrates the logarithm of $P_o$ (Eq. (1)) over the range of view angles. For multiple samples, the method used to average $P_o$ needs careful attention because two averaging methods ($\ln\overline{P_o(\theta)}$ *vs* $\overline{\ln P_o(\theta)}$) exist (Lang and Xiang, 1986) and consequently there are many circumstances when they provide different $L_e$ estimates. The two approaches assume a random distribution of leaves in space within the sampling domain ($\ln\overline{P_o(\theta)}$) and within the sensor's field-of-view ($\overline{\ln P_o(\theta)}$). Thus, one could hypothesize that the latter approach provides an estimate closer to $L$ since clumping effects are partially considered at scales larger than the shoot (Lang and Xiang, 1986).

The LAI-2000 Plant Canopy Analyzer (Li-COR, Nebraska, NE, USA) has been routinely used to quantify $L_e$ (Chen et al., 2006; Smolander and Stenberg, 1996), yet few studies have explored how to estimate $L_e$ consistently using the LAI-2000 instrument. Researchers have mainly used the software provided by the vendor (i.e. C2000.exe or FV2000.exe) to post-process LAI-2000 measurements. The software calculates $L_e$ using the $\overline{\ln P_o(\theta)}$ averaging method (Welles and Norman, 1991), which potentially incorporates clumping effects (Fassnacht et al., 1994). The combination of LAI-2000 and Tracing Radiation and Architecture of Canopies instrument (TRAC; 3rd Wave Engineering, ON, Canada)

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has been proposed to quantify $L_e$ and clumping at scales larger than the shoot, combined with independent destructive estimates of clumping within shoot (e.g. conifers) to estimate $L$ (Chen et al., 2006). Thus, separating clumping effects from $L_e$ is critical to quantify $L$ correctly.

The information on the spatial distribution of leaves ($\Omega$) is crucial to model canopy photosynthesis (Baldocchi and Harley, 1995; Baldocchi and Wilson, 2001; Norman and Jarvis, 1974, 1975) and radiative transfer accurately (Acock et al., 1970; Baldocchi et al., 1985, 1984; Norman and Welles, 1983), yet most land surface models have not incorporated this information. Though there have been some pioneering efforts to map clumping factors globally (Chen et al., 2005), our understanding of $\Omega$ is still limited due to the difficulty in quantifying $\Omega$ from field-based measurements. For example, Ryu et al. (2010) reported that three instruments (TRAC, digital hemispheric photography, and traversing radiometer system) showed significantly different $\Omega$ values in an open savanna ecosystem. Also, clumping effects appear at multiple scales from shoot level (Chen, 1996; Norman and Jarvis, 1974, 1975), between-crown level (Kucharik et al., 1997; Nilson, 1999), and ecosystem level, such as savannas (Ryu et al., 2010). The multi-scale nature of clumping effects makes it hard to quantify $\Omega$ correctly. Thus, quantifying and understanding spatial and temporal variability of the upper limit of $\Omega$ will be useful to constrain and characterize $\Omega$ correctly.

In this study, we focus on $L_e$ instead on $L$ because quantifying $L_e$ using optically based indirect methods is the first step to estimate true $L$. The accurate estimation of $L_e$ will help to constrain $\Omega$ as well. The goal of this study is to investigate the correct estimation of $L_e$. The scientific questions include: (1) which $P_o$ averaging method results in theoretically consistent $L_e$? (2) If two methods give different $L_e$ estimates, what causes these differences? (3) To what degree are clumping effects captured by LAI-2000 measurements? (4) How can LAI-2000 derived clumping effects be used to constrain the true clumping index in a spatial and temporal context? We address these questions through theoretical considerations, a forest gap fraction model (Nilson, 1999; Nilson and Kuusk, 2004), and raw LAI-2000 data surveyed across a range of vegetation types collected from 41 sites.

## 2. Methods and materials

### 2.1. Theory

Monsi and Saeki (1953, 2005) proposed the $P_o$ theory. Under certain conditions, the probability of beam penetration can be described by the Poisson distribution:

$$P_o = \exp\left(\frac{-L_e G(\theta)}{\cos\theta}\right) = \exp\left(\frac{-L\Omega(\theta)G(\theta)}{\cos\theta}\right) \tag{1}$$

where $G$ is the leaf projection function (Warren Wilson, 1960) and $\theta$ is the view zenith angle. For simplicity, woody material is ignored as leaves tend to present themselves to obscure underlying stems from sun (Kucharik et al., 1998). Miller (1967) proposed a theorem for the inverse estimation of $L_e$ that does not require a prior knowledge of the $G(\theta)$:

$$L_e = 2\int_0^{\pi/2} -[\ln P_o(\theta)]\cos\theta\sin\theta\, d\theta \tag{2}$$

For multiple samples, $L_e$ can be derived by two slightly different approaches (Lang and Xiang, 1986):

$$L_e = 2\int_0^{\pi/2} -[\ln\overline{P_o(\theta)}]\cos\theta\sin\theta\, d\theta \tag{3}$$

$$L_e = 2\int_0^{\pi/2} -[\overline{\ln P_o(\theta)}]\cos\theta\sin\theta\, d\theta \tag{4}$$

We define the ratio of Eq. (3) to Eq. (4) to be an "apparent" clumping index ($\Omega_{\text{app}}$):

$$\Omega_{\text{app}} = \frac{2\int_0^{\pi/2} -[\ln\overline{P_o(\theta)}]\cos\theta\sin\theta\, d\theta}{2\int_0^{\pi/2} -[\overline{\ln P_o(\theta)}]\cos\theta\sin\theta\, d\theta} \tag{5}$$

$\Omega_{\text{app}}$ is always less than 1 because of the convexity of the logarithmic function. Thus, the greater the degree of clumping, the lower $\Omega_{\text{app}}$. Eq. (5) follows the definition of $\Omega$ by using the ratio of measured $L_e$ to approximated $L$ as used in the previous studies (Leblanc et al., 2005; van Gardingen et al., 1999).

To characterize $\Omega_{\text{app}}$ using a forest gap fraction model (Nilson, 1999; Nilson and Kuusk, 2004), we apply second order Taylor's expansion:

$$-\overline{\ln P_o(\theta)} \approx -\ln\overline{P_o(\theta)} - \frac{1}{2}(\ln\overline{P_o(\theta)})''Var(P_o(\theta)) \tag{6}$$

which includes the second derivative of logarithm and the variance of gap fraction ($Var(P_o(\theta))$)

Taking the second derivative of logarithm $(= -1/(\overline{P_o(\theta)})^2$ and integrating Eq. (6) over the zenith angle we obtain

$$\int_0^{\pi/2} -\overline{\ln P_o(\theta)}\cos\theta\sin\theta\, d\theta \approx \int_0^{\pi/2} -\ln\overline{P_o(\theta)}\cos\theta\sin\theta\, d\theta + \frac{1}{2}\int_0^{\pi/2} \frac{Var(P_o(\theta))}{\left[\overline{P_o(\theta)}\right]^2}\cos\theta\sin\theta\, d\theta \tag{6a}$$

We refer to the second term on the right hand side as a non-linearity correction term. The greater the variance of gap fraction at the view angle $\theta$, the greater non-linearity correction term. Then, $\Omega_{\text{app}}$ may be expressed as follows after rearrangement of Eq. (6a):

$$\Omega_{\text{app}} \approx 1 - 0.5\frac{\int_0^{\pi/2} Var(P_o(\theta))/[\overline{P_o(\theta)}]^2\cos\theta\sin\theta\, d\theta}{\left[\int_0^{\pi/2} -\overline{\ln(P_o(\theta))}\cos\theta\sin\theta\, d\theta\right]} \tag{7}$$

The second term on the right hand side is a normalized-non-linearity correction term. The LAI-2000 instrument has no ability to measure $P_o$ at the shoot level, thus $\Omega_{\text{app}}$ (Eq. (5)) does not consider clumping effects at the shoot level. Chen (1996) proposed the concept of the element clumping index ($\Omega_{\text{E}}$), which quantifies clumping effects at scales larger than the shoot level. Because $\Omega_{\text{app}}$ does not fully account the clumping effects at larger than shoot scale, it is expected that $\Omega_{\text{app}}$ is greater than $\Omega_{\text{E}}$.

