1. Theory

Crown shapes of trees in a forest determine the vertical and horizontal distributions of gaps in a canopy. Canopy gap fractions, in turn, determine two key variables needed in modeling primary productivity: the spatial distribution of sunlit foliage within the canopy and the fraction of visible ground. In optical remote sensing applications, the angular profiles of canopy gap fractions also influence the joint probability that a leaf in the canopy is sunlit and that there is a free line of sight to this point from the viewing direction, in other words the probability that radiation reflected from the sunlit crown or ground will reach a remotely located sensor (e.g., Rautiainen et al., 2004).

The shape of the gap fraction vs zenith angle curve is influenced by canopy structure, and varies with stand- and crown-level variables such as the tree pattern and crown shape, which are not present in the idealized case of a horizontally uniform canopy with randomly (Poisson) distributed leaves. In such canopy, the angular dependency of the gap fraction, or the uncollided transmittance \( T(\theta) \), at a specific value of the leaf area index \( L \) is simply a function of the so called “mean projection of unit foliage area” \( G(\theta) \) (Ross and Nilson, 1965), which is determined by the leaf (needle) orientation and shape. Leaves are traditionally considered to be flat and infinitely thin, but the \( G \)-function for coniferous needles depends on their cross-sectional shape (Stenberg, 2006). In both cases, however, irrespective of the leaf angle distribution, the spherically averaged value of \( G \) is exactly 0.5 (Miller, 1967), and this property is used in the inversion from measured values of \( T \) to \( L \) by optical techniques:

\[
T(\theta) = \exp \left( \frac{-G(\theta)L}{\cos \theta} \right)
\]

\[
\leftrightarrow
-2 \int_0^\frac{\pi}{2} \ln \left[ T(\theta) \right] \cos \theta \sin \theta d\theta = 2 \int_0^\frac{\pi}{2} G(\theta) L \sin \theta d\theta = L
\]

(1a)

(1b)

In real forest canopies, where clumping of foliage at different hierarchical levels typically occurs, a modified expression for the canopy gap fraction can be formulated as (Stenberg et al., 2014):

\[
T(\theta) = \exp \left( \frac{-\beta(\theta) G(\theta)L}{\cos \theta} \right)
\]

(2a)

where the directional clumping index \( \beta(\theta) \) is introduced to correct for deviation in the relationship between \( T(\theta) \) and \( L(\theta) \) from that...
of a Poisson canopy composed of randomly distributed leaves. The product \( \beta(\theta)G(\theta) \) corresponds to the radiation extinction coefficient in the modified Beer’s law equation (Eq. (2a)). There is an obvious link between the light extinction coefficient and crown shape: for example, in a canopy of Poisson distributed trees, \( \beta(\theta)G(\theta) \) corresponds to the mean projection of unit crown area in the direction \( \theta \) (Oker-Blom and Kellomäki, 1983).

The inversion of Eq. (2a) in this case does not produce the true \( L \) but corresponds to the effective leaf area index \( (L_e) \) defined as (Black et al., 1991):
\[
L_e = -\int_0^\pi \ln \frac{I(\theta)}{I_e} \, \cos^2 \theta \, d\theta = 2 \int_0^\pi \beta(\theta)G(\theta) \, \cos^2 \theta \, d\theta - \beta L \tag{2b}
\]

parameter \( \beta \) in Eq. (2b), in turn, is the ratio of \( L_e - L \) and is called the total hemispherical clumping index (Stenberg et al., 2014):
\[
\beta = 2 \int_0^\pi \beta(\theta)G(\theta) \, \sin \theta \, d\theta \tag{3}
\]

Species-specific values of the \( G \)-function for a number of deciduous species have recently been measured by Pisek et al. (2011, 2013); but the technique cannot be applied to needle-leaved canopies. Studies on the \( G \)-function of coniferous species, on the other hand, are scarce (e.g., Stenberg et al., 1993). Data on the magnitude and angular dependency of \( \beta \) are even more limited because it cannot be directly measured and its indirect estimation from canopy transmittance \( (T) \) (by means of Eq. (2a)) requires knowledge of both the true leaf area index \( (L) \) and the \( G \)-function. In this study, the focus is not on the magnitude of the clumping index \( \beta \) but on the angular dependency of the extinction coefficient \( \beta(\theta)G(\theta) \). To characterize this dependency, we define the shape function \( \psi(\theta) \) as the ratio of \( \beta(\theta)G(\theta) \) to its spherically averaged value \( (0.5\beta) \):
\[
\psi(\theta) = \frac{\beta(\theta)G(\theta)}{0.5\beta} \tag{4a}
\]

we note that, if there is no variation in \( \psi(\theta) \), then \( \psi = 1 \) for all \( \theta \).

