

Short communication

On the angular dependency of canopy gap fractions in pine, spruce and birch stands



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ARTICLE INFO

Article history:

Received 30 December 2014

Received in revised form 24 February 2015

Accepted 25 February 2015

Available online 9 March 2015

Keywords:

G-function

Clumping

Beer's law

LAI-2000

Coniferous

Boreal

ABSTRACT

The angular profiles of canopy gap fraction curves are influenced by canopy structure, and are commonly expected to vary with stand- and crown-level variables such as tree pattern, crown shape and leaf orientation. In this study, measurements of canopy structure, gap fractions and effective LAI in 986 plots of Scots pine, Norway spruce and Silver birch stands in Finland were used to assess how similar the angular canopy gap fraction profiles are for common boreal tree species. The profiles were characterized with help of the shape function $\psi(\theta)$, defined as the normalized value of the canopy light extinction coefficient at zenith angle (θ). Variation in $\psi(\theta)$ would be induced not only by a non-spherical leaf orientation, but also by differences in the directional clumping indices, such as could result from species-specific differences in crown shape. Our results showed that there is wide variation in the shape of ψ in the individual plots of the three different species. The species-specific mean curves $\psi(\theta)$, however, showed relatively small variation with θ , except for a sudden drop at large zenith angles, and the shape of the curves was similar for the different tree species. Results indicate that differences in crown shape of the study species do not significantly affect the angular profiles of canopy gap fraction.

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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), 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) (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:

$$T(\theta) = \exp\left(\frac{-G(\theta)L}{\cos\theta}\right) \quad (1a)$$

$$\Leftrightarrow -2 \int_0^{\pi/2} \ln [T(\theta)] \cos\theta \sin\theta d\theta = 2 \int_0^{\pi/2} G(\theta) L \sin\theta d\theta = L \quad (1b)$$

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):

$$T(\theta) = \exp\left[\frac{-\beta(\theta) G(\theta) L}{\cos\theta}\right] \quad (2a)$$

where the directional clumping index $\beta(\theta)$ is introduced to correct for deviation in the relationship between $T(\theta)$ and $L(\theta)$ from that

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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 (θ) (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):

$$L_e = -2 \int_0^{\frac{\pi}{2}} \ln [T(\theta)] \cos\theta \sin\theta d\theta = 2 \int_0^{\frac{\pi}{2}} \beta(\theta) G(\theta) L \sin\theta d\theta = \beta L \quad (2b)$$

parameter β in Eq. (2b), in turn, is the ratio of $L_e - L$, and is called the total hemispherical clumping index (Stenberg et al., 2014):

$$\beta = 2 \int_0^{\frac{\pi}{2}} \beta(\theta) G(\theta) \sin\theta d\theta \quad (3)$$

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 β 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 of interest is not on the magnitude of the clumping index β 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 (0.5β):

$$\psi(\theta) = \frac{\beta(\theta)G(\theta)}{0.5\beta} \quad (4a)$$

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

Given data on canopy transmittance (T) in all directions (θ) 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)):

$$\psi(\theta) = \frac{-2 \ln [T(\theta)] \cos\theta}{L_e} \quad (4b)$$

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:

Puumala (336 plots; 61°31.6'N, 28°42.4'E) in June 2000, Suonenjoki (327 plots; 62°40.9'N, 27°28.7'E) in August 2001, and Hyytiälä (307 plots; 61°50'N, 24°17'E) in June–July 2013 using the same sampling design. The plots were located in a regular grid: in Puumala and Suonenjoki, they were 50 m apart, and in Hyytiälä, 100 m apart from each other. Plot size corresponded to the field-of-view of the LAI-2000 PCA instrument. The plots covered the typical range of forest structures and species compositions in the southern boreal forests of Finland (Table 1). In our analyses, a plot was defined “pure” when 90% of the trees (by stem count) belonged to the given tree species.

Canopy gap fractions were measured in the five zenith angle rings of the LAI-2000 PCA centered at zenith angles (θ_i): 7°, 23°, 38°, 53° and 68°. The measurements were carried out in standard overcast conditions or close to sunset or sunrise. Above canopy measurements were collected by automatic logging every 15–30 s in an open area or tower located adjacent to or in the middle of the study sites. Below canopy readings for each plot were averaged over 15 measurements: three readings taken at the plot center point, and at 6 m distance from the center point in each of the four cardinal directions (North, South, East and West).

The effective LAI was computed at plot level using the mean angular gap fractions (‘GAPS’) derived from these 15 measurements as:

$$L_e(\text{PCA}) = -2 \sum_{i=1}^5 \ln [\text{GAPS}(\theta_i)] \cos\theta_i W_i \quad (5)$$

where the weights W_i correspond to $\sin\theta_i d\theta_i$ and sum up to one.

The shape function (Eq. (4)), finally, was estimated as:

$$\psi(\theta_i) = \frac{-2 \ln [\text{GAPS}(\theta_i)] \cos\theta_i}{L_e(\text{PCA})} \quad (6)$$

3. Results

There was wide variation in the shape of $\psi(\theta)$ in the individual plots of the three different species (Fig. 1A). However, it was to large extent due to the expected variability of $\psi(\theta)$ in the uppermost zenith angle ring (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 ($\sim 0.95 - 1.09$) 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.

Table 1
Description of the study stands.

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

^a Direct outputs of the LAI-2000 PCA instrument. L_e = effective leaf area index, DIFN = canopy diffuse non-interceptance.

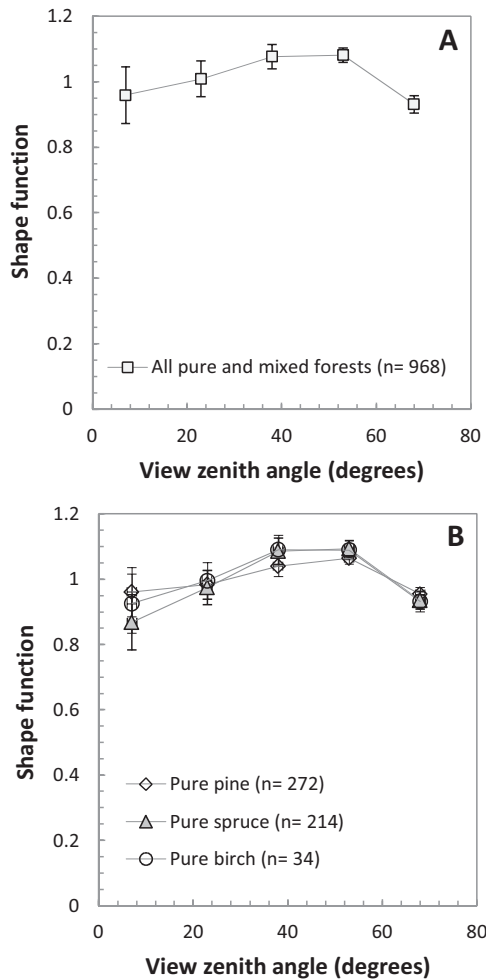


Fig. 1. The dependency of canopy gap fraction on the zenith angle (θ), described by the shape function $\psi(\theta)$ (Eq. (5)). (A) For all 986 plots, including mixed and monospecific forests. (B) For monospecific forests: 272 Scots pine, 214 Norway spruce and 34 Silver birch plots. The error bars show 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.

Acknowledgements

We thank Ms. Titta Majasalmi for the data set from Hyttiälä. The study was funded by the Academy of Finland.

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