### 2.2. Forest gap fraction model

By a forest gap fraction model (Nilson, 1999; Nilson and Kuusk, 2004), we can obtain the mean value and variance of between-crown $P_o(\theta)$ in forests. In particular, the variance of the gap fraction at a fixed angle $\theta$ and averaged over the azimuth (as in the LAI-2000 instrument) can be calculated. In model simulation of variance for a LAI-2000 ring, a $P_o(\theta)$ reading on a single LAI-2000 ring may be treated as an integral over the azimuth of a random function-gap probability at a fixed zenith angle. To calculate the variance of an integral of a random function, we need to know the autocorrelation function of gap probability, in our case along the azimuth at a fixed zenith angle. We use the Nilson and Kuusk (2004) model to describe the between-crown gap probability and its autocorrelation. For a binary (1: gap, 0: no gap) variable, the covariance ($cov(\theta,\phi)$) of the occurrence of gaps at two directions having the same $\theta$ but separated by the azimuth difference $\phi$ can be calculated

as

$$cov(\theta,\phi) = P_{11}(\theta,\phi)d\phi - P_o^2(\theta) \quad (8)$$

where $P_{11}(\theta,\phi)$ is the bi-directional gap probability that two lines of sight with the same view zenith angle $\theta$, but separated by the azimuth difference $\phi$, both occur in a between-crown gap. To calculate the variance of the gap fraction reading in a LAI-2000 ring, we have to calculate the double integral over the covariance function. Since the covariance is supposed to depend on the azimuth difference, only, the double integral is reduced to a single integral (Sveshnikov, 1968). In Nilson and Kuusk (2004), the following formula was derived to calculate the variance of between-crown gap fraction averaged over the azimuth ring $\theta$:

$$Var(P_o(\theta)) = \frac{2}{\pi^2}\int_0^{\pi}(\pi-\phi)P_{11}(\theta,\phi)d\phi - P_o^2(\theta) \quad (9)$$

Here, we have to note that this equation tends to somewhat underestimate the variance, since it assumes the variance of the integral over the azimuth from 0 to $2\pi$ is two times of the same integral from 0 to $\pi$, thus ignoring the possible correlation between the two halves. However, all the qualitative effects should be adequately described by Eq. (9). The calculation of $P_{11}(\theta,\phi)$ is reduced to finding the overlap area of two tree crown projections in the two directions. If these projections do not overlap, the respective covariance is zero. The larger the angular dimensions of crowns as viewed from the height of LAI-2000 measurements (especially diameter), the further extends the covariance along the azimuth and the greater the variance. The LAI-2000 can screen light in some portions of azimuthal range using various angular sizes of view caps. In principle, the model can consider the effect of view cap size in LAI-2000 measurements on the variance of $P_o(\theta)$, but we did not consider the use of view cap in the model throughout this manuscript.

The model requires input data including crown width, crown depth, canopy height, measurement height, tree distribution pattern and canopy cover. By changing the input data, it is possible to study the magnitude of the non-linear correction term and its dependence on canopy structures. For the simulation, we used input data as crown width (6-m), tree height (13-m) and measurement height (1-m). The tree distribution pattern was assumed to follow a Poisson distribution. We changed canopy cover (0.1, 0.2, . . ., 0.9) by modulating tree density under the Poisson distribution-based tree distribution pattern. We changed crown shape by modulating crown depth (1, 3, 6, 9, and 12-m) given the crown width. To explicitly consider between-crown gaps, we made crowns opaque by allocating high $L$ (e.g. 100).

### 2.3. Data

We compiled raw data from the LAI-2000 instrument at 41 sites that were distributed across six plant functional types ranging from tropical to boreal climatic zones (Table 1). First, we calculated $P_o(\theta)$ at each location where a LAI-2000 reading was taken. Then, we applied the two $P_o(\theta)$ averaging methods (Eqs. (3) and (4)) and calculated $\Omega_{app}$ at each site. Independently estimated element clumping index ($\Omega_E$), i.e. the clumping index at scales larger than shoots (Chen, 1996), was available at 18 sites. The methods to calculate $\Omega_E$ include a gap size distribution model (Chen and Cihlar, 1995; Leblanc, 2002), a forest gap fraction model (Nilson, 1999; Nilson and Kuusk, 2004), $\Omega_E$ model (Kucharik et al., 1999), and $L_e/L_t$ by direct measurements of both variables ($L_t$ is total plant area index) (Ryu et al., 2010). Since it is practically impossible to separate the contribution of within shoot gaps to the overall $P_o$, we compared $\Omega_{app}$ with $\Omega_E$ to investigate how much the LAI-2000 instrument could incorporate clumping effects. We performed paired $t$-tests between $\Omega_{app}$ and $\Omega_E$ within each plant functional type using JMP (SAS Institute Inc. v7.0, 2007, Cary, NC, USA).

### 2.4. Spatial scaling of apparent clumping index

To investigate the spatial scaling behavior of $\Omega_{app}$, we used the LAI-2000 raw data measured at Metolius, OR (Law et al., 2001b). At this site, LAI-2000 measurements were made on a systematic grid over twenty 100 m × 100 m plots. Each plot includes ~120 $P_o$ readings. The plots were distributed over a 10 km × 15 km area to capture the range of variation in canopy structure over the landscape for a radar validation study; 18 of the plots were dominated by ponderosa pine and two contained primarily Douglas-fir. To study the impact of sample size (i.e. number of plots) on the calculation of $\Omega_{app}$, we selected sample sizes from 1 to 20. For each sample size, we followed the bootstrap technique and created 10,000 data sets by drawing random subsets of the respective size from all 20 plots without replacement (Efron and Tibshirani, 1993). Then we calculated $\Omega_{app}$ for each sample size by averaging 10,000 resamplings.

## 3. Results and discussion

### 3.1. Theoretically consistent $L_e$

We employed a simple theoretical model to investigate which $P_o$ averaging method provides a correct $L_e$ estimate (Fig. 1). For the turbid media case (i.e. homogeneous canopy), there was no difference between the two $P_o$ averaging methods based on $L_e$ values (Fig. 1a). However, for a clumped canopy, the two $P_o$ averaging methods resulted in different $L_e$ estimates (Fig. 1b). As conceptualized in Fig. 1b, the leaves are not randomly distributed due to a clumping effect caused by between-crown gaps (Nilson, 1999). The $\overline{\ln P_o(\theta)}$ method provided the true $L$ ($L = L_e = 1$), indicating that this method incorporates clumping effects by locally applying the Poisson assumption (Lang and Xiang, 1986). The $\ln\overline{P_o(\theta)}$ approach quantifies $L_e$ correctly by assuming clumped leaves to be randomly distributed within the experimental domain. Thus, we confirm that the $\ln\overline{P_o(\theta)}$ method must be used to estimate $L_e$, and the ratio of $L_e$ to $L$ (i.e. the clumping index) is 0.74. Consequently, we believe that the LAI-2000 software does not produce a theoretically consistent estimate of $L_e$, but it approximates true $L$ by incorporating clumping effects via the $\overline{\ln P_o(\theta)}$ approach.

### 3.2. The effect of canopy structure on apparent clumping index

We used a theoretical $P_o$ model (Nilson, 1999; Nilson and Kuusk, 2004) to investigate how LAI-2000 derived $\Omega_{app}$ changes with crown shape, canopy cover and canopy height, which are important variables modulating clumping effects (Kucharik et al., 1999) (Fig. 2). The simulated variance of $P_o$ was the largest in the inner ring (ring 1) of the LAI-2000 instrument and monotonically decreased along with the view zenith angle (Fig. 2a). The maximum variance of $P_o$ occurred at around 0.4 of canopy cover (e.g. savannas) in the first ring while this maximum shifted towards lower canopy covers in the lower rings. The variance increased with vertically prolonged crown shape (Fig. 2b). The non-linearity correction term and the normalized-non-linearity correction term were found to be highest at higher canopy cover and vertically prolonged crown shapes (Fig. 2c and d). $\Omega_{app}$ was lower for problate spheroids and greater for oblate spheroids. Generally, $\Omega_{app}$ was greater where crown shape was spherical, resulting in similar path lengths at any view angles (Fig. 2e). Another key factor in the $\Omega_{app}$ is the angular size of the crown as seen from the height of measurements. For instance, in another

**Table 1**
LAI-2000 raw data survey from 39 sites. $\Omega_{app}$ is clumping index derived from LAI-2000 gap fraction measurement (Eq. (5)). $\Omega_E$ is element clumping index. DHP is digital hemispheric photography. TRAC is Tracing radiation and architecture of canopies. CC is clumping index calculated by Leblanc (2002). $L_e/L_t$ is the ratio of effective leaf area index to total leaf area index.

