Comparison of methods for measuring gap size distribution and canopy nonrandomness at Järvelja RAMI (RAdiation transfer Model Intercomparison) test sites

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A B S T R A C T

Methods for analyzing foliage nonrandomness by means of the TRAC instrument, digital hemispheric photography, and a gap fraction model are assessed at two RAMI (RAdiation transfer Model Intercomparison) mature stands in Järvelja, Estonia. The six different methods involve calculation of the canopy element clumping index, at scales coarser than that of a shoot. The major aim was to define the merits and limitations of the various methods. We conclude the gap size distribution and beyond-shoot clumping is very stable across the stands for the solar zenith angle range from 30° to 60°. Estimates based on the gap size distribution and the combination of gap size and logarithm methods performed the best while compared with an independent gap fraction model. We clarify the effect of the assumed leaf inclination angle distribution on gap size distribution and differences between estimates of beyond-shoot clumping. We show that the modified, gap-size distribution based method of Chen and Cihlar can provide reliable beyond-shoot clumping estimates without any a priori assumptions about the total gap fraction, segment length or the leaf inclination angle distribution. We also illustrate the changes in element clumping with measurement height. The compiled data extend the original parameter dataset to be used in the next phase of RAMI for different benchmark tests and reflectance modeling experiments, and contribute toward systematic validation efforts of radiative transfer models, operational algorithms, and field instruments, as promoted by the Committee on Earth Observation Satellites (CEOS).

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1. Introduction

RAdiation transfer Model Intercomparison (RAMI) was designed as an ongoing mechanism to benchmark radiation transfer (RT) models used to simulate the transfer of radiation at or near the Earth’s terrestrial surface, i.e. in plant canopies and over soil surfaces (Pinty et al., 2001). For the future phases of intercomparisons, one of the expected goals would be to investigate the potential of RT models to reproduce in situ measurements of transmitted light by various methods such as Tracing Radiation and Architecture of Canopies (TRAC; 3rd Wave Engineering, ON, Canada) instrument or digital hemispherical photography (DHP) (Widowski et al., 2007). The intensive collection of the optical measurements in the RAMI-selected real world forest stands is thus required.

Besides the information about the canopy gap fraction \((P)\) and radiation regime at the forest floor, concurrent TRAC and DHP measurements would be also vital to address current challenges of the indirect methods with respect to quantifying architecture of forest canopies. One of the recurrent themes for the investigations concerning the vegetation structure is clumping of plant canopies (Bréda, 2003; Walter et al., 2003). Clumping describes the spatial aggregation of foliage elements. The clumping has been quantified by the aggregation or dispersion parameter \((\text{Nilson}, 1971; \text{Lemeur and Blad}, 1974)\), also called clumping index \((\text{Chen and Black}, 1992)\). The clumping index \((\Omega)\) thus describes the level of foliage grouping within distinct canopy structures, such as tree crowns, shrubs, and row crops, relative to a random distribution \((\text{Nilson}, 1971; \text{Chen and Black}, 1992; \text{Weiss et al.}, 2004)\). \(\Omega\) is useful in ecological and meteorological models because it provides additional structural information to the effective leaf area index \(L_e\) obtained from optical indirect measurements \((\text{Chen and Black}, 1991)\), where \(L_e\) is defined as one half of the total area of light intercepting leaves per unit horizontal ground surface area, assuming the foliage spatial distribution is random \((\text{Black et al.}, 1991)\). Clumping, through a better separation of sunlit and shaded leaves, has profound effects on the radiation regime of a plant canopy and photosynthesis...
(Oker-Blom, 1985; Oker-Blom et al., 1983; Wang and Jarvis, 1993; Davi et al., 2006). \( \Omega \) larger than unity implies the foliage is regularly distributed; \( \Omega = 1 \) for a random distribution and in the case of foliage more clumped than random, \( \Omega < 1 \) (Chen et al., 2005). Ignoring the clumping effects may lead to incorrect estimates of radiation interception and distribution within the canopy with important implications to modeling of fluxes (Lacaze et al., 2002; Walcroft et al., 2005).

As suggested by Chen (1996), the total clumping index \( \Omega \) can be separated into two components (\( \Omega_E/\Omega_S \)), which are measured separately in the field and in the lab. \( \gamma_E \) is the needle-to-shoot area ratio (Fassnacht et al., 1994; Steinberg et al., 1994; Chen et al., 1997) quantifying the effect of foliage clumping within a shoot (for reference values for different species see Bréda, 2003); for broadleaves \( \gamma_S = 1 \) (Chen et al., 1997). Element clumping index \( \Omega_E \) includes the effect of foliage clumping at scales larger than the elements (shoots for needleleaf species and leaves for broadleaf species).

Various methods were proposed for the assessment of the non-random spatial distribution from field measurements (Lang and Xiang, 1986; Chen and Cihlar, 1995a,b; Kucharik et al., 1999; Wilson et al., 2003; Leblanc et al., 2005). Considerable differences were observed between the approaches to quantify \( \Omega_E \) (e.g. Walter et al., 2003; Leblanc et al., 2005; Macfarlane et al., 2007; Gonsamo and Pellikka, 2009), yet the role of important factors, such as the common practice of assuming spherical leaf projection function, the choice of segment size (Chen and Black, 1992; van Gardingen et al., 1999), or the assumed consistency between measurements while using different instruments (Leblanc et al., 2005), has been seldom assessed (Kucharik et al., 1997; Ryu et al., 2010a; Gonsamo et al., 2010). This practice calls for a comprehensive investigation to evaluate the performance and consistency of the methods with the commonly used instruments, and to define their merits and limitations.

The objective of our study is to determine the canopy nonrandomness at one Silver birch and one Scots pine RAMI stand in Järvselja, Estonia. To achieve this goal, we acquired information about the leaf inclination angles \( \theta_1 \), carried out extensive measurements by means of TRAC, DHP, and LAI-2000 instruments, and finally characterized \( \Omega_E \) based on six different methods found in the literature. We report on the following issues: (a) how spatially homogeneous are the two Järvselja RAMI stands with respect to the foliage clumping; (b) how does \( \Omega_E \) change with the view zenith angle and measurement height over the stands; (c) what are the strengths and limits of various methods, and which one performs the best; (d) what are the implications of assuming spherical leaf distribution function on calculating \( \Omega_E \); (e) characteristics and goodness of the agreement between results derived from TRAC and DHP. Finally, we suggest a modification to an existing gap size distribution-based method of Chen and Cihlar (1995a) to provide reliable estimates of beyond-shoot clumping that requires no a priori assumptions common to the other tested methods.

