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Modeling of light transmission under heterogeneous forest canopy: model description and validation

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Introduction

Growth and survival of regeneration saplings and understorey vegetation development is closely related to light available below the forest trees. Manipulating the forest structure by thinning adult trees is a major tool to control light transmission to the understorey. The transmission is related to the attenuation of light which is usually estimated with the Beer-Lambert law assuming homogeneous foliage within the canopy. However forest canopies are far from homogeneous, which requires models that can take into account the effect of clumping between and within trees. In this work we present a model that can be readily used with both coarse or detailed parameterization to generate any type of stand and compute the distribution of light transmitted below the canopy. To evaluate the accuracy of the model, we compared model results with field measurement from several stands of *Pinus sylvestris L.* in the French Massif Central.

Material

The pine stands are located in the Chaîne des Puys, a mid-elevation volcanic mountain range (45°42' N, 2°58'E) at a place named Fontfreyde. The elevation is 900 m a.s.l., mean annual rainfall is about 820 mm, and mean annual temperature is about 7°C. The soil is a volcanic brown soil at pH 6.0 with no mineral deficiency. The pines were 30-year-old at time of measurement, with a density ranging from 500 to 4000 stem ha^{-1}. All trees in an area of 30 by 30 m were located by their x,y coordinates, and measured for their total height (14.1 ± 2 m mean ± SD) and DBH (16.3 ± 5 cm mean ± SD). Crown height was also measured. Crown extents was assessed by visually projecting to the soil its characteristic points (i.e. the points that better describe the crown irregularities) in, at least, four directions. The azimuth and distance of those points from trunk were then measured (see Figure 1).

Methods

Envelope reconstruction

To reconstruct the 3D envelopes of the trees from the field measurements, we used the PlantGL library [Boudon et al., 2001]. This library contains several geometric models, including different types of envelopes and algorithm to reconstruct the geometry of plants at different scales. For this particular case, we used the *skinned surface* implemented in PlantGL which is a generalization of surface of revolution with varying profiles being interpolated. This surface is thus built from any number of profiles with associated direction. The profiles we defined were inspired by *Cescatti* work [Cescatti, 1997]. A profile is supposed to pass through top and bottom points and an intermediate point at maximum radius. Two shape factors, C_T and C_B, are used to describe the shape of the profiles above and below the maximum width. Mathematically, two quarters of super-ellipse of degree C_T and C_B are used to define the top and bottom part of the profiles. Isopoints of the profiles are interpolated with B-Spline curves of given degree. Note that our envelopes can be viewed as extension of *Cescatti*'s asymmetric hull with profiles in any direction instead of restricted directions (cardinal directions). Flexibility of our model enables us to measure the most adequate profiles in case of irregular crowns.

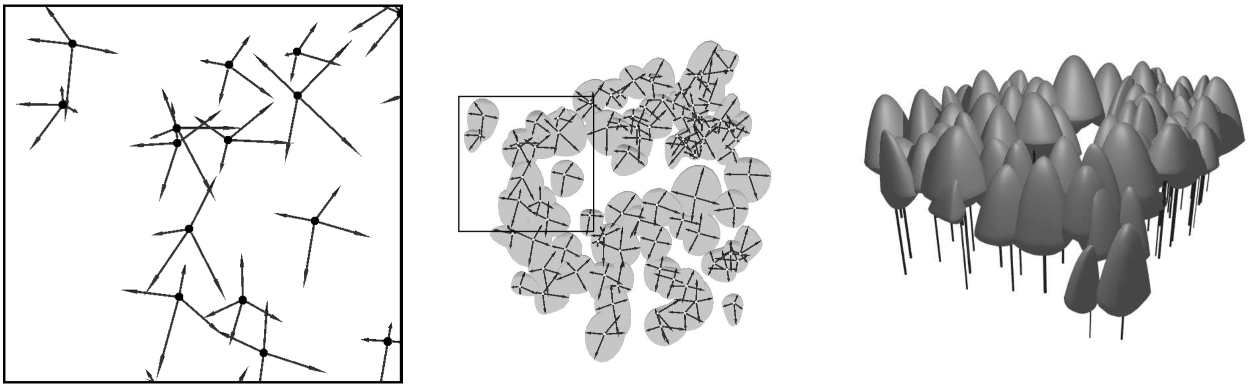

Figure 1: From left to right : Field data sample. Each circle locates a tree and each connected arrow defines a specific azimuth and distance from the tree trunk. Field data along with their matching projected crown. 3D reconstruction using *skinned surface hulls* from PlantGL library with maximum radius at the quarter of crown height and $C_T = C_B = 2$.