| Plant functional types | Country | Site | Latitude | Longitude | Climate | Species | $L_e$ (Eq. (3)) | $L_e$ (Eq. (4)) | $\Omega_{app}$ | LAI-2000 data source | $\Omega_E$ from literature (method) | $\Omega_E$ source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CRO | Japan | Nagaoka | 37.49°N | 138.78°E | Temperate | Rice[a] | 2.43 | 2.72 | 0.89 | Kobayashi (unpublished data) | | |
| | Japan | Nagaoka | 37.49°N | 138.78°E | Temperate | Rice[b] | 2.28 | 2.84 | 0.80 | Kobayashi (unpublished data) | | |
| | USA | Ponca city | 36.45°N | 97.05°W | Continental | Wheat | 3.65 | 3.78 | 0.97 | Burba and Verma (2005) | | |
| | USA | Twitchell island | 38.11°N | 121.64°W | Mediterranean | Rice | 5.21 | 5.56 | 0.94 | This study | | |
| | USA | Villinger | 38.11°N | 121.34°W | Mediterranean | Corn | 0.31 | 0.39 | 0.79 | This study | | |
| | USA | Clements | 38.20°N | 121.09°W | Mediterranean | Grape | 0.44 | 0.53 | 0.83 | This study | | |
| DBF | Estonia | Järvselja | 58.29°N | 27.26°E | Boreal | Birch | 3.65 | 3.75 | 0.97 | VALERI project and (Kodar et al., 2008) | 0.98 (Nilson and Kuusk, 2004) | This study |
| | Italy | Roccarespampani 1 | 42.41°N | 11.93°E | Mediterranean | Oak | 3.28 | 3.70 | 0.89 | Tedeschi et al. (2006) | | |
| | Italy | Roccarespampani 2 | 42.39°N | 11.92°E | Mediterranean | Oak | 4.42 | 4.57 | 0.97 | Tedeschi et al. (2006) | | |
| | Japan | Takayama | 36.14°N | 137.42°E | Temperate | Oak | 3.56 | 3.66 | 0.97 | Nasahara et al. (2008) | 0.93 (CC, TRAC) | Nasahara et al. (2008) |
| | Korea | Gwangneung | 37.76°N | 127.15°E | Temperate | Oak | 3.99 | 4.57 | 0.87 | Kwon (unpublished data) | | |
| | USA | Coweeta | 35.05°N | 83.45°W | Temperate | Oak-hickory | 5.00 | 5.51 | 0.91 | Hwang et al. (2009) | | |
| | USA | Chestnut ridge | 35.93°N | 84.33°W | Temperate | Oak | 3.5 | 3.53 | 0.99 | Heuer (unpublished data) | | |
| | USA | Walker branch | 35.96°N | 84.29°W | Temperate | Oak | 3.74 | 3.92 | 0.95 | Heuer (unpublished data) | 0.84 ($L_e/L_t$) | Baldocchi (1997) |
| | USA | Harvard | 42.54°N | 72.17°W | Temperate | Oak | 4.81 | 5.19 | 0.93 | Urbanski et al. (2007) | | |
| EBF | Australia | Dwellingup | 32.61°S | 116.03°E | Mediterranean | Eucalyptus | 1.62 | 1.69 | 0.96 | Macfarlane et al. (2007) | 0.89 (CC, DHP) | Macfarlane et al. (2007) |
| | France | Puéchabon | 43.74°N | 3.60°E | Mediterranean | Oak | 2.94 | 3.06 | 0.95 | Rambal et al. (2003) | 0.72 (Kucharik et al., 1999) | Rambal et al. (2003) |
| | Thailand | Kog-Ma | 18.8°N | 98.9°E | Tropical | *Lithocarpus* | 3.50 | 3.65 | 0.96 | Tanaka et al. (2008) | 0.93 (CC, TRAC) | Nasahara unpublished data) |
| ENF | Canada | Campbell river | 49.91°N | 125.37°W | Boreal | Douglas fir[c] | 3.57 | 3.88 | 0.92 | Chen et al. (2006) | 0.91 (CC, DHP) | Chen et al. (2006) |
| | Canada | Campbell river | 49.52°N | 124.90°W | Boreal | Douglas fir[d] | 2.13 | 2.75 | 0.77 | Chen et al. (2006) | 0.89 (CC, DHP) | Chen et al. (2006) |
| | Canada | Sandhill | 53.80° N | 104.62°W | Boreal | Black spruce | 2.54 | 2.75 | 0.93 | Sonnentag (unpublished data) | 0.90 (CC, TRAC) | Chen et al. (2006) |
| | Canada | Sandhill | 53.80° N | 104.62°W | Boreal | Jack pine and black spruce | 3.57 | 3.73 | 0.96 | Sonnentag (unpublished data) | | |
| | Canada | Sandhill | 53.80° N | 104.62°W | Boreal | Black spruce[e] | 1.73 | 2.16 | 0.80 | Sonnentag (unpublished data) | | |
| | Canada | Sandhill | 53.80° N | 104.62°W | Boreal | Jack pine | 2.09 | 2.38 | 0.88 | Sonnentag (unpublished data) | 0.85 (CC, TRAC) | Chen et al. (2006) |
| | Estonia | Järvselja | 58.30°N | 27.26°E | Boreal | Scots pine | 2.57 | 2.61 | 0.99 | VALERI project and (Kodar et al., 2008) | 0.83 (Nilson and Kuusk, 2004) | This study |
| | Estonia | Järvselja | 58.30°N | 27.24°E | Boreal | Norway Spruce | 3.05 | 3.12 | 0.98 | VALERI project and (Kodar et al., 2008) | 0.95 (Nilson and Kuusk, 2004) | This study (Ryu et al., 2010) |
| | Korea | Gwangneung | 37.76°N | 127.16°E | Temperate | Pine | 4.14 | 4.44 | 0.93 | Kwon (unpublished data) | | |
| | USA | Howland (Main) | 45.20°N | 68.74°W | Temperate | Red spruce | 3.92 | 4.09 | 0.96 | Richardson (unpublished data) | 0.98 (CC, TRAC) | Richardson (unpublished data) |
| | USA | Howland (BlockA) | 45.21°N | 68.74°W | Temperate | Red spruce | 1.72 | 1.94 | 0.89 | Richardson (unpublished data) | 0.88 (CC, TRAC) | Richardson (unpublished data) |
| | USA | US-NC2 | 35.48°N | 76.40°W | Temperate | Loblolly pine | 3.94 | 4.23 | 0.93 | Noormets et al. (2009) | | |
| | USA | Metolius | 44.30°N | 121.37°W | Mediterranean | Douglas fir | 0.99 | 1.27 | 0.78 | Law et al. (2001) | 0.77 (CC, TRAC)[f] | Law et al. (2001) |
| GRA | Canada | Sandhill | 53.79° N | 104.62°W | Boreal | Sedges | 0.99 | 1.10 | 0.90 | Sonnentag et al. (in press) | | |
| | USA | Sherman Island | 38.04°N | 121.75°W | Mediterranean | Invasive weed | 0.50 | 0.61 | 0.83 | Sonnentag (unpublished data) | | |
| | USA | Shidler | 36.56°N | 96.41°W | Continental | Tallgrass | 5.22 | 5.32 | 0.98 | Burba and Verma (2005) | | |
| | USA | Twitchell island | 38.11°N | 121.65°W | Mediterranean | Tule | 4.45 | 5.24 | 0.85 | This study | | |
| | USA | Vaira | 38.41°N | 120.95°W | Mediterranean | Grass | 0.71 | 0.99 | 0.71 | This study | | |
| MF | Canada | Timmins | 48.22° N | 82.16°W | Boreal | Aspen, Spruce, Birch, Fir | 3.29 | 3.50 | 0.94 | Chen et al. (2006) | 0.93 (CC, DHP) | Chen et al. (2006) |
| | Estonia | Järvselja | 58.29°N | 27.25°E | Boreal | Birch and Spruce | 3.44 | 3.59 | 0.96 | VALERI project and (Kodar et al., 2008) | 0.82 (Nilson and Kuusk, 2004) | This study |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | USA | Washington park arboretum | 47.64° N | 122.30°W | Mediterranean | Fir, Maple, Cedar, Hemlock | 1.73 | 2.91 | 0.60 | Richardson et al. (2009) | | |
| OSH | Canada | Mer Bleue | 45.4° N | 75.5°W | Boreal | Evergreen shrubs | 2.41 | 2.69 | 0.90 | Talbot et al. (in review) | 0.49 ($L_e/L_t$) | Ryu et al. (2010) |
| WSA | USA | Tonzi | 38.43°N | 120.97°W | Mediterranean | Blue oak | 0.56 | 0.68 | 0.83 | Ryu et al. (2010) | | |

CRO: crop, DBF: deciduous broad-leaved forest, EBF: evergreen broad-leaved forest, ENF: evergreen needle-leaved forest, GRA: grass, MF: mixed forest, OSH: open shrub land, and WSA: woody savanna.
[a] Early planted.
[b] Later planted.
[c] Old Douglas fir.
[d] Young Douglas fir.
[e] Black spruce with many dead trees.
[f] CC method that was not corrected by Leblanc (2002).

numerical experiment tree height was assumed to be 26 m instead of 13 m (Fig. 2f). The simulated $\Omega_{app}$ values of the 13 m height were lower by ~0.04 than for the 26 m height. In taller canopies, the different view angles of the LAI-2000 instrument include more crowns, which cause the leaves to appear almost randomly distributed. Thus, we could expect that LAI-2000 derived $\Omega_{app}$ is dependent on canopy architecture, including crown shape, canopy cover, and canopy height, as is $\Omega_E$ (Kucharik et al., 1999). These results justify the use of $\Omega_{app}$ to quantify clumping effects with respect to canopy structures.