### 2. Theory

#### 2.1. Leaf projection function and leaf inclination distribution function

The leaf projection function \( G \) is the projection coefficient of unit foliage area on a plane perpendicular to the view direction (Ross, 1981). \( G \) is essential to calculate the canopy gap fraction \( P \) and light regime at specific view zenith angles (Ross, 1981). \( G \) may be expressed as (Warren Wilson, 1960, 1967):

\[
G(\theta) = \int_0^{\pi/2} A(\theta_1, \theta_2) f(\theta, \theta_1) d\theta_1 \tag{1}
\]

where

\[
A(\theta, \theta_1) = \begin{cases} \cos \theta \cos \theta_1 [1 + (2/\pi)(\tan \psi - \psi)], & \cot \theta \cot \theta_1 > 1 \\ \cos \theta \cos \theta_1[1 + (2/\pi)(\tan \psi - \psi) - 1], & \text{otherwise} \end{cases}
\]

where \( \theta \) is view zenith angle, \( \theta_1 \) is leaf inclination angle, and \( \psi \) is \( \cos^{-1}(\cot \theta \cot \theta_1) \). Several special distributions have been developed to describe leaf inclination distribution function \( f(\theta) \) (for their overview see Weiss et al., 2004); Wang et al. (2007) evaluated the two-parameter Beta-distribution (Goel and Strebel, 1984) as the most appropriate for describing the probability density of \( \theta_1 \):

\[
f(\theta) = \frac{1}{B(\mu, v)} (1 - \theta)^{\mu-1} \theta^{v-1} \tag{3}
\]

where \( t = 2\theta_1/\pi \). The Beta function \( B(\mu, v) \) is defined as:

\[
B(\mu, v) = \int_0^1 (1 - x)^{\mu-1} x^{v-1} dx = \frac{\Gamma(\mu)\Gamma(v)}{\Gamma(\mu + v)} \tag{4}
\]

The leaf inclination distribution can be described by the gamma function and two parameters, \( \mu \) and \( v \):

\[
\mu = (1 - \overline{E}) \left( \frac{\sigma_0^2}{\sigma_1^2} - 1 \right) \tag{5}
\]

\[
\nu = \overline{E} \left( \frac{\sigma_0^2}{\sigma_1^2} - 1 \right) \tag{6}
\]

where \( \sigma_0^2 \) is the maximum standard deviation with expected mean \( t \) and \( \sigma_1^2 \) is variance of \( t \) (Wang et al., 2007).

#### 2.2. Element clumping index

##### 2.2.1. Clumping index from gap size distribution (\( \Omega_{CC}, \Omega_{CMN} \))

\( \Omega_{CC} \) is given based on the gap size distribution from the corrected (CC) method of Chen and Cihlar (1995a) by Leblanc (2002):

\[
\Omega_{CC}(\theta) = \frac{\ln[F_m(0, \theta)] - 1}{\ln[F_m(0, \theta)] - 1} \tag{7}
\]

where \( F_m(0, \theta) \) is the accumulated canopy gap fraction and, \( F_m(0, \theta) \) is the reduced gap–size accumulated fraction after removal of the large, non-random gaps. \( F_m(0, \theta) \) is obtained by a sequential removal of large non-random gaps from the measured gap size accumulation curve \( F_m(\lambda) \), until the pattern of gap size accumulation resembles that of an equivalent canopy with a random spatial distribution of foliage, \( F_0(\lambda) \). \( F_0(\lambda) \) is calculated following the modifications by Chen and Cihlar (1995a) to the original equation by Miller and Norman (1971) as:

\[
F_0(\lambda) = \left( 1 + L_p \frac{\lambda}{W_p} \right) \exp \left[ -L_p \left( 1 + \frac{\lambda}{W_p} \right) \right] \tag{8}
\]

where

\[
L_p = \frac{G(\theta) L}{\cos \theta} \tag{9}
\]

and

\[
W_p = \frac{W_E}{\cos \theta_p} \tag{10}
\]

\( W_E \) is the width of an element projected on a plane perpendicular to the direction of the solar beam, \( \lambda \) is the size of gaps, and \( \cos \theta_p \) is obtained following Chen and Cihlar (1995a). \( \cos \theta_p \) compensates for the elongation of the element shadow on a horizontal plane in the direction of the transect (Chen and Cihlar, 1995b). While \( W_p \) can be found from the measurements of leaf or shoot samples, \( L \) (true leaf area index) is usually unknown because it is in fact the goal of finding appropriate \( \Omega \) (Chen and Cihlar, 1995b).

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Clumping index from logarithmic average ($\Omega_{\text{CMN}}$) 

\[
\Omega_{\text{CMN}}(\theta) = \frac{\ln[P(\theta)]}{\ln[P(\theta)]}
\]

2.2.2. Clumping index from logarithmic average ($\Omega_{\text{LX}}$) 

For the finite-length (LX) method of Lang and Xiang (1986), the clumping is calculated on small segments, preferably 10 times the length associated with the second method. As larger segments might not be homogeneous, the gap size distribution method is used to assess the within segment foliage heterogeneity, instead. The overall clumping index is then calculated over $n$ segments as (CLX method):

\[
\Omega_{\text{CLX}}(\theta) = \frac{\sum_{k=1}^{n} \ln[P(\theta)]}{\ln[P(\theta)]} / \Omega_{\text{CLX}}(\theta)
\]

2.2.3. Clumping index from the combination of gap size and logarithmic methods ($\Omega_{\text{CLX}}$) 

Leblanc et al. (2005) combined the gap size distribution and the finite-length methods to address the problems of segment length associated with the second method. As larger segments might not be homogeneous, the gap size distribution method is used to assess the within segment foliage heterogeneity, instead. The overall clumping index is then calculated over $n$ segments as (CLX method):

\[
\Omega_{\text{CLX}}(\theta) = \frac{\sum_{k=1}^{n} \ln[P(\theta)]}{\ln[P(\theta)]} / \Omega_{\text{CLX}}(\theta)
\]

where $\Omega_{\text{CLX}}(\theta)$ is the element clumping index of segment $k$ using the Chen and Cihlar (1995a) method and $P(\theta)$ is the gap fraction of segment $k$. 

2.2.4. Pielou’s coefficient of spatial segregation ($\Omega_{\text{PCS}}$) 

Pielou (1962) originally suggested a method (PCS) to calculate the segregation of one species with respect to another by using information from field transects through plant populations. Walter et al. (2003) applied the method while integrating clumping effects in forest canopy with DHP. In this approach, the probabilities of encountering pixels of categories $B$ (no gap) and $W$ (gap) at $0$ are $b$ and $w$, and for randomly distributed pixels $b + w = 1$. The probability of obtaining an uninterrupted sequence of $b$ pixels of $B$ is $b^{-1}w$ for a sequence of $j$ pixels of W is $w^{-1}b$. The distribution of run lengths for B and W pixels is thus geometric (Pielou, 1962). Assuming that $B$ and $W$ are dispersed randomly, it follows with 95% probability:

\[
\Omega_{\text{PCS}}(\theta) = b + w = \frac{1}{m_w} + \frac{1}{m_b} = 1 \pm 1.96 \sqrt{s_b^2 + s_w^2},
\]

where $b$ and $w$ are the maximum likelihood estimates of $B$ and $W$ pixels; $m_b$ and $m_w$ are the mean lengths of $B$ and $W$ sequences in numbers of pixels; $s_b^2$ and $s_w^2$ are the variances of $B$ and $W$ pixels with regard to $b$ and $w$; and $n_b$ and $n_w$ are the numbers of sequences of $B$ and $W$ pixels, respectively (Walter et al., 2003; Gonsamo and Pellikka, 2009). Canopy elements are thus interpreted as clumped if large openings are intermingled with small one and $b + w$ (i.e. $\Omega_{\text{PCS}}$) < 1. 