Given data on canopy transmittance \( (T) \) in all directions \( (\theta) \) of the upper hemisphere, the effective leaf area index \( (L_e = \beta L) \) arrives from Eq. (2b) and the shape function can be computed as (see Eqs. (2a), (2b) and (4a)):
\[
\psi(\theta) = -2\ln \frac{\left[T(\theta)\right]}{L_e} \cos\theta \tag{4b}
\]

In this short communication paper, measurements of canopy structure, gap fractions and effective LAI in 986 plots of Scots pine, Norway spruce and Silver birch stands are used to assess how similar the vertical canopy gap fraction profiles (as described by the shape function \( \psi(\theta) \)) are for common boreal tree species.

### 2. Materials

Regular forest inventory data and angular profiles of canopy gap fractions for 986 Scots pine (Pinus sylvestris), Norway spruce (Picea abies) and Silver birch (Betula pendula) plots in boreal Finland were measured with the LAI-2000 Plant Canopy Analyzer (PCA) (Li-Cor Inc., Nebraska, USA). The data were acquired from three forest sites:

<table>
<thead>
<tr>
<th>Species composition</th>
<th>Number of plots</th>
<th>Stand density (trees/ha)</th>
<th>Mean tree height (m)</th>
<th>Mean crown length (m)</th>
<th>( L_e )</th>
<th>DIFN</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>968</td>
<td>20–7900</td>
<td>0.3–28.0</td>
<td>0.3–20.5</td>
<td>0.14–4.95</td>
<td>0.02–0.89</td>
</tr>
<tr>
<td>Scots pine (&gt;90%)</td>
<td>272</td>
<td>50–7000</td>
<td>2.5–27.0</td>
<td>1.4–13.5</td>
<td>0.23–3.85</td>
<td>0.06–0.85</td>
</tr>
<tr>
<td>Norway spruce (&gt;90%)</td>
<td>214</td>
<td>20–7900</td>
<td>0.3–28.0</td>
<td>0.3–20.5</td>
<td>0.22–4.95</td>
<td>0.03–0.86</td>
</tr>
<tr>
<td>Silver birch (&gt;90%)</td>
<td>34</td>
<td>90–6000</td>
<td>4.0–21.0</td>
<td>3.0–13.5</td>
<td>0.14–4.14</td>
<td>0.03–0.89</td>
</tr>
</tbody>
</table>

* Direct outputs of the LAI-2000 PCA instrument. \( L_e = \) effective leaf area index, DIFN = canopy diffuse non-interception.

There was wide variation in the shape of \( \psi(\theta) \) in the individual plots of the three different species (Fig. 1A). However, it was of large extent due to the expected variability of \( \psi(\theta) \) in the uppermost zenith angle range (7°) which covers only a very small part of the sky. The species-specific plot-wise averaged values of \( \psi(\theta) \) showed relatively small variation with zenith angle except for a sudden drop at the largest zenith angle ring (ring 5; from 61° to 74°) which occurred for all species. The small variation with zenith angle would be in agreement with a planophile distribution of needles (Stenberg, 2006); however, the sudden drop at the largest zenith angle cannot be explained by any needle angle distribution. We rather believe that the drop is explained by the increased scattering at large zenith angles, which has been reported to cause overestimation of the gap fraction of ring 5 by the LAI-2000 instrument (Li-Cor Inc., 1992; Stenberg et al., 1994). Apart from this drop, mean \( \psi(\theta) \) remained close to constant (−0.95 to 0.09) throughout the zenith angle range of rings 1–4 in birch and pine, whereas there was a slightly more notable increase in \( \psi(\theta) \) (from 0.86 to 1.09) with zenith angle in spruce forests. The differences in the shape functions between the species, however, were statistically insignificant in our data set.
Fig. 1. The dependency of canopy gap fraction on the zenith angle ($\theta$), described by the shape function $\psi(\theta)$ (Eq. (5)). (A) For all 986 plots, including mixed and monospecific forests. (B) For monospecific forests: 272 Scots pine, 214 Norway spruce and 34 Silver birch plots. The error bars show standard deviations.

4. Conclusions

The observed patterns provided some support for the hypothesis (e.g., Kucharik et al., 1999) that variation in $\psi(\theta)$ is largest in spruce, followed by pine and birch. The reasons for this are most likely related to differences in crown shape so that crowns of spruce exhibit the most elongated form, i.e., they have a small ratio of crown diameter to length. However, the absolute differences in $\psi(\theta)$ between tree species were small, indicating that crown geometry in (managed) forests composed of these species is relatively similar. Furthermore, the variation in $\psi(\theta)$ was clearly smaller than the hypothetical variation in the projection area of (opaque) crowns of different geometrical shapes. This is because in directions where the projected area of the crown envelope is small, the length of the path within the crown increases, and vice versa.

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References