### 3.3. Clumping effects accounted for by the LAI-2000 instrument

We analyzed LAI-2000 raw data from 41 sites covering 8 plant functional types to investigate the degree of clumping accounted for by the LAI-2000 instrument (Table 1). Overall, $\Omega_{app}$ was $0.90 \pm 0.08$ (mean ± standard deviation) ranging from 0.60 to 0.99. It is notable that wheat and tall grass prairie sites where the LAI-2000 instrument was developed and tested (Welles and Norman, 1991) showed $\Omega_{app} \approx 1$, implying closed, homogeneous canopies. The mean values of $\Omega_{app}$ for each plant functional type ranged from 0.83 (mixed forest and woody savanna) to 0.96 (evergreen broad-leaved forest). The LAI-2000 instrument incorporated 35% (woody savanna site, Tonzi) to 100% of the clumping effects by comparison with independent $\Omega_E$ estimates reported in the literature (Table 1). The combination of $\overline{\ln P_o(\theta)}$ averaging method derived $L_e$ with independent $\Omega_E$ estimates overestimated $L$ up to 30% (Douglas-fir young forest).

We investigated the difference between $\Omega_{app}$ and $\Omega_E$ across diverse plant functional types (Fig. 3). We found that there was no significant difference in evergreen needle-leaved forest, deciduous broad-leaved forest, mixed forest, and evergreen broad-leaved forest ($p > 0.05$, paired $t$-test) (Fig. 3). We had only one sample at open shrub land and woody savanna which needed more sampling for statistical analysis. However, one woody savanna site (Tonzi ranch) showed a large discrepancy between $\Omega_{app}$ (0.83) with $\Omega_E$ (0.49). The discrepancy was expected because the assumption of randomly distributed leaves in space within each ring's footprint is violated due to large spatial heterogeneity in savannas (Ryu et al., 2010). We recommend combining the LAI-2000 instrument and zenith direction digital cover photography to obtain correct $\Omega_E$ in very heterogeneous canopies (Ryu et al., 2010).

### 3.4. Implications of apparent clumping index to vegetation clumping study

#### 3.4.1. Constraint on true clumping index

The $\Omega_{app}$ could be an upper limit of true $\Omega_E$ which is hard to quantify exactly. In Eq. (5), we assumed the numerator ($L_e$) may be estimated correctly by using LAI-2000. However, the denominator ($L$) needs special attention because individual measurements must meet the turbid media assumption (i.e. Poisson model of beam penetration through the canopy). Within one sample of the LAI-2000, light intensity at each ring is averaged over some azimuth range depending on the size of the view cap. However the Poisson assumption within each ring's footprint is likely violated for heterogeneous canopies like a woody savanna site (Tonzi ranch) (Ryu et al., 2010). Thus, the denominator measured from the LAI-2000 is same or smaller than true $L$, consequently, $\Omega_{app}$ is the same or greater than $\Omega_E$. Therefore $\Omega_{app}$ is a useful quantity to check and constrain estimates of $\Omega_E$.

Our results suggest that the methodologies to quantify $\Omega_E$ might underestimate clumping effects because we did not find a significant difference between $\Omega_E$ and $\Omega_{app}$. For example, we compared $\Omega_{app}$ with TRAC-based $\Omega_E$ using a gap-size distribution analysis, the CC method (Chen and Cihlar, 1995; Leblanc, 2002).

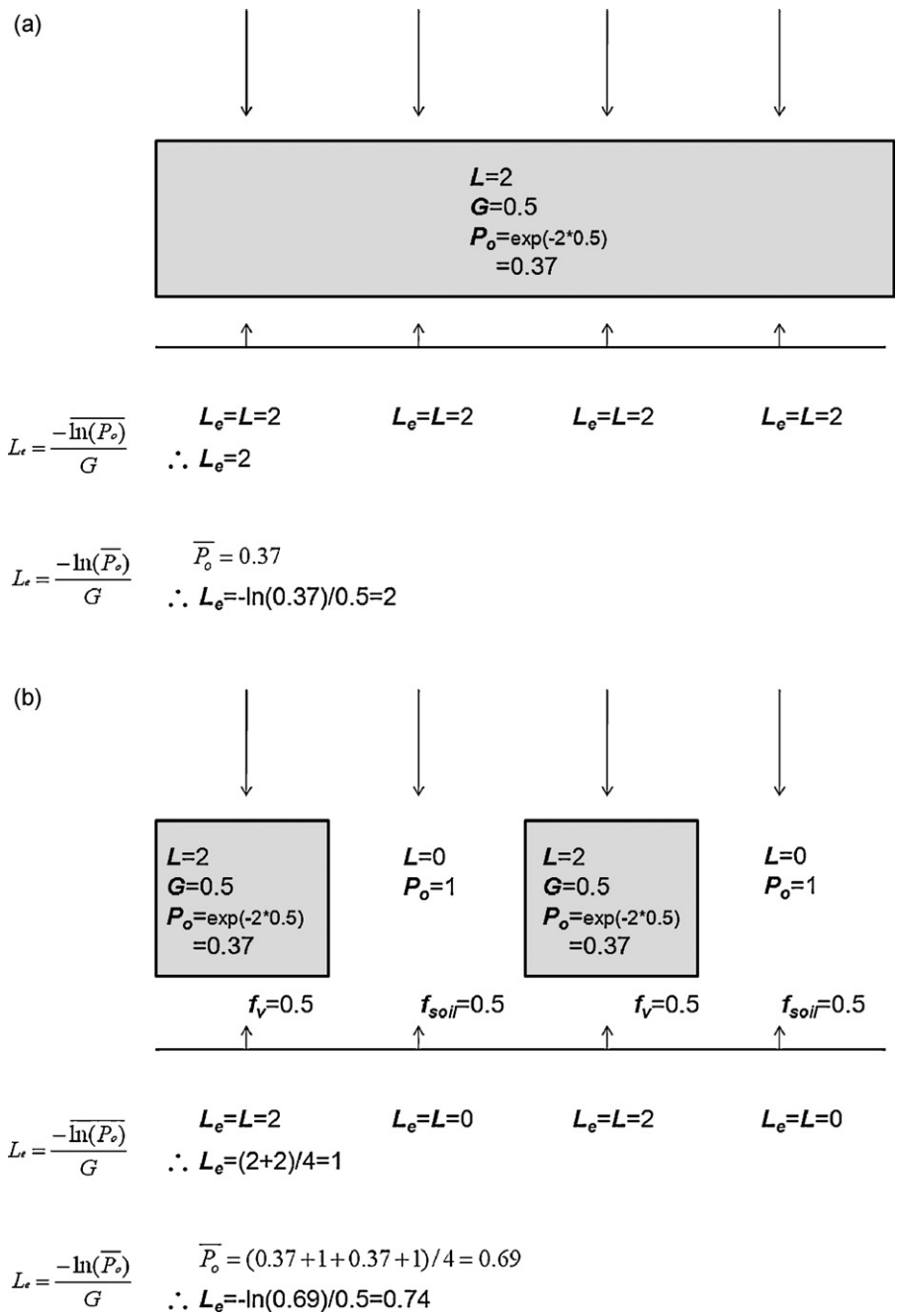


**Fig. 1.** A conceptual diagram to calculate $L_e$. We assume direct beam originates from zenith direction (downward long arrows), leaf area index ($L$) in each crown is 2, there is no clumping within each crown, leaf inclination angle distribution is spherical (i.e. $G = 0.5$ where $G$ is the leaf projection coefficient, Warren Wilson, 1960), and four measurements are taken as indicated by upward short arrows. $P_o$ is gap fraction. (a) A case of turbid media (homogeneous canopy). Two $P_o$ averaging methods give same result. (b) A case of clumped canopy. The vegetation cover fraction ($f_v = 0.5$) and soil cover fraction ($f_{soil} = 0.5$) are same. Two $P_o$ averaging methods give different results.