2.2.5. The clumping index at the zenith, $\Omega_0(0)$, and $\Omega_0(\theta)$ from empirical equations by Kucharik et al. (1999) 

From simulated canopy images, Kucharik et al. (1999) developed empirical equations for both the clumping index at the zenith, $\Omega_0(0)$, and $\Omega_0(\theta)$ from the crown ratio $\chi$ (ratio of crown depth to crown diameter), the crown porosity $\Phi$ (proportion of within crown gaps) and crown cover $f_c$ (the proportion of ground area covered by the vertical projection of crowns, assuming the crowns to be solid, Walker and Tunstall, 1981). $\Omega_0(0)$ may be calculated as:

\[
\Omega_0(0) = a_0 + a_1f_c + a_2\phi + a_3f_c\phi + a_4\phi^2 + a_5\phi^2f_c + a_6\phi^3 + a_7\phi^3f_c
\]

where $a_0...a_7$ are coefficients derived from Monte Carlo simulations (see Table 4 in Kucharik et al., 1999). The relationship of $\Omega_0(\theta)$ with changing view angle is then described as:

\[
\Omega_0(\theta) = \frac{\Omega_{\text{K, max}}(\theta)}{[1 + b \exp(-k(\theta))^p]} (20)
\]

and

\[
p = -0.461\chi + 3.8
\]

where $k = 2.2$ and $b$ is solved from a rearrangement of Eq. (20) using a known value of $\Omega_0(0)$ (e.g. $\theta = 0$). Finally, the maximum (i.e. closest to the random case) value of the element clumping index $\Omega_{\text{K, max}}$ is given by Kucharik et al. (1999):

\[
\Omega_{\text{K, max}} = \begin{cases} \left(\frac{N_iD}{\sqrt{A}}\right)^{0.7} & \text{if } \left(\frac{N_iD}{\sqrt{A}}\right) > 1.0 \\ 1 & \text{otherwise} \end{cases}
\]

$N_i$ is the number of stems within ground area $A$, and $D$ is crown diameter. 

2.2.6. Clumping index from the gap fraction model of Nilsson (1999) ($\Omega_N$) 

To test $\Omega_k$ estimates from the indirect methods above, we used a gap-fraction model of Nilsson (1999) that explicitly considers clustering of foliage into crowns. In this interpretation the clumping...
Table 1
Stand characteristics.

<table>
<thead>
<tr>
<th>Stand</th>
<th>Birch</th>
<th>Pine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>49</td>
<td>124</td>
</tr>
<tr>
<td>Stand densitya (trees/ha)</td>
<td>645</td>
<td>1115</td>
</tr>
<tr>
<td>Stand densityb (trees/ha)</td>
<td>377</td>
<td>7</td>
</tr>
<tr>
<td>Mean tree heightm (m)</td>
<td>25.0</td>
<td>15.6</td>
</tr>
<tr>
<td>Mean length of live crown (m)</td>
<td>9.2</td>
<td>4.2</td>
</tr>
<tr>
<td>Mean maximum crown radius (m)</td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td>LAIm/d</td>
<td>3.93</td>
<td>1.86</td>
</tr>
<tr>
<td>LAI γ</td>
<td>2.89</td>
<td>3</td>
</tr>
</tbody>
</table>

a Upper layer.
b Lower layer.

The index $\Omega_N(\theta)$ describes the effect of between-crown clumping. It is expressed as (Nilson and Kuusk, 2004; Ryu et al., 2010a):

$$\Omega_N(\theta) = \frac{c(\theta)(NS(\theta) \cos \theta)}{(G(\theta)/L/\gamma_e + BAI)}$$

(23)

where

$$c(\theta) = -\ln[1 - (1 - P(\theta))(1 - GI)]$$

(24)

and

$$P(\theta) = \exp \left(-\frac{G(\theta)/L/\gamma_e + BAI}{(NS(\theta) \cos \theta)}\right)$$

(25)

$N$ is the tree density (trees m$^{-2}$), $S(\theta)$ is the area of projection of the average tree crown envelope on the horizontal plane, BAI is the branch area index, $P(\theta)$ is the mean gap fraction within a single tree crown, and GI is the relative variance of the number of trees in the area $S(\theta)$. Eq. (23) is obtained when Chen (1996) and Nilson (1999) gap fraction formulas are set equal and the beyond-shoot clumping index found from the equality. For more details on the gap fraction model see Nilson (1999) and Nilson and Kuusk (2004).

3. Materials

3.1. Description of the Järvselja RAMI sites

Measurements with TRAC, DHP and the LAI-2000 PCA were carried out in two mature stands (Table 1) in Järvselja, Estonia (58° 17′ N, 27° 17′ E). The first RAMI site was a 49-year-old Silver Birch (Betula pendula Roth) dominated stand growing on a fertile site. Average height of the upper tree layer is 25.0 m with a ~2 m high hazelnet (Corylus avellana) and Tilia cordata understory and a mixture of several grass species. The second RAMI site, a 124-year-old Scots Pine (Pinus sylvestris L.) stand, grows on a transitional bog. Average tree height is 15.6 m; the forest understory consisted of various Sphagnum moss species and marsh tea (Ledum palustre). Each stand contains one 100 m × 100 m sample plot. All the optical measurements were acquired within the existing 30 m × 30 m sampling grid of nine sampling points (Fig. 1). More detailed site information may be found in Kuusk et al. (2008, 2009).

3.2. Measurements and data processing

TRAC measurements were acquired on 30 July 2009 in the birch stand and on 21, 24, and 28 July 2009 in the pine stand under cloudless conditions. We used the TRAC instrument along five 60–84.5 m long segments in each stand (Fig. 1a and b). The TRAC instrument was employed at each transect in approximately 30-min intervals over the course of a half-day to cover a wide range of $\theta$. Reference measurements were acquired by placing TRAC sensors in the center of nearby sunflecks at the start of each measurement series. In the birch stand, TRAC was carried with sensors measuring at 2 m height from the ground to avoid the effect of shrub layer. One transect (Fig. 1a) was also repeatedly walked with TRAC sensors ~0.05 m just above the ground to assess the effect of understory on the clumping and gap distribution at the forest floor. All TRAC measurements in the pine stand were taken at approximately 0.5 m above the forest floor. Additional set of measurements from eight transects arranged in a circle with $A = 22.5^\circ$ (Fig. 1c) was acquired to assess the spatial homogeneity of the pine stand. A particular transect was measured when perpendicular to the solar position. The complete set contains 110 TRAC walked transects measurements from the two 100 m × 100 m sample plots.

