Quantitative characterization of clumping in Scots pine crowns

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Highlights: The stochastic approach of modeling tree crowns as geometric shapes filled with a random medium was tested on twelve Scots pine trees generated with the LIGNUM model. Results supported the capability of the stochastic approach in characterizing clumping in crowns given that the outer shell of the tree crown is well represented.

Keywords: photon recollision probability, LIGNUM, STAR, crown shape, canopy structure

INTRODUCTION

The spatial aggregation of plant elements in a canopy, also referred to as 'clumping', is an adaptive strategy of individual plants and plant communities. The spatial distribution of foliage controls the interaction of radiation with vegetation, and thus indirectly also plant growth and reproduction. Clumping can occur at various hierarchical scales from microscale (shoots in coniferous canopies) to macroscale (spatial tree patterns in forest stands). Clumping causes a decrease in the fraction of sunlit leaf area and a downward shift in the vertical distribution of the sunlit leaf area. From the production ecological point-of-view, these effects may be translated into a decrease in the fraction of absorbed photosynthetically active radiation (FAPAR) but a more even distribution of irradiance on the canopy leaf area and, thus, higher light use efficiency. Especially for canopies carrying a high leaf area index (LAI) the combined effect may be beneficial for the photosynthetic production (Stenberg 1998).

Proper characterization of the clumped structure of forests allowing, e.g., calculation of scattered and absorbed radiation regimes and photosynthetic production in different parts of the canopy, has proved to be a challenging task. This concerns in particular statistical canopy radiation models, where probability density functions are used to describe the spatial distribution and orientation of foliage, and the transfer of radiation is described using a stochastic variable – the gap probability. Another option is to use deterministic three dimensional (3D) structural models, where the plant elements have exact locations and the radiation reaching any specific point in the canopy can be determined by ray tracing. Limitations of such models, however, are their reliance on detailed descriptions of canopy architecture and lack of generality. Statistical models would be preferred for many larger scale applications, given that the models are realistic enough to produce reasonable results. Uncertainties in statistical models depend on how well the within-crown structure is characterized by the models which typically are based on oversimplifications.

In this paper, the focus of our interest is on the degree and quantitative characterization of within-crown clumping in Scots pine (*Pinus sylvestris* L.). Using a statistical (nested Poisson) model, we first present a theoretical analysis of the clumping of the canopy and how it is related to the spherically averaged silhouette to total area ratio (STAR) of shoots and crown. The latter is directly related to a novel and powerful concept in quantifying canopy structure, the photon recollision probability (p). A series of differently-sized pine trees is constructed using the LIGNUM model (Perttunen et al. 1996), by which the crown silhouette area and amount of self-shading can be exactly calculated. These exact values are compared to results produced by the statistical model to examine how well the statistical models are able to characterize the within-crown clumping.
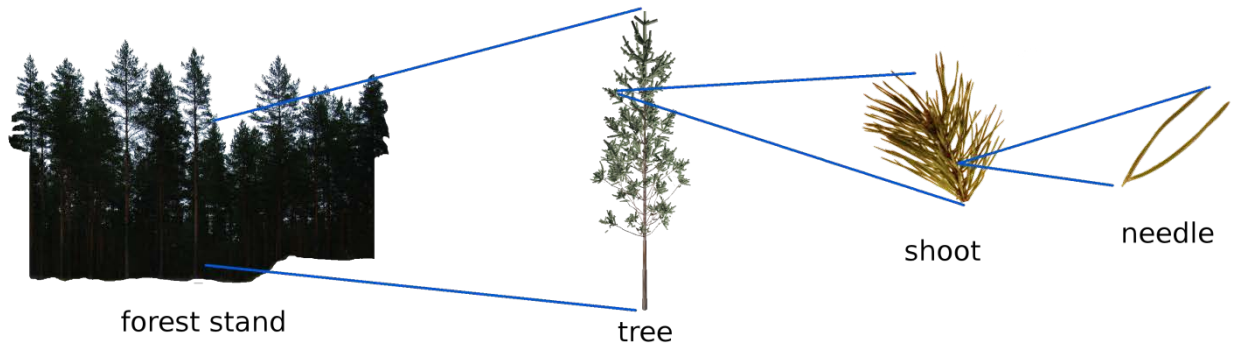
Fig. 1. The different structural levels used in describing the structure of a coniferous stand.

PHOTON RECOLLISION PROBABILITY

The spectrally invariant parameter p is defined as the probability by which a photon scattered from a leaf or needle in the canopy will interact within the canopy again (Smolander and Stenberg 2003). It provides a link between the absorption and scattering properties at different canopy structural levels, e.g., between the levels of the whole canopy and the shoot, or the levels of the shoot and the needle. The different structural levels commonly used in modeling a forest canopy are shown in Fig. 1. However, additional intermediate levels can be introduced if necessary and when data are available, e.g., those of a branch or a whorl.

If canopy structure is described as a nested Poisson process, where the hierarchical levels ("clumps") at which clumping of foliage occur are Poisson distributed, the canopy p value can be decomposed as:

$$p(\text{canopy}) = p_1 + (1 - p_1)p_2 + \cdots + (1 - p_1)..(1 - p_{n-1})p_n , \qquad (1)$$

where n is the number of levels and p_i is the probability that a photon leaving a "clump" at the hierarchical level i-1 will collide with a clump at level i. In the case with Poisson distributed trees and shoots within the tree crowns (n=3), p_1 in Eq. 1 would represent the recollision probability within a shoot, p_2 the recollision probability of a shoot leaving photon within the crown, and p_3 the recollision probability of a crown leaving photon with another crown. Smolander and Stenberg (2003) showed that a close to perfect linear relationship exists between the p value of an individual coniferous shoot (p_{shoot}) and its spherically averaged silhouette to total area ratio (STAR$_{\text{shoot}}$). Mathematically, the observed linear relationship:

$$p_i = 1 - \text{STAR}_i/STAR_{i-1}, \qquad (2)$$

where STAR$_0$=1/4 is the spherically averaged silhouette to total area ratio of an individual needle, applies to all structural levels i. Thus, the knowledge of tree-level STAR would enable to quantify the relationship between the optical properties of a forest stand and those of a single needle.