The TRAC instrument measures sun-flecks over the forest floor and quantifies $\Omega_E$ using actual $P_o(\theta)$ and reduced $P_o(\theta)$ after removing large gaps that cannot happen in randomly distributed leaves (Leblanc, 2002). The TRAC CC method has been widely used to quantify $\Omega_E$ but critical appraisal of this method has been rare (Macfarlane et al., 2007; Ryu et al., 2010). We found that $\Omega_{app}$ and TRAC CC based $\Omega_E$ showed very good agreement ($y = 0.98x$, $r^2 = 0.89$, $p < 0.01$) and there was no significant difference between the two methods ($p > 0.05$, paired $t$-test) (Fig. 4). Because TRAC and LAI-2000 use direct beam and diffuse radiation respectively, the direct comparison can lead to a mismatch of the spatial and angular footprints. Thus, the good agreement implies: (1) the limited spatial (dependent on limited transect length) and angular (dependent on solar position) footprint of the TRAC instrument may not account for some clumping effects, especially for heterogeneous ecosystem like savanna (Ryu et al., 2010) (instrument footprint issue) or (2) the large-gap removal process in the TRAC CC method may not perform correctly (algorithm performance issue). The first issue is an innate limitation of the TRAC instrument but the second issue could be improved using a new algorithm that combines the CC with the Lang and Xiang (1986) approach (Leblanc et al., 2005), which locally incorporates clumping effects using the CC method to make sure the denominator of Eq. (6) is close to true $L$. Actually, Leblanc et al. (2005) reported that the mean $\Omega_E$ from 29 boreal forest sites was ~0.2 lower for the new algorithm than the CC method. Among the

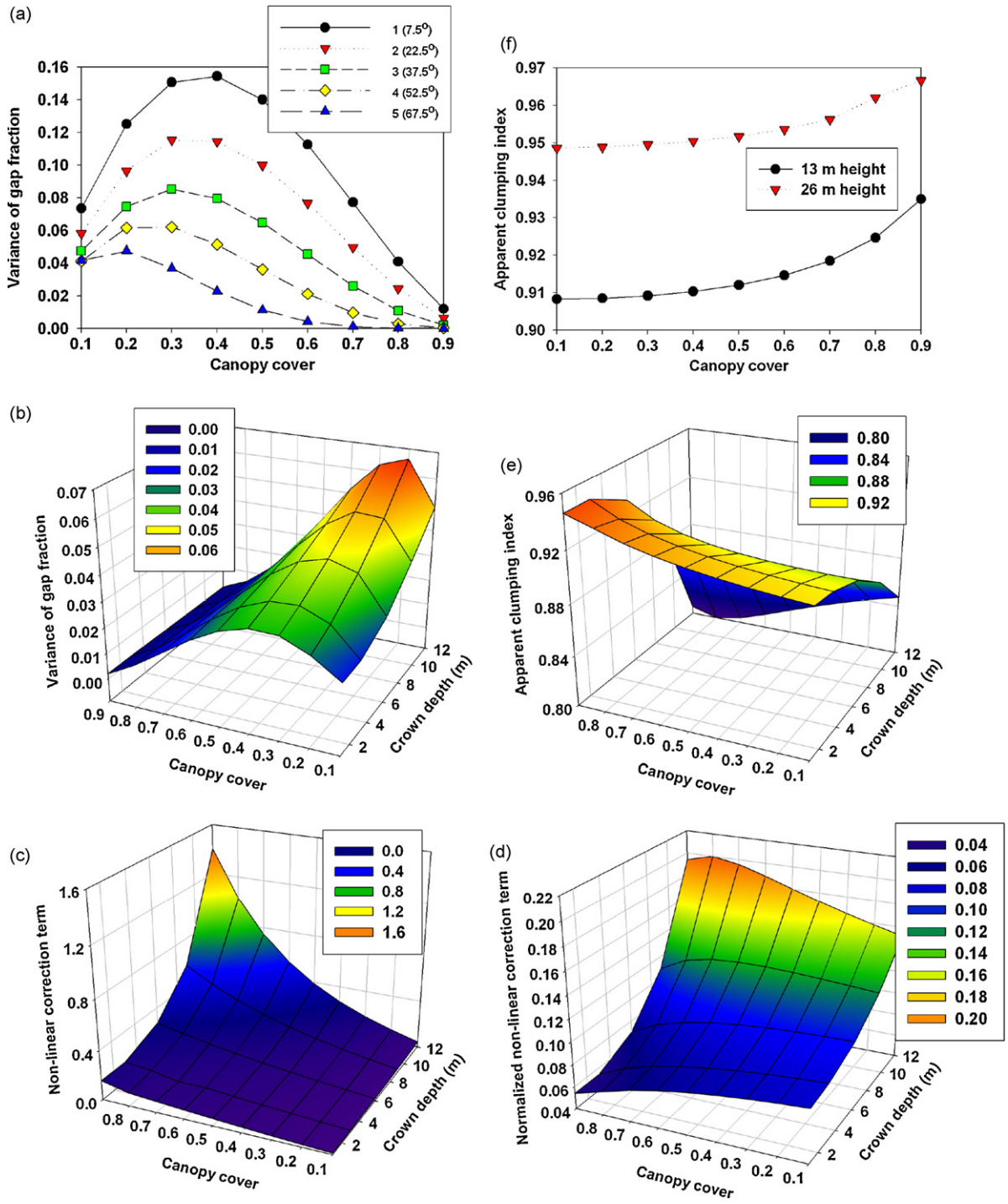


**Fig. 2.** (a) The relation between canopy cover and variance of gap fraction at each view zenith angles corresponding with LAI-2000 rings. (b)–(e) The relation between canopy cover, crown shape and several variables in forest gap fraction model including (b) variance of gap fraction (Var in Eq. (6)) averaged over the view angles weighted by $\cos(\theta)\sin(\theta)$ where $\theta$ is the view zenith angle, (c) non-linear correction term (Eq. (6a)), (d) normalized-non-linearity correction term (Eq. (7)), and (e) apparent clumping index ($\Omega_{app}$ in Eq. (7)). All calculations are made with a gap fraction model (Nilson, 1999; Nilson and Kuusk, 2004) with input data of crown width (6-m), tree height (13-m) and measurement height (1-m). Tree distribution pattern is assumed to be Poisson distribution. Leaf area index is 100 to make crowns opaque to explicitly consider between-crown gaps. Canopy cover changes by modulating tree density. (f) The relation between apparent clumping index and canopy cover for different canopy height (13 m and 26 m). All other crown parameters are same with the above.

complied LAI-2000 data base, few investigators reported the improved algorithm based $\Omega_E$; thus it was impossible to test the difference in $\Omega_E$ between CC and the improved algorithm across a diverse vegetation types. To quantify $\Omega_E$ correctly, further theoretical and experimental study is warranted and $\Omega_{app}$ will be a good quantity to constrain $\Omega_E$. Also the removal of between-crown gaps from total gaps to quantify LAI-2000-derived $\Omega_E$ is a subject for further study.