DHPs were acquired at 18 sampling points (9 per plot) (Fig. 1) on 30 July 2009 in the birch stand and on 28 July 2009 in the pine stand under diffuse illumination conditions. Laboratory-calibrated Canon 5D camera with Sigma 8 mm, F3.5 EX DG optics on leveled tripod was used for imaging. Data were stored in raw files (unprocessed sensor readings) and further processed according to Lang et al. (2010) to obtain above canopy blue channel reference from below canopy image. The method of Lang et al. (2010) is based on fitting simple sky radiance model on radiance data from canopy gaps to derive above canopy reference, and avoids all bias-related problems caused by classical thresholding of compressed JPEG format images and accounts for illumination variation. Sky radiance value for each pixel in above canopy image was calculated as a distance weighted estimate from sky radiance model and three marked values of nearest canopy gaps. Instead of thresholding, each gap fraction image was calculated by dividing below canopy image by the obtained above canopy reference. Overcast sky radiance does have sometimes a lot of local spatial variability and the random error on pixel level (usually less than 4% of gap fraction estimate) can result in transparency > 1.0 in canopy gap pixels. To decrease salt and pepper noise in canopy gaps, pixel level gap fraction estimate was set to $P(\theta) = 1.0$ if it exceeded 1.0 when preparing images for software used to calculate canopy indices. This was important, since individual images instead of stand level mean estimates were analyzed. For further processing with existing software, the individual 1400 × 1400 pixel images of true transmittance were scaled into standard 8-bit range.

LAI-2000 PCA readings were collected at the same time and at the same points as DHPs. One device was operated on a tripod as a reference on the open place ~2 km away from test areas and the second one was handheld during below canopy measurements. 180° view restrictors were used. At each of the nine sampling points, four 0.5 m shifted readings were taken for better averaging. Compass was used to check the view direction to coincide with the open area device. LAI-2000 software was used for data processing. When the results were compared against earlier measurements (Lang et al., 2010) and DHPs, it appeared that measurements from the pine stand in the two near zenith LAI-2000 rings were slightly influenced by illumination spatial trend which was not detectable by eye during data collection.

Leaf angle data were obtained for three birch trees in a nearby mixed stand with a 25 m high tower in 2002. The angles were measured with a clinometer at 5 heights (6.7 m, 11.2 m, 14 m, 16.1 m, and 18.9 m). 100 leaves were measured per every height.

We created five new datasets based on the original TRAC data, where transects were segmented by 1 m, 2 m, 5 m, 7 m, and the original 15 m or 21 m long step, respectively. This was done in order to assess the sensitivity of LX and the combined CLX method to the segment length while using TRAC data. All TRAC measurements were then post-processed using the TRACWin software (v4.1.1) (Leblanc, 2008).

In order to estimate the proportions of within- and between-crown gaps from DHP images, a method based on mathematical morphology (Korhonen and Heikkinen, 2009) was applied. In this method, black-and-white canopy images are processed with mor-
phological closing and opening operations: closing operation is used to eliminate small gaps inside the tree crowns, and opening to clean the image by removing unnecessary details produced by the closing. As a result, a filter for large between-crown gaps is obtained, after which proportions of gaps inside and between individual crowns can be calculated (Fig. 2).

The transmittance images produced by the method of Lang et al. (2010) could not be used directly in the morphological calculations, as the method requires binary inputs. Therefore, binary images corresponding to annular 15° gap fractions obtained from the transmittance images were produced by iteratively selecting such thresholds that minimized the differences in ring-wise gap fraction between the transmittance and binary images.

The thresholded images were used in the software package CIMES (Walter, 2008) to calculate \( \Omega_{\text{PCS}} \). The CAN-EYE software (http://www.avignon.inra.fr/caneye) is another commonly used software for the processing of DHP (Demarez et al., 2008; Garrigues et al., 2008; Kraus et al., 2009). We obtained \( \Omega_{\text{DHP}} \) estimates with the finite-length method of Lang and Xiang (1986) applied in the CAN-EYE. The segment sizes were 2.5° and 5° in the zenithal and azimuthal direction, respectively. CAN-EYE describes the clumping factor variation with \( \theta \) by a fitted curve, and the results from CAN-EYE are thus reported in similar fashion.

The TRAC gap size theory has been also applied to the original non-thresholded DHPs. By using pixels at a given view zenith angle, a gap size distribution can be estimated from hemispherical photographs. This gap size distribution is angular and does not relate to a physical length like the one from the TRAC. Similar to the TRAC data treatment, we inserted markers into the extracted TRAC-like profiles to split a 360° annulus into 5°, 15°, and 45° long segments. The profiles were then analyzed with the TRACwin to obtain \( \Omega_{\text{CC}} \), \( \Omega_{\text{DX}} \), and \( \Omega_{\text{CLX}} \) estimates. Table 2 summarizes the list of the used instruments and the acquired parameters.

3.3. Simulations with the gap fraction model of Nilson (1999)

Nilson’s gap fraction model and the calculation of \( \Omega_{\text{N}} \) (Eqs. (23)–(25)) were set up with parameters from Table 1 and Kuusk et al. (2009). GI was obtained by randomly dropping a circular sub-sample \( S(\theta) \) on the modeled plot 10,000 times. The subsample areas were chosen to be equal to the projection areas of the average tree crown envelope at angles \( \theta \) corresponding to the ring centers of LAI-2000 instrument. At each time, the number of trees occurring on this subsample was counted and statistics for given case of \( \theta \) were calculated. Shoot-level clumping factor \( \gamma_{\text{E}} \) was assumed to be 1 for birch and 1/0.56 for pine (Oker-Blom and Smolander, 1988). Branch area index (BAI) was supposed to be 18% of LAI for pine and 10% for birch.

4. Results and discussion

4.1. Leaf inclination angle distribution function and leaf projection function

The mean inclination angle for Silver birch was 34°, and the leaf angle distribution became more planophile while the transmittance of the diffuse radiation in the canopy decreased (Table 3). A Beta-distribution function was fitted to the measurements and the \( f(\theta_{h}) \) was obtained (Section 2.1). Finally, \( G(\theta) \) was acquired using Eq. (1). The \( G(\theta) \) was close to that of the planophile case (Fig. 3a).

Fig. 3b shows the implications of replacing the assumed spherical distribution of leaf angles with the measurement-based \( G(\theta) \) values in the gap fraction model of Nilson (1999) for the birch stand. The measured \( f(\theta_{h}) \) modifies the gap size and gap fraction. The change in \( \Omega_{\text{E}} \) with \( \theta \) becomes more pronounced with the non-spherical leaf angle distribution. The change is linked to the \( f(\theta_{h}) \) modification of the gap size and gap fraction. As the measured \( f(\theta_{h}) \) is rather further away from spherical case (Fig. 3a), the effect is...
Table 2
Description of measurements, processing, and indirect instruments to estimate clumping factors.