TREE CROWN MODELS

We used LIGNUM to generate 12 realistic pine trees with heights of 3, 6, 9, 12, 15 and 18 m. Two needle area configurations were used when generating the trees: "dense" and "sparse". The two configurations were chosen to simulate varying growth conditions and between-tree competition scenarios. Total (all-sided) needle areas for the generated trees varied between 15 and 200 m^2 (Table 1). The projection areas for the computer-generated trees were calculated at 15-degree steps from the horizontal direction to vertical. Using appropriate weights for the directions, we calculated the hemispherically averaged STAR$_{\text{crown}}$ (Table 1).

Next, we tested the suitability of different simple geometric crown shape models for scaling between the canopy structural levels. We divided the realistic pine tree crown (Fig. 2 left) into segments with a thickness of 30 cm, calculated the maximum extent of the crown in each segment, and represented the tree crown as a stack of cylindrical segments (Fig. 2 middle). To test the suitability of an even simpler crown shape model, we determined the maximum horizontal and vertical extents of a tree crown and modeled the crown as an ellipsoid of rotation (Fig. 2 right). We assumed a uniform distribution of shoots (exponential attenuation) within the geometric volumes to calculate the silhouette areas of the crowns.

Table 1. Basic characteristics of LIGNUM-generated trees.

Tree height (m)	3.0	6.0	9.0	12.0	15.0	18.0
Needle area (sparse) (m^2)	15.9	35.5	69.4	101.6	117.2	164.6
Needle area (dense) (m^2)	23.8	42.5	96.5	110.3	144.2	188.1
Crown STAR (sparse)	0.067	0.060	0.061	0.058	0.062	0.059
Crown STAR (dense)	0.059	0.059	0.057	0.061	0.055	0.056

Fig. 2. A sample computer-generated tree (height 9 m, sparse) and the corresponding geometric crown shapes.
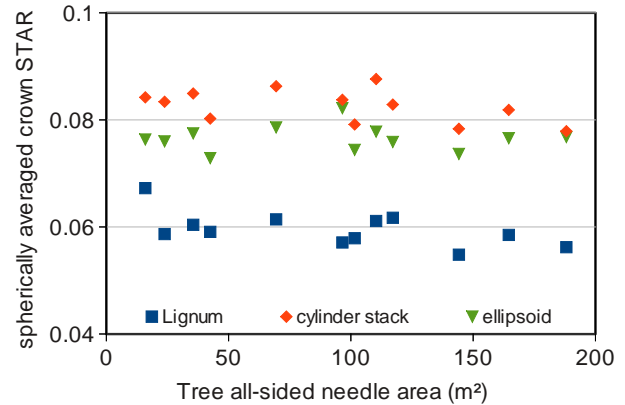

Fig. 3. STAR$_{crown}$ values calculated using the three crown models presented in Fig. 2 plotted against crown all-sided needle area.

RESULTS AND DISCUSSION

The crown STAR (and thus p) was rather independent of tree height, needle area or growth conditions (Fig. 3). Although a slightly decreasing trend with needle area may be noted, LIGNUM predicts a species-specific value of STAR$_{crown}$=0.06. The two other approaches used in the study considerably overestimated STAR$_{crown}$. However, this does not invalidate the stochastic approach (modeling tree crowns as geometric shapes filled with a random medium). Indeed, the crown shape determination method presented here was chosen to simulate a visual measurement in a forest where a person performing the measurements would determine the maximum extent of the crown at different heights. By doing so, we (and the measurer) have included a considerable amount of empty space into the crown. As actual tree crowns are not rotationally symmetric and their projected width depends on direction, using the maximum extent overestimates average crown width. Thus, we have decreased the needle area density within the crowns, increased average crown transmittance and its projected area.

The near-constant difference between the STAR$_{crown}$ values produced by the two geometric models and and LIGNUM (Fig. 3) gives evidence of the applicability of the stochastic approach (and thus also p-theory) inside individual tree crowns. However, for quantitatively accurate results, a more physical method for determining the outer shell of a tree crown has to be developed.

Interestingly, modeling the crown as an ellipsoid yields better results than the more detailed stack model. This indicates that the scaling approach based on photon recollision probability can be applied robustly with a small number of input parameters. This finding, together with the small variation in the value of STAR$_{crown}$, supports further development of the p-theory as a reliable method to connect the smallest and the largest scales in a forest canopy.

LITERATURE CITED

Perttunen J, Sievänen R, Nikinmaa E, Salminen H, Saarenmaa H, Väkevä J 1996. LIGNUM: A tree model based on simple structural units. *Annals of Botany* **77**: 87-98.

Smolander S, Stenberg P 2003. A method to account for shoot scale clumping in coniferous canopy reflectance models. *Remote Sensing of Environment* **88:** 363-373.

Stenberg P 1998. Implications of shoot structure on the rate of photosynthesis at different levels in a coniferous canopy using a model incorporating grouping and penumbra. *Functional Ecology* **12**: 82-91.