### 3.4.2. Spatial scaling of clumping index

The spatial scaling of clumping effects has been unexplored in spite of its significance on large-scale ecosystem modeling. From

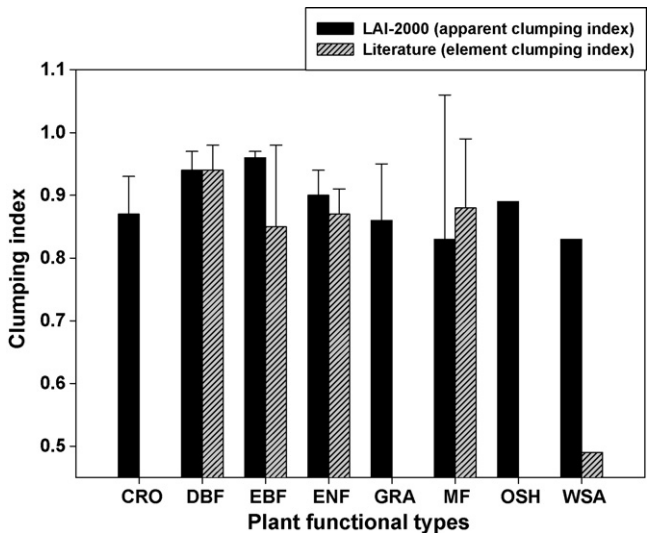


**Fig. 3.** Comparison of element clumping index between LAI-2000 derived method and independent estimate from literature (Table 1). Error bar indicates 95% confidence interval. Error bar appears only for the plant functional types whose sample size is greater than three. CRO: crop, DBF: deciduous broad-leaved forest, EBF: evergreen broad-leaved forest, ENF: evergreen needle-leaved forest, GRA: grass, MF: mixed forest, OSH: open shrub land, and WSA: woody savanna.

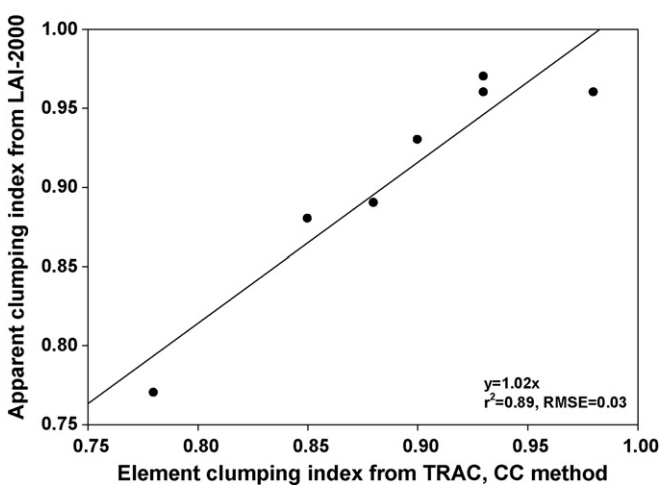


**Fig. 4.** The scatterplot between apparent clumping index from LAI-2000 and element clumping index estimated from TRAC CC method (Chen and Cihlar, 1995) that is corrected later by Leblanc (2002). The linear regression was forced to pass the origin.

LAI-2000 datasets collected at landscape scale (see Section 2.4), we tested how $\Omega_{app}$ changes with sample size (i.e. number of plots) (Fig. 5). First, we estimated $\Omega_{app}$ for each plot by applying Eq. (5). Then we averaged the values of $\Omega_{app}$ across the 20 plots, which resulted in 0.95. It is very close to the turbid media ($\Omega_{app} = 1$). Second, we estimated $\Omega_{app}$ differently by compiling all $P_o(\theta)$ data over 20 plots, then applying Eq. (5), it produced 0.76. The two different calculation methods gave quite different $\Omega_{app}$ estimates. This highlights the non-linearity in clumping effects (logarithmic function in Eq. (5)) at the landscape scale, and thus calculating the arithmetic average of $\Omega_E$ over multiple plots must be avoided. For example, let us assume that there are two plots; both plots have randomly distributed leaves in space but have different LAI (say, 1 vs 5). In this case, the arithmetic mean of $\Omega_{app}$ over the two plots will be 1. However, compiling all $P_o(\theta)$ data over the two plots and applying Eq. (5) should produce less than 1 because most importantly, the variance of $P_o(\theta)$ is no longer zero when

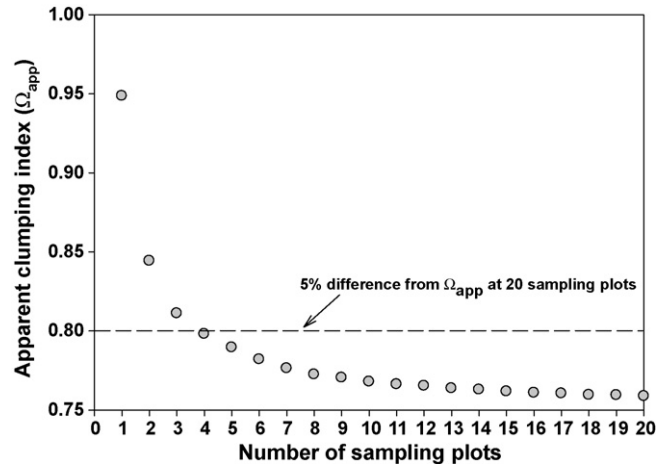


**Fig. 5.** The relation between number of sampling plots and apparent clumping index derived from 20 plots (~120 LAI-2000 readings per plot) in Metolius, OR, USA (Law et al., 2001). The calculation of apparent clumping index at each sample size is explained in Section 2.4.

combining two plots that have very different $L$. To determine $\Omega_{app}$ of a larger single plot that includes the two smaller plots, the latter approach must be used. In the ponderosa pine ecosystem, where stands are mature, the $\Omega_{app}$ at the landscape scale can be obtained with only four plots within 5% difference from the landscape level $\Omega_{app}$, yet it is important to note that a landscape with relatively recent disturbances (harvest, fire) would require more plots. The magnitude of variation and shape of the curve will depend on the variation of canopy structures within ecosystems and the size of individual plots. Currently, the calculation methods of $\Omega_E$ are limited within one transect (TRAC) or one photo (digital hemispheric photography). To obtain $\Omega_E$ from multiple transects or photos, the non-linear process in spatial scaling of $\Omega_E$ must be incorporated, which would be relevant to validate a 7 km resolution global $\Omega$ map (Chen et al., 2005).

### 3.4.3. Seasonal variation of clumping index

The land surface modeling community has assumed that clumping is constant over seasons (Baldocchi et al., 2002; Houborg et al., in press; Sampson et al., 2006) thus its temporal variation has been ignored. We found that $\Omega_{app}$ shows strong seasonality in phase with $L_e$ in a temperate deciduous forest (Harvard forest) (Fig. 6a). During the dormant period, $\Omega_{app}$ (~0.83) was low mostly because of occasional evergreen trees (~10%, Urbanski et al., 2007), which caused the canopy to appear more clumped. With leaf out in deciduous species, $\Omega_{app}$ started to increase and it maintained peak values (~0.91) during summer. However, if a $\Omega_{app}$ value of 0.91 is used for the dormant period of over story trees, then the direct beam penetrating the canopy will be underestimated by 16% which might be influential in interpreting the biogeochemistry of the understory, for example when calculating methane flux (Borken et al., 2006). On the other hand, an invasive plant infestation (Sherman Island) showed out-of-phase of $\Omega_{app}$ with $L_e$ (Fig. 6b). We assume that the observed pattern is related to the spatial heterogeneity of vegetation. During the growing season, the spatial distribution of pepperweed is heterogeneous and some portions of the landscape are bare soil, which creates a clumped canopy structure (lower $\Omega_{app}$). During the vegetation senescence, the pepperweed canopy transforms to a less clumped $\Omega_{app}$, a pattern opposite to that of the deciduous forest. The difference between maximum and minimum $\Omega_{app}$ reached ~0.2 in the invasive infestation. Because the LAI-2000 has been routinely measured in various ecosystems, $\Omega_{app}$ could constrain the seasonal variation of $\Omega$, which may improve land surface models.

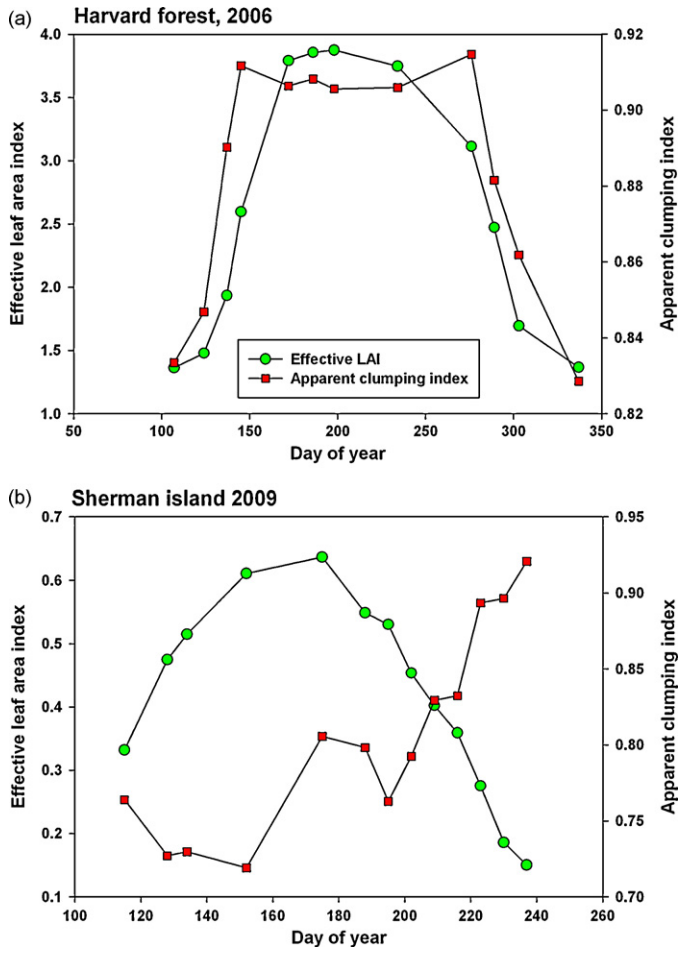


**Fig. 6.** The seasonal variation of apparent clumping index with effective leaf area index measured from a temperate deciduous forest (Harvard forest) in 2006 and an invasive weed site (Sherman Island) in 2009.