<table>
<thead>
<tr>
<th>LAI-2000</th>
<th>TRAC</th>
<th>DHP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial sampling number</td>
<td>18</td>
<td>110</td>
</tr>
<tr>
<td>Range of view zenith angles</td>
<td>7°–68°</td>
<td>31°–79°</td>
</tr>
<tr>
<td>Segment length</td>
<td>–</td>
<td>1 m; 2 m; 5 m; 7 m; 15 m or 21 m</td>
</tr>
<tr>
<td>Total gap fraction</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Within crown gap fraction</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Clumping factor</td>
<td>Ωn</td>
<td>ΩCC; ΩAS; ΩDXX; ΩCMN</td>
</tr>
</tbody>
</table>

Table 3
Leaf inclination angle measured at five height levels of Silver birch (mean ± 95% confidence interval).

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Leaf inclination angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.9 m</td>
<td>56 ± 3.8</td>
</tr>
<tr>
<td>16.1 m</td>
<td>37 ± 3.6</td>
</tr>
<tr>
<td>14 m</td>
<td>28 ± 2.9</td>
</tr>
<tr>
<td>11.2 m</td>
<td>21 ± 2.7</td>
</tr>
<tr>
<td>6.7 m</td>
<td>27 ± 3.0</td>
</tr>
<tr>
<td>Total</td>
<td>34 ± 1.8</td>
</tr>
</tbody>
</table>

For the Scots Pine stand, the measured f(θL) information was not available. A spherical leaf angle distribution (i.e. G=0.5) was assumed, which is often considered to be a reasonable assumption for many conifer shoots (Leblanc and Chen, 2001; Walter et al., 2003).

4.2. Gap fraction

Multi-angle gap fraction values were measured using LAI-2000, DHP, TRAC and modeled with Nilson (1999) (Fig. 4). For the birch stand, the estimates of the canopy gap fraction distribution P(θ) from LAI-2000, DHP, and Nilson (1999) were not significantly different (P<0.01). There was an excellent agreement between LAI-2000 observations and Nilson (1999) in particular after the assumed spherical case of leaf angle distribution in the gap fraction model was replaced with the measured distribution from Section 3.1. The total gap fraction estimates from LAI-2000 and DHP were also not significantly different in the pine stand (P>0.005, Fig. 4b). Beside other detailed stand characteristics, the estimates of P(θ) with Nilson (1999) also depend on l (Eq. (23)). Nilson (1999) provided slightly higher values of the total gap fraction in the pine stand (P<0.005, Fig. 4b) for L=1.86, yet the changes in the P(θ) followed the same trend with LAI-2000 and DHP. However, if L is obtained as an inversion of LAI-2000 and DHP data, both P(θ) values and between crown gap fractions from Nilson (1999) and DHP show a very close match (Fig. 4b) similar to the birch stand (Fig. 4a). These results indicate the allometric L=1.86 for the RAMI pine stand might be underestimated.

TRAC measurements provided similarly lower values of P(θ) to other methods in both stands. Fig. 4 shows TRAC accounts correctly for all between crown gaps at all view zenith angles, however an increasing portion of within crown gaps with decreasing view zenith angle is being omitted. The ratio of within-crown gap fraction to total gap fraction is smaller for the birch stand as the deciduous species in general have higher crown closure (Kucharik et al., 1999).

The underestimation of the smaller gap (few centimeters and less) contribution by TRAC has been observed before (Kucharik et al., 1997; Leblanc et al., 2005) and it is related to the resolution of the sensor. However, the foliage clumping information is primarily confined in the presence of large gaps, since they are more frequently observed in clumped canopies than in canopies with spatial leaf distribution close to random case (Chen and Cihlar, 1995a). Importantly, Fig. 4 demonstrates that the gap removal technique of Chen and Cihlar (1995a) correctly identifies large gaps. The underestimation of smaller gaps by TRAC then does not necessarily

Fig. 3. (a) Leaf projection function (G) against view zenith angle (θ). Planophile and spherical cases were drawn for comparison based on de Wit (1965). (b) Element clumping index calculated according to Nilson (1999) with view zenith angle, using the spherical (G=0.5) and the measured distribution of leaf angles. Both cases in (b) are calculated assuming l = 3.93.

[Please cite this article in press as: Pisek, J., et al., Comparison of methods for measuring gap size distribution and canopy nonrandomness at Järvselja RAMI (RADiation transfer Model Intercomparison) test sites. Agric. Forest Meteorol. (2010), doi:10.1016/j.agrformet.2010.11.009]
compromise the estimates of the element clumping index based on the TRAC measurements.

Data inputs and methodologies to estimate the proportions of within- and between-crown gaps differ among Nilson (1999) and Korhonen and Heikkinen (2009). The good agreement in the amount of between crown gaps in Fig. 4 is thus very encouraging evidence about the good performance of the two methods and it indicates the acquired proportions of within- and between-crown gaps in the two RAMI stands are correct.

4.3. Element clumping index

Fig. 5a–f show the \( \Omega_E \) variation with a method used and zenith angle \( \theta \) from the two stands. The reference results from the gap fraction model of Nilson (1999) are depicted as a range bounded by the cases with applied \( L \) values from Table 1 for each stand. Plotting the range instead of a single value for every \( \theta \) allows to account for the uncertainties in obtaining \( \Omega_E \) with the reference gap fraction model of Nilson (1999).

The general trend is that \( \Omega_E \) increases with view zenith angle \( \theta \) as suggested by Kucharik et al. (1997) for similar semi-boreal forest biomes. The birch stand appears to be as much clumped as the pine stand at scales larger than a shoot. The birch stand has been thinned in 2004 and the created large gaps are still apparent (Fig. 1a). Since it is gaps between crowns that dominantly cause the gap size distribution function to deviate from random (Kucharik et al., 1999), the beyond-shoot clumping may not be that different between the deciduous and the coniferous RAMI stand in Järvselja.

The gap size distribution-based methods gave consistent angular variation for both stands in the shared range of the zenith angle 30–60° (Fig. 5a and d). The changes in \( \Omega_E \) are also overall very consistent with the results from the gap fraction model of Nilson (1999) for the CC method. In the pine stand, the sudden increase in CC/TRAC estimates beyond \( \theta > 77° \) is due to the limited number of measured transects \((n = 2)\) and the quality of the collected data. As the sun is not above the tree crowns at such high \( \theta \) and the stand is not located on the verge of a forest, very little direct light penetrates the stand from the side and virtually no large gaps are detectable, although theoretically present. In contrast to gradual changes of \( \Omega_{CC} \) with \( \theta \), Pielou's gap size distribution-based method shows a sudden increase in \( \Omega_E \) by order of two for \( \theta > 52° \). \( \Omega_{PCS} \) is very close to Nilson (1999) at \( \theta = 62° \) in both stands, but except this particular angle the values are not reliable. In agreement with previous studies (Gonsamo and Pellikka, 2009; Ryu et al., 2010a,b), \( \Omega_{CC} \) values tend to underestimate the beyond-shoot clumping. The disagreement between the CC estimates using TRAC and DHP can be explained by the used sampling scheme in the stands (Fig. 1a and b). TRAC measures the gap size distribution along linear transects in one direction towards the sun, while DHP provided single location photographs 30 m apart with a footprint of 360° in azimuth. Taking the DHPs at shorter distances apart would close the gap, as Leblanc et al. (2005) observed that sampling every 10 m on linear transect reduced the best mean absolute relative difference of their estimates from TRAC and DHP to 4%.

