Assessing the light environment for Scots pine in the functional-structural tree model LIGNUM

Jari Perttunen[1], Risto Sievänen[1] and Eero Nikinmaa[2]
1. Finnish Forest Research Institute, Vantaa Research Unit
P.O. Box 18, FI-01301 Vantaa, Finland
2. Department of Forest Ecology, University of Helsinki
P.O. Box 27, FI-00014 Helsinki, Finland
jari.perttunen@metla.fi

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Introduction

The functional-structural tree model LIGNUM (Perttunen et. al., 1996) represents coniferous and deciduous trees with simple structural units called tree segment, bud, branching point and axis that have close resemblance to real tree parts. These units model both the functioning of the tree and the dimensional architecture of a tree crown.

We present the work which aims at solving the computational problems related to the assessment of the radiation regime of the tree crown enabling us to calculate the self shading of fully developed Scots pine trees and extend our approach from a single tree to forest stands.

Light models approximate radiative fluxes received by a plant. This requires the description of radiative interactions between light and plant parts and integration of the local phenomena to whole plant structure. The complexity of the descriptions for light absorption and scattering depends on the level of detail in the structural description of the plant.

The turbid medium approaches (e.g. Sinoquet et. al., 2001) consider the transmission of light through a continuous medium. To model the spatial heterogeneousness of the foliage the canopy is divided into volume elements and the properties of the foliage contained in a volume element is described in an aggregated manner. The volume element can be for example a horizontal layer of foliage or a cubic cell also known as voxel.

The surface based approaches (Chelle and Andrieu, 2007) describe the three dimensional structure of canopy explicitly with suitable geometric elements for plant parts and foliage. The advantage is that the size, position and orientation of each plant part can be taken into consideration. The disadvantage is the computational