## 4. Summary and conclusions

In this study, we used a simple theoretical model, a forest gap fraction model, and LAI-2000 instrument raw data collected at 41 sites to investigate the correct estimation of $L_e$. Our main findings include:

(1) The $\overline{\ln P_o(\theta)}$ averaging method must be employed to obtain theoretically consistent $L_e$ from $P_o(\theta)$ measurements made with the LAI-2000 instrument.
(2) When using $\overline{\ln P_o(\theta)}$ as implemented in the LAI-2000 instrument and the accompanying software, clumping effects are partially considered and consequently estimates of $L_e$ more or less approximate $L$. A number of studies have quantified $L_e$ using the LAI-2000 instrument and accompanying software, and divided $L_e$ by $\Omega$ to obtain $L$ (Chen et al., 2006; Law et al., 2001a). This approach overcorrects for clumping effects and thus causes overestimation of $L$.
(3) A forest gap fraction model showed that $\Omega_{\text{app}}$ was lowest for short tree heights, vertically prolonged crown shape and 80% canopy cover.
(4) LAI-2000-derived $\Omega_{\text{app}}$ is a useful quantity that constrains true $\Omega_{\text{E}}$. Theoretically $\Omega_{\text{app}}$ is likely larger than $\Omega_{\text{E}}$ because of violation on the random distribution of leaves in space within each ring's footprint in the LAI-2000 instrument. However, there was no significant difference between them in the four plant functional types. Thus current methods to calculate $\Omega_{\text{E}}$ might underestimate clumping effects.
(5) $\Omega_{\text{app}}$ provides new insights into spatial and temporal variation of clumping effects. The individual $\Omega_{\text{E}}$ values at each plot must not be arithmetically averaged to obtain landscape level $\Omega_{\text{E}}$ due to the non-linear nature of the clumping index calculation. $\Omega_{\text{app}}$ showed seasonality in a deciduous forest site and an invasive plant infestation.

The method used to estimate $P_o$ correctly applies to digital hemispherical photography as well. First, $P_o(\theta)$ must be averaged over all photographs, then Miller's theorem must be applied to quantify $L_e$. The results of our study have important implications for the evaluation of a satellite-based $L$ product or airborne laser scanning (LiDAR) based $L_e$. For example, the CYCLOPES $L$ product does not consider clumping effect at plant and canopy scale (Baret et al., 2007), thus to evaluate this product adequately, correct estimation of $L_e$ is crucial. Recently, LiDAR derived $L_e$ mapping has been proposed (Richardson et al., 2009; Solberg et al., in press) but these studies used $\overline{\ln P_o(\theta)}$ or the median of $P_o(\theta)$ instead of using $\ln\overline{P_o(\theta)}$, which both incorporated clumping effects. We recommend the $\ln\overline{P_o(\theta)}$ method be used to calculate $L_e$ in the protocols of canopy structure measurement (Law et al., 2008). Finally, the spatial and temporal variation of $\Omega_{\text{app}}$ would be useful to evaluate coarse resolution of a global $\Omega$ map and improve land surface models.

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## References

Acock, B., Thornley, J.H.M., Warren Wilson, J., 1970. Spatial variation of light in the canopy. In: Proceeding IBP/PP Technical Meeting, Trebon, Czech, PUDOC, Wageningen.
Baldocchi, D., 1997. Measuring and modelling carbon dioxide and water vapour exchange over a temperate broad-leaved forest during the 1995 summer drought. Plant Cell and Environment 20 (9), 1108–1122.
Baldocchi, D.D., Harley, P.C., 1995. Scaling carbon dioxide and water vapour exchange from leaf to canopy in a deciduous forest. II. Model testing and application. Plant Cell and Environment 18 (10), 1157–1173.
Baldocchi, D.D., Hutchison, B.A., Matt, D.R., McMillen, R.T., 1985. Canopy radiative transfer models for spherical and known leaf inclination angle distributions—a test in an oak hickory forest. Journal of Applied Ecology 22 (2), 539–555.
Baldocchi, D.D., Matt, D.R., Hutchison, B.A., McMillen, R.T., 1984. Solar radiation within an oak-hickory forest: an evaluation of the extinction coefficients for several radiation components during fully-leafed and leafless periods. Agricultural and Forest Meteorology 32, 307–322.
Baldocchi, D.D., Wilson, K.B., 2001. Modeling $CO_2$ and water vapor exchange of a temperate broadleaved forest across hourly to decadal time scales. Ecological Modelling 142 (1–2), 155–184.