The method of Kucharik et al. (1999) provides a relatively good estimate of \( \Omega_E \) at \( \theta = 0° \) in case of the spherical leaf angle distribution function (i.e. \( G(\theta) = 0.5 \)) in the pine stand; Fig. 5e). If the \( G \) varies with \( \theta \) (i.e. the birch stand), \( \Omega_E(0) \) is inaccurate (Fig. 5b). The \( \Omega_E \) at \( \theta > 30° \) tends to be rather underestimated in both stands.

The \( \Omega_{IX} \) estimates from different instruments and used software are mutually consistent in the birch stand (Fig. 5b). The difference at high \( \theta \) between plotted DHP \( \Omega_{IX} \) is due to the fitting-curve procedure applied within the CAN-EYE software. The gap between the DHP and TRAC-derived estimates from the CC method does not appear anymore, as the original TRAC transects are segmented into 1 m long bits in order to meet more easily the assumption of the random foliage within the finite length segments. However, the conditions of Lang and Xiang (1986) are clearly not met even for these smaller segments in the pine stand, as the TRAC-derived \( \Omega_{IX} \) values show actual decrease with \( \theta \) (Fig. 5e). Despite the overall differences with Nilson (1999), \( \Omega_{IX} \) estimates are generally within the one standard deviation from Nilson (1999) at \( \theta = 55° \) in both stands, irrespective of the used instrument or the applied software.
Fig. 5. Element clumping index $\Omega_\varepsilon$ with view zenith angle $\theta$ measured from TRAC, DHP, Nilson (1999) and Kucharik et al. (1999). $\Omega_\varepsilon$ from Nilson (1999) are plotted as a range of values bounded by two $L$ cases from Table 1. $\Omega_\varepsilon$ from Nilson (1999) are plotted as a range of values bounded by two $L$ cases from Table 1.

$\Omega_{\text{CLX}}$ and $\Omega_{\text{CMN}}$ show the best agreement with Nilson (1999) (Fig. 5c and f). The agreement is remarkable considering the tested approaches are not theoretically equivalent, and that the stands represent two different cases of the leaf angle distribution function. The results from Fig. 5f also support findings by Chen and Cihlar (1995a) and Law et al. (2001), who advised extreme high and low $\theta$ to be avoided to reduce error in the measurements (e.g. difficulty of distinguishing small gaps at $\theta > 60^\circ$).

All the $\Omega_\varepsilon$ estimates were significantly correlated ($P < 0.01$) per acquisition methods (Table 4). The lower correlations of $\Omega_{\text{LX}}$ relative to other methods from TRAC data are related to decreasing $\Omega_{\text{LX}}$ with $\theta$ in the pine stand. All $\Omega_{\text{LX}}$ correlations are higher than 0.7 if only the results from the birch stand are considered. Our results indicate that it is difficult to meet both segment size assumptions (presence of gaps and the random distribution of gaps within the segments), and LX method needs to be used carefully, particularly in the needleleaf canopies (but see also López-Lozano et al., 2009). Interestingly, overall the studies dealing with the broadleaf canopies also tended to be more successful in using the finite-length LX method (Baret et al., 1993; Sommer and Lang, 1994;...
Brenner et al., 1995; van Gardingen et al., 1999; Macfarlane et al., 2007). The PCS method did not seem to be particularly well correlated with either of the other gap size based CC method performed on DHP. The PCS correlations with other methods also did not improve even when only the results for $\theta < 53^\circ$ (Fig. 5a and d) were considered. The results from Table 4 and Fig. 5a and d suggest the other methods should be preferred to PCS while correcting for clumping effects.

Despite the obvious differences between the methods (Fig. 5), the quite high correlations in Table 4 are very encouraging with airborne or satellite remote sensing (Chen et al., 2005). If the remotely based $\Omega$ estimates are linked to or validated using one method (e.g. CC method; Pisek et al., 2010; Simic et al., 2010), they could be easily converted to relatively accurate estimates from another method (e.g. CLX or CMN). Alternatively, results from different methods could serve for evaluation of the same remotely based foliage clumping map.

Table 4
Pearson correlation coefficient of clumping index estimated using five methods for TRAC (in bold) and DHP acquisitions.

<table>
<thead>
<tr>
<th></th>
<th>CC</th>
<th>LX</th>
<th>CLX</th>
</tr>
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<tbody>
<tr>
<td>CMN</td>
<td>0.92</td>
<td>0.38</td>
<td>0.78</td>
</tr>
<tr>
<td>CC</td>
<td>0.78</td>
<td>0.56</td>
<td>0.69</td>
</tr>
<tr>
<td>LX</td>
<td>0.82</td>
<td>0.86</td>
<td>0.72</td>
</tr>
<tr>
<td>PCS</td>
<td>0.54</td>
<td>0.62</td>
<td>0.69</td>
</tr>
</tbody>
</table>

4.3.1. What are the strengths and weaknesses of multiple methods to assess $\Omega_E$ in the two RAMI stands?

As demonstrated in the analysis above, the combination of logarithmic gap averaging and gap size distribution approach (CLX) and the modified gap size distribution method (CMN) performed the best while compared to the independent estimates from the gap fraction model of Nilson (1999). However, the choice of the suitable method might be also influenced by the assumptions or specific requirements behind them.

The advantage of the CC method is that there are no spatial pattern assumptions made about canopy elements unlike logarithmic gap fraction averaging methods (Chen and Cihlar, 1995a,b). Leblanc (2002) added a missing normalization factor to the original equation, which tended to induce a considerable positive bias for open clumped stands, although the bias was negligible for less clumped and closed stands (Law et al., 2001). Despite the introduced correction, it has been noted the method still sometimes tends to underestimate the foliage clumping (Walter et al., 2003; Macfarlane et al., 2007; Ryu et al., 2010a,b) and this was confirmed in this study (Fig. 5a,d). Since most studies employing TRAC sensor have used the CC method, special attention is required when using $\Omega_E$ values from the literature (Ryu et al., 2010b).

The finite-length LX method requires a modification of experimental design to ensure spatial sampling effectively captures the relevant scales of foliage clumping, but does not demand additional information about the canopy beyond the radiometric measurements. Macfarlane et al. (2007) also suggested LX in preference of CC, unless the gap size distribution is known and very precise. On the other hand, the LX method has been also known to give erroneous results, as gaps may not exist over the short length of

Fig. 6. The changes in $\Omega_E$ with segment length using (a) DHP and (b) example of TRAC data ($\theta = 39.6^\circ$) in the pine stand. The dashed line (RAMI) in (b) marks the estimated mean element width in the birch RAMI stand.