Light Transmission Model

The presented model derives from Oker-Blom's model [Oker-Blom et al., 1989] where crowns are considered as porous envelopes but extends it to the more complex ones described above (p.1). Light interception by a crown $\mathcal{C}$ is related to the crown projection area, $S_\Omega(\mathcal{C})$, in the sun direction Ω [Nilson, 1999]. In the case of an isolated tree, let $\mathcal{E}(\mathcal{C})$ be a convex hull of $\mathcal{C}$, we will use the projected area of $\mathcal{E}(\mathcal{C})$ as the area of interest. Hence, the fraction of light intercepted by $\mathcal{C}$, $p_\Omega(\mathcal{C})$, can be expressed as the ratio between $S_\Omega(\mathcal{C})$ and the area of interest, $S_\Omega(\mathcal{E}(\mathcal{C}))$

$$S_\Omega(\mathcal{C}) = S_\Omega(\mathcal{E}(\mathcal{C}))p_\Omega(\mathcal{C}) \tag{1}$$

$p_\Omega(\mathcal{C})$ acting as an opacity factor for the envelope of $\mathcal{C}$. In a crown, leaves can either be uniformly distributed or assigned to specific spatial positions. In the case of uniform distribution the light attenuation is a function of the distance the solar beam travels within the crown. In the other case, the attenuation depends on the relative position of the beam and the leaf. Hence we discretize the volume $\mathcal{E}(\mathcal{C})$ using a set $\mathcal{B}$ of β parallelepipedic voxels of direction Ω representing light beams. The set of beams is large enough so that the discretization does not change volume or projected area. Let $p_\Omega^b(\mathcal{C})$ be the probability for the beam b to be intercepted by $\mathcal{C}$ (i.e. the opacity of $\mathcal{C}$ for the beam b), therefore the probability that b is not intercepted by $\mathcal{C}$, $1 - p_\Omega^b(\mathcal{C})$, is a function of the number of leaves in $\mathcal{C}$ and can be expressed using Beer-Lambert law or a binomial law if leaf size is to be taken into account :

$$p_\Omega^b(\mathcal{C}) = 1 - \prod_{\ell \in \mathcal{L}(\mathcal{C})} \left[1 - p_\Omega^b(\ell)\right] \tag{2}$$

where ℓ is a leaf, $\mathcal{L}(\mathcal{C})$ the set of leaves of $\mathcal{C}$. The probability, $p_\Omega^b(\ell)$, for b to be intercepted by the leaf ℓ is known when spatial positions of leaves are taken into account; in the uniform distribution case, it can be shown that $p_\Omega^b(\mathcal{C})$ can be expressed as a function of projected leaf area, $S_\Omega(\ell)$, volume of crown, $\mathcal{V}(\mathcal{C})$, and the distance b travels within the crown, $l^b(\mathcal{C})$ [Sinoquet et al., 2005]:

$$p_\Omega^b(\mathcal{C}) = 1 - \prod_{\ell \in \mathcal{L}(\mathcal{C})} \left[1 - \frac{S_\Omega(\ell) l^b(\mathcal{C})}{\mathcal{V}(\mathcal{C})}\right] \tag{3}$$

Hence we can compute the light transmission for each beam in both cases, when position of leaves is known and when we assume an homogeneous distribution, finally global opacity for $\mathcal{C}$ is simply the mean of beam opacity.

Since Eq.(2) and (3) do not depend on scale, leaf scale is not mandatory and there is no restriction concerning the number of scales being used. This forest stand application illustrates the multi-scale approach with two scales, the finest one being the tree crown scale, and also illustrates how to take into account the finite size of a stand. Therefore, in this specific case and using above notations, $\mathcal{L}(\mathcal{C})$ is the set of tree crowns in $\mathcal{C}$ and $p^b_\Omega(\ell)$ is the opacity of the crown ℓ for the beam b that can be either computed using Eq.(2) or (3) recursively if informations on finner scale is available or set with empirical or measured value.