Baldocchi, D.D., Wilson, K.B., Gu, L.H., 2002. How the environment, canopy structure and canopy physiological functioning influence carbon, water and energy fluxes of a temperate broad-leaved deciduous forest-an assessment with the biophysical model CANOAK. Tree Physiology 22 (15–16), 1065–1077.
Baret, F., Hagolle, O., Geiger, B., Bicheron, P., Miras, B., Huc, M., Berthelot, B., Nino, F., Weiss, M., Samain, O., Roujean, J.L., Leroy, M., 2007. LAI, fAPAR and fCover CYCLOPES global products derived from VEGETATION. Part 1. Principles of the algorithm. Remote Sensing of Environment 110 (3), 275–286.
Black, T.A., Chen, J.M., Lee, X.H., Sagar, R.M., 1991. Characteristics of shortwave and longwave irradiances under a Douglas-fir forest stand. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 21 (7), 1020–1028.
Borken, W., Davidson, E.A., Savage, K., Sundquist, E.T., Steudler, P., 2006. Effect of summer throughfall exclusion, summer drought, and winter snow cover on methane fluxes in a temperate forest soil. Soil Biology and Biochemistry 38 (6), 1388–1395.
Burba, G.G., Verma, S.B., 2005. Seasonal and interannual variability in evapotranspiration of native tallgrass prairie and cultivated wheat ecosystems. Agricultural and Forest Meteorology 135 (1–4), 190–201.
Chason, J.W., Baldocchi, D.D., Huston, M.A., 1991. A Comparison of direct and indirect methods for estimating forest canopy leaf-area. Agricultural and Forest Meteorology 57 (1–3), 107–128.
Chen, J.M., 1996. Optically-based methods for measuring seasonal variation of leaf area index in boreal conifer stands. Agricultural and Forest Meteorology 80 (2–4), 135–163.
Chen, J.M., Cihlar, J., 1995. Plant canopy gap-size analysis theory for improving optical measurements of leaf-area index. Applied Optics 34 (27), 6211–6222.
Chen, J.M., Govind, A., Sonnentag, O., Zhang, Y.Q., Barr, A., Amiro, B., 2006. Leaf area index measurements at Fluxnet-Canada forest sites. Agricultural and Forest Meteorology 140 (1–4), 257–268.
Chen, J.M., Menges, C.H., Leblanc, S.G., 2005. Global mapping of foliage clumping index using multi-angular satellite data. Remote Sensing of Environment 97 (4), 447–457.
Efron, B., Tibshirani, R.J., 1993. An Introduction to the Bootstrap. Chapman & Hall, New York.
Fassnacht, K.S., Gower, S.T., Norman, J.M., McMurtric, R.E., 1994. A comparison of optical and direct methods for estimating foliage surface area index in forests. Agricultural and Forest Meteorology 71 (1–2), 183–207.
Houborg, R., Anderson, M.C., Norman, J.M., Wilson, T. and Meyers, T., in press. Intercomparison of a 'bottom-up' and 'top-down' modeling paradigm for estimating carbon and energy fluxes over a variety of vegetative regimes across the U.S. Agricultural and Forest Meteorology.
Hwang, T., Band, L.E., Hales, T.C., 2009. Ecosystem processes at the watershed scale: extending optimality theory from plot to catchment. Water Resources Research 45 (W11425), doi:10.1029/2009WR007775.
Kodar, A., Kutsar, R., Lang, M., Lukk, T., Nilson, T., 2008. Leaf area indices of forest canopies from optical measurements. Baltic Forestry 14 (2), 185–194.
Kucharik, C.J., Norman, J.M., Gower, S.T., 1998. Measurements of branch area and adjusting leaf area index indirect measurements. Agricultural and Forest Meteorology 91 (1–2), 69–88.
Kucharik, C.J., Norman, J.M., Gower, S.T., 1999. Characterization of radiation regimes in nonrandom forest canopies: theory, measurements, and a simplified modeling approach. Tree Physiology 19 (11), 695–706.
Kucharik, C.J., Norman, J.M., Murdock, L.M., Gower, S.T., 1997. Characterizing canopy nonrandomness with a multiband vegetation imager (MVI). Journal of Geophysical Research-Atmospheres 102 (D24), 29455–29473.
Lang, A.R.G., Xiang, Y., 1986. Estimation of leaf area index from transmission of direct sunlight in discontinuous canopies. Agricultural and Forest Meteorology 37 (3), 229–243.
Law, B.E., Arkebauer, T., Campbell, J.L., Chen, J.M., Sun, O., Schwartz, M., Ingen, C.v., Verma, S., 2008. Terrestrial Carbon Observations: Protocols for Vegetation Sampling and Data Submission. TCO—Terrestrial Carbon Observations panel of the Global Terrestrial Observing System (GTOS), Rome, Italy.
Law, B.E., Cescatti, A., Baldocchi, D.D., 2001a. Leaf area distribution and radiative transfer in open-canopy forests: implications for mass and energy exchange. Tree Physiology 21, 777–787.
Law, B.E., Van Tuyl, S., Cescatti, A., Baldocchi, D.D., 2001b. Estimation of leaf area index in open-canopy ponderosa pine forests at different successional stages and management regimes in Oregon. Agricultural and Forest Meteorology 108 (1), 1–14.
Leblanc, S.G., 2002. Correction to the plant canopy gap-size analysis theory used by the Tracing Radiation and Architecture of Canopies instrument. Applied Optics 41 (36), 7667–7670.
Leblanc, S.G., Chen, J.M., Fernandes, R., Deering, D.W., Conley, A., 2005. Methodology comparison for canopy structure parameters extraction from digital hemispherical photography in boreal forests. Agricultural and Forest Meteorology 129 (3–4), 187–207.
Macfarlane, C., Hoffman, M., Eamus, D., Kerp, N., Higginson, S., McMurtrie, R., Adams, M., 2007. Estimation of leaf area index in eucalypt forest using digital photography. Agricultural and Forest Meteorology 143 (3–4), 176–188.
Miller, J.B., 1967. A formula for average foliage density. Australian Journal of Botany 15 (1), 141–144.
Monsi, M., Saeki, T., 1953. Über den Lichtfaktor in den Pflanzengesellschaften und seine Bedeutung für die Stoffproduktion. Japanese Journal of Botany 14, 22–52.
Monsi, M., Saeki, T., 2005. On the factor light in plant communities and its importance for matter production. Annals of Botany 95 (3), 549–567.
Nasahara, K.N., Muraoka, H., Nagai, S., Mikami, H., 2008. Vertical integration of leaf area index in a Japanese deciduous broad-leaved forest. Agricultural and Forest Meteorology 148 (6–7), 1136–1146.
Nilson, T., 1971. Theoretical analysis of frequency of gaps in plant stands. Agricultural Meteorology 8 (1), 25–38.
Nilson, T., 1999. Inversion of gap frequency data in forest stands. Agricultural and Forest Meteorology 98–99, 437–448.
Nilson, T., Kuusk, A., 2004. Improved algorithm for estimating canopy indices from gap fraction data in forest canopies. Agricultural and Forest Meteorology 124 (3–4), 157–169.
Noormets, A., Gavazzi, M.J., Mcnulty, S.G., Domec, J.-C., Sun, G., King, J.S., Chen, J., 2009. Response of carbon fluxes to drought in a coastal plain loblolly pine forest. Global Change Biology, doi:10.1111/j.365-2486.009.01928.x.
Norman, J.M., Jarvis, P.G., 1974. Photosynthesis in sitka spruce (*Picea-sitchensis* (Bong) carr). 3. Measurements of canopy structure and interception of radiation. Journal of Applied Ecology 11 (1), 375–398.
Norman, J.M., Jarvis, P.G., 1975. Photosynthesis in Sitka Spruce (*Picea-Sitchensis* (Bong) Carr). 5. Radiation penetration theory and a test case. Journal of Applied Ecology 12 (3), 839–878.
Norman, J.M., Welles, J.M., 1983. Radiative transfer in an array of canopies. Agronomy Journal 75 (3), 481–488.
Rambal, S., Ourcival, J.M., Joffre, R., Mouillot, F., Nouvellon, Y., Reichstein, M., Rocheteau, A., 2003. Drought controls over conductance and assimilation of a Mediterranean evergreen ecosystem: scaling from leaf to canopy. Global Change Biology 9 (12), 1813–1824.
Richardson, J.J., Moskal, L.M., Kim, S.-H., 2009. Modeling approaches to estimate effective leaf area index from aerial discrete-return LIDAR. Agricultural and Forest Meteorology 149 (6–7), 1152–1160.
Ryu, Y., Sonnentag, O., Nilson, T., Vargas, R., Kobayashi, H., Wenk, R., Baldocchi, D.D., 2010. How to quantify tree leaf area index in a heterogeneous savanna ecosystem: a multi-instrument and multi-model approach. Agricultural and Forest Meteorology 150, 63–76.
Sampson, D.A., Janssens, I.A., Ceulemans, R., 2006. Under-story contributions to stand level GPP using the process model SECRETS. Agricultural and Forest Meteorology 139 (1–2), 94–104.
Smolander, H., Stenberg, P., 1996. Response of LAI-2000 estimates to changes in plant surface area index in a Scots pine stand. Tree Physiology 16 (3), 345–349.
Solberg, S., Brunner, A., Hanssen, K.H., Lange, H., Næset, E., Rautiainen, M., Stenberg, P., in press. Mapping LAI in a Norway spruce forest using airborne laser scanning. Remote Sensing of Environment.
Sonnentag, O., van der Kamp, G., Barr, A.G. and Chen, J.M., in press. On the relationship between water table depth and water vapor and carbon dioxide fluxes in a minerotrophic fen. Global Change Biology.
Sveshnikov, A.A., 1968. Prikladnye metody teoriy sluchainykh funktsiy. (Applied Methods in Random Function Theory (in Russian)).Nauka, Moscow, 464 pp.
Tanaka, N., Kume, T., Yoshifuji, N., Tanaka, K., Takizawa, H., Shiraki, K., Tantasirin, C., Tangtham, N., Suzuki, M., 2008. A review of evapotranspiration estimates from tropical forests in Thailand and adjacent regions. Agricultural and Forest Meteorology 148 (5), 807–819.
Tedeschi, V., Rey, A., Manca, G., Valentini, R., Jarvis, P.G., Borghetti, M., 2006. Soil respiration in a Mediterranean oak forest at different developmental stages after coppicing. Global Change Biology 12 (1), 110–121.
Urbanski, S., Barford, C., Wofsy, S., Kucharik, C., Pyle, E., Budney, J., McKain, K., Fitzjarrald, D., Czikowsky, M., Munger, J.W., 2007. Factors controlling CO2 exchange on timescales from hourly to decadal at Harvard Forest. Journal of Geophysical Research-Biogeosciences 112 (G02020), doi:10.1029/2006JG000293.
van Gardingen, P.R., Jackson, G.E., Hernandez-Daumas, S., Russell, G., Sharp, L., 1999. Leaf area index estimates obtained for clumped canopies using hemispherical photography. Agricultural and Forest Meteorology 94 (3–4), 243–257.
Warren Wilson, J., 1960. Inclined point quadrats. New Phytologist 59 (1), 1–7.
Welles, J.M., Norman, J.M., 1991. Instrument for indirect measurement of canopy architecture. Agronomy Journal 83 (5), 818–825.