Fig. 7. Two gap size distribution cases estimated in the birch RAMI stand by TRAC at a solar zenith angle $\theta = 68.48^\circ$ (a) at $\theta = 41^\circ$. A measured distribution $F_{\text{mr}}$, the final distribution of $F_{\text{mr}}$, the matched distribution $F_r$ from CC method, and $F_r$ reconstructed using the known true $L$ and sample projection coefficients $G(\theta)$ are plotted.
the suggested 10-leaf width segments in a clumped canopy (Chen and Black, 1992; Whitford et al., 1995). Although our $\Omega_{LX}$ results seemed to provide close estimates around $\theta \approx 55^\circ$ in both stands, the overall changes in $\Omega_{LX}$ with $\theta$ seem to agree more with the latter findings. Furthermore, Demarez et al. (2008) found their $\Omega_{LX}$ estimates to be correlated with the size of cells used to compute the clumping index. This suggests the LX method requires an optimization. Our reported results provided the closest agreement with Nilson (1999) while the data were segmented into 1 m (TRAC)/15° (DHP) intervals. However, the TRAC gap size profiles from Järvselja exhibit presence of 1 m gaps in both stands. The method thus cannot correctly account for large between crown gaps – spatial dimensions incompatible with the theory of Lang and Xiang (1986).

The approach of Kucharik et al. (1999) requires measurements of stem density, crown diameter and depth, and the canopy fraction towards the zenith (within $15^\circ$) partitioned into between-crown and within-crown components. No detailed measurements of canopy gap size distribution are needed. Our results indicate the method can estimate $\Omega_L(0)$ accurately if the leaf angle distribution is close to the spherical case (i.e. the RAMI pine stand). The $\Omega_L(0)$ values might be further away than the stated 15% of the actual value by Kucharik et al. (1999) with the non-spherical leaf angle distribution (i.e. the measured planophile case of the birch stand; Fig. 5b). The predicted $\Omega_L(0) = 0.62$ for the birch stand would be within 15% of the value estimated by Nilson (1999) only if the spherical leaf angle distribution were assumed, instead (Fig. 5b). The estimation of $\Omega_L$ at low zenith angles using the other methods and DHP was repeatedly found not very reliable due to the high proportion of mixed pixels (van Gardingen et al., 1999; Leblanc et al., 2005), and $\Omega_L(0)$ could serve as an alternative if the foliage orientation can be considered a random case. Beside $\theta = 0^\circ$, our results indicate that the method might not be the most suitable choice compared to the other approaches. Interestingly, the simulated $\Omega_L$ values are overestimated in both stands even at $\theta = 55^\circ$ where the other methods tend to rather coincide.

The PCS method is concerned only with following the sequences of gap/no-gap pixels. There are no assumptions common to the other methods. However, strong behavioral differences between the PCS method and other methods were observed, which underlines the advantage of the method’s simplicity. PCS distributions tend to fit an exponential curve, whereas distributions of $\Omega_L$ by other methods are closer to a sigmoid curve in the two RAMI stands. The observed PCS underestimation of $\Omega_L$ is in agreement with the previous studies (Walter et al., 2003; Gonsamo and Pellikka, 2009). The core of the underestimation is in too high sensitivity of PCS to small structural variations on the pixel-by-pixel basis, whereas the foliage clumping information is predominantly related to the presence of large gaps in the canopy (Chen, 1996).

The good performance of the CLX method and the good results obtained from the CMN method compared to Nilson (1999) together suggest that the amount of correction for element foliage clumping from these two methods is about right. However, the requirements and assumptions behind the two methods differ. Leblanc et al. (2005) cautioned the choice of the correct segment size is as important for the CLX method as for the LX method, yet no guidance was provided how to determine the appropriate size. Consequently, the applied segment sizes for DHP analyses varied from 5° (Gonsamo and Pellikka, 2009) up to 45° (Leblanc et al., 2005; MacFarlane et al., 2007). Fig. 6a illustrates the effect of the segment size on the $\Omega_{CLX}$ estimates in the pine stand. The differences can reach up to 0.2 between the various $\Omega_{CLX}$ retrievals for the identical $\theta$. The differences decrease from $\theta > 60^\circ$ as the overall amount of gaps in the canopy is too low (Fig. 3b) and the segments become more similar irrespective of their size (Fig. 2). The $\Omega_{CLX}$ estimates from TRAC are equally sensitive to the segment size (Fig. 6b). Fig. 6b further illustrates the importance of the choice of the mean element width $W_E$ on $\Omega_{CLX}$. Similarly to CC method, the calculated $\Omega_{CLX}$ reaches values close to the asymptote at inputs approximately equal to the element characteristic width. This suggests the combined CLX method also retains the feature of being not very sensitive to the choice of the element width $W_E$ within a reasonable range.

The choice of CMN method would retain all the advantages of CC approach without the underestimation of $\Omega_L$ (Fig. 5c and f). The CMN method does not require any additional substantial data processing as the needed variables $F_m(0, \theta)$ and $F_m(0, \theta)$ are provided as standard outputs from TRACWin or CIMES. The only difference between the $\Omega_{CMN}$ and $\Omega_{CC}$ is omission of the normalization part from Eq. (7). The factor could be entirely omitted if it is proven $F_m(0, \theta)$ values are in reality matched by Eq. (8) with the known true $\theta$ (Kuusk et al., 2009) and $G(\theta)$ corresponding to the leaf angle distribution within the stand.

4.3.2. Leaf projection function $G(\theta)$ within the gap size distribution-based methods

Fig. 7 shows the $F_m(0, \theta)$ values indeed match $F_l(0, \theta)$ for the RAMI birch stand with the known true $\theta$ coming from Kuusk et al. (2009) and $G(\theta)$ plugged into Eq. (8). The different $F_l(\lambda)$ functions in Fig. 7a and b were reached by keeping the true $L$ and $W_E$ in Eq. (8) constant and altering the value of $G(\theta)$ only. The close match between $F_m(0, \theta)$ and $F_l(0, \theta)$ with true $L$ is observed only if the $G(\theta)$ values deviate from the spherical case and follow the independently measured planophile case of $f(\theta)$ of the birch stand (Fig. 3a). The small differences between the measurement-based and reconstructed $G$ values for selected, perpendicular-to-the-sun transects in Fig. 3a are due to the fact that (a) the measured $f(\theta)$ values were not coming from the birch trees in the RAMI stand, but from the nearby mixed stand, instead, and (b) the true $L$ would also vary slightly within the stand. Nevertheless, Figs. 3a, 7a and b provide evidence the predicted $F_l(0, \theta)$ values corresponds reasonably well to the true $L$, $G(\theta)$ and no normalization is needed in Eq. (7).

The measurements of $f(\theta)$ were not available for the RAMI pine stand, but the reconstructed $G(\theta)$ values following the approach described above did not change significantly with $\theta$. The spherical case of $G(\theta)$ is also indicated by the small changes in both $\Omega_{CC}$, $\Omega_{PCS}$ with $\theta$ (Fig. 5d). Similarly to the birch RAMI stand, the omission of the normalization factor and application of Eq. (11) (CMN method) instead of Eq. (7) (CC method) leads to the improved estimates of $\Omega_L$ (Fig. 5f). The gap size distribution-based CMN method can be thus considered a sound alternative to CLX without the uncertainties of the latter due to the effect of the segment size on the results.