Results

Using this model, we computed the light attenuation for each cast beam and therefore generated a shadow map for different directions Ω; in this study we use the 46 directions sky discretization proposed in [Den Dulk, 1989]. Computations were done for the stand reconstruction (Fig.1), uniform foliage distribution hypothesis, and random positioning of reconstructed crowns in forest space. The results (Fig.2) clearly show that if we are interested in light distribution in transmission classes, the hypothesis of uniform foliage distribution does not hold and thus cannot be used to model stands (Fig.2 b.). The distribution of light transmitted by stands generated using a random spatial ditribution of the reconstructed crowns (Fig.2 c.) was much closer to the distribution found with the real stand (fig.2 a.). However, the higher gap frequency in the random stand (see transmission class of 100 %) suggests that the tree distribution in real stands is slightly more regular than random. Further investigations on spatial distribution characterisation are being done in order to obtain more simple way of recreating stands with better light interception properties.

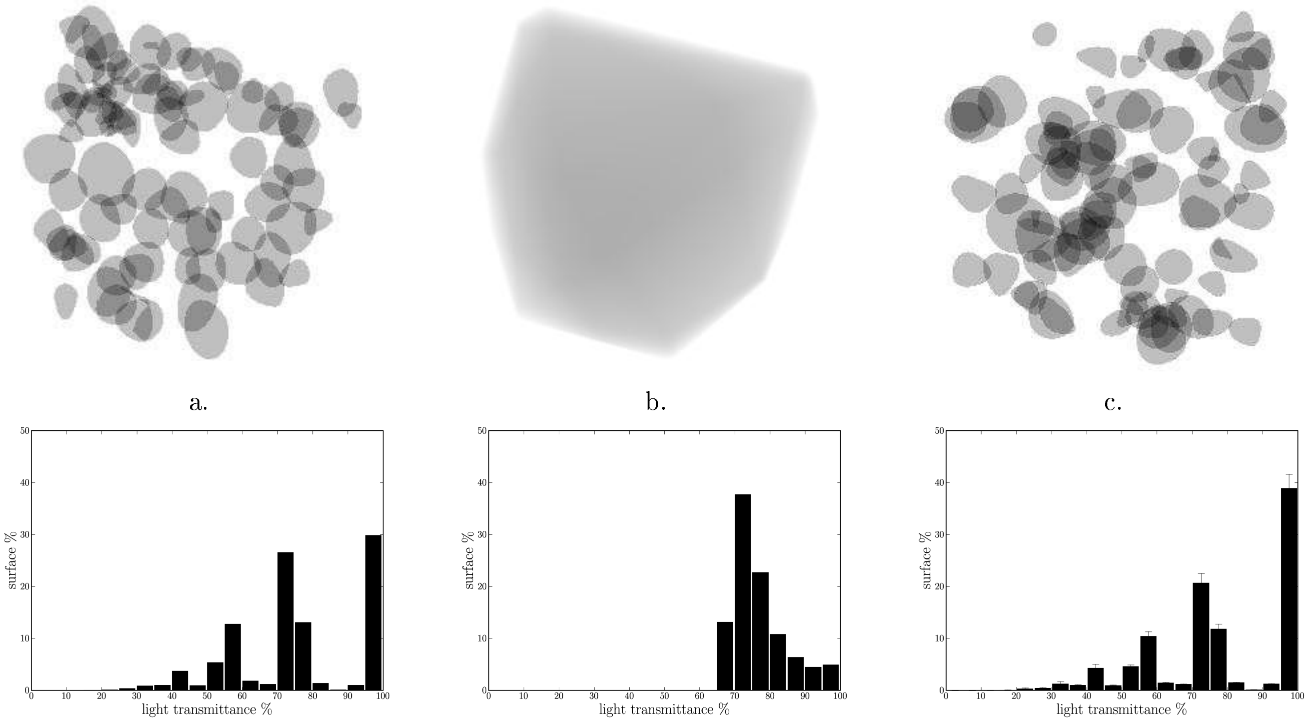

Figure 2: Top view shadow maps with associated grey level histogram of: a. stand reconstruction, b. uniform foliage hypothesis and c. one example of random distribution of reconstructed crowns, in this case the histogram shows the mean light transmitance over a set of 20 random distributions. Azimuth is 180° and elevation is 90° for all views. Each tree crown has an overall direction opacity of 0.25.

Concluding remarks and perspectives

The integration of all those directional maps onto a ground projection yields a global shadow map that will allow us to study light intensity distribution over different time period and quantify the impact of clumping between and within trees. A light mesurement campaign is being done in order to obtain data for validation purpose. This better characterization and understanding of light transmission will hopefully lead us toward simplified and efficient models.

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