4.3.3. Spatial homogeneity of $\Omega_L$ and gap fractions within the RAMI stands

Our results indicate that the RAMI pine stand is spatially very homogeneous as very consistent $\Omega_L$ estimates can be observed regardless of the transect orientation as long as TRAC is walked perpendicularly to the sun direction (Fig. 8). The observed variation in the gap fraction and $\Omega_L$ is mainly effect of the changes in $\theta$. The experiment with the set of perpendicular transects was not carried in the birch stand due to time and optimal weather limitations. However, since the birch and pine stand showed similar magnitudes of the $\Omega_L$ standard deviation values using DHP (Fig. 5), the birch stand seems to be equally suitable for the RAMI exercises. The desired good spatial homogeneity of the real world RAMI stands (Widlowski et al., 2007) is an important property at this stage, as theoretically it should be easier for RAMI participants to mimic the stand architectures inside their models and produce outputs relatively free of the errors due to the mismatch between the reality and the modeled input. The outputs might be then compared not only to the results from other models, but against the
4.3.4. Changes of element clumping index with height

The dependence of $\Omega_E$ on the view zenith angle and the height $h$ in the birch stand is depicted in Fig. 9. $\Omega_E$ varies from 0.7 to 0.9 with lower (canopy less clumped) values obtained in deeper canopy layer. $\Omega_E$ increases with $\theta$ at both measurement heights due to increasing probability of encountering canopy elements for the incoming direct solar radiation. The presence of shrub layer between $h \approx 0$ m (ground) and $h = 2$ m results in the further decrease of the canopy transmittance and the presence of large gaps at the forest floor. $\Omega_N$ values are in better agreement with the TRAC measurements at $h = 2$ m because the gap fraction model of Nilson (1999) did not consider the shrub layer. Considering that for a random canopy $\Omega_E = 1$, results presented in Fig. 9 serve as a verification of the modeling work of the changes of the foliage clumping with height by Mottus (2004) and Ryu et al. (2010b).

5. Conclusion

In this study, we quantified $\Omega_E$ using a gap fraction model, six different methods and multiple instruments at one Silver birch and one Scots Pine RAMI stand in Järvselja, Estonia. Our main findings include:

1. The two Järvselja RAMI stands are horizontally quite homogeneous with respect to the foliage clumping and gap fraction.
2. The clumping index depends on view zenith angle and the leaf projection function in both stands. The dependence is greater in the planophile–like birch stand than in the more spherical case of the pine stand. In addition, the element clumping depends on the measurement height in the birch stand.
3. The combination of logarithmic gap averaging and gap size distribution approach (CLX) and the modified gap size distribution method (CMN) performed the best while compared to the independent estimates from the gap fraction model of Nilson (1999). The performance of CLX method is affected by the choice of segment size. Unfortunately, we could not identify scientifically sound way how to determine the appropriate size a priori.
4. The application of the normalization factor in the CC method is the cause of the $\Omega_E$ underestimation. We demonstrated the normalization might not be necessary as the needed equivalent canopy to the measured canopy gap fraction with a random spatial distribution of foliage was in fact the product of true $L$ and the appropriate leaf projection coefficient $G$. The modified, without-normalization CMN approach possesses an advantage of not depending on the choice of the segment size as the CLX method, while simultaneously being capable of delivering similarly close $\Omega_E$ estimates.
5. The quite high correlations between various methods are very encouraging with prospects of estimating and validating the foliage clumping from airborne or satellite remote sensing.

Our results were obtained over two spatially homogeneous and well documented hemiboreal stands and may be still evaluated at other ecosystems prior to their generalization to the whole range of existing canopies, such as crops or savannas.

The compiled data extend the original parameter dataset for Järvselja to be used in the next phase of RAMI for different benchmark tests and reflectance modeling experiments, and contribute toward systematic validation efforts of radiative transfer models, operational algorithms, and field instruments, as promoted by the Committee on Earth Observation Satellites (CEOS).

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Appendix A. Nomenclature

\( b \) probability of encountering pixels of category \( B \) (no gap)
\( \hat{b} \) the maximum likelihood estimates of \( B \) pixels
\( B \) no gap pixels
BAI the branch area index
CEOS Comitee on Earth Observation Satellites
\( D \) crown diameter
DHP digital hemispherical photography
\( f(h) \) leaf inclination distribution function
\( f_c \) the proportion of ground area covered by the vertical projection of crowns, assuming the crowns to be solid
\( F_m(0, \theta) \) measured overall canopy gap fraction
\( F_m(\lambda, \theta) \) reduced gap–size accumulated fraction after removal of the large, non-random gaps
\( F_1(\lambda) \) equivalent canopy to the measured canopy gap fraction with a random spatial distribution of foliage
\( G \) projection coefficient of unit foliage area on a plane perpendicular to the view direction
GI the relative variance of the number of trees in the area \( S(\theta) \)
\( h \) measurement height
\( L \) leaf area index
\( L_c \) effective leaf area index
\( \hat{m}_B \) the mean length of \( B \) sequences in numbers of pixels
\( m_B \) the mean length of \( B \) sequences in numbers of pixels
\( m_G \) the number of sequences of \( B \) (no gap) pixels
\( m_W \) the number of sequences of \( W \) (gap) pixels
\( N \) the tree density (trees m\(^{-2}\))
\( P \) canopy gap fraction
\( P_1(\theta) \) mean gap fraction within a single tree crown
RAMI RAdiation transfer Model Intercomparison
RT radiation transfer
\( S_B^G \) the variance of \( B \) pixels with regard to \( \hat{b} \)
\( S_W^G \) the variances of \( W \) pixels with regard to \( \hat{w} \)
\( S(\theta) \) the area of projection of the average tree crown envelope on the horizontal plane
TRAC Tracing Radiation and Architecture of Canopies
\( W \) probability of encountering pixels of category \( W \) (gap)
\( \hat{w} \) the maximum likelihood estimates of \( W \) pixels
\( W_G \) gap pixels
\( W_E \) mean element width
\( \theta \) view zenith angle
\( \theta_L \) leaf inclination angle
\( \Omega \) clumping index
\( \Omega_L \) element clumping index
\( \Omega_L \) element clumping index calculated by corrected Chen and Cihlar (1995a) by Leblanc (2002)
\( \Omega_L \) element clumping index calculated by the combined CC and CLX method (Leblanc et al., 2005)
\( \Omega_L \) clumping index calculated by Chen and Cihlar (1995a,b) without the normalization factor
\( \Omega_N \) element clumping index calculated using the empirical equations of Kucharik et al. (1999)
\( \Omega_L \) element clumping index calculated from logarithmic average by Lang and Xiang (1986)
\( \Omega_S \) element clumping index from the gap fraction model of Nilson (1999)
\( \Omega_{PCS} \) Piérou’s coefficient of spatial segregation (Piérou, 1962; Walter et al., 2003)
\( Y_E \) needle-to-shoot area ratio
\( \chi \) ratio of crown depth to crown diameter
\( \Phi \) proportion of within crown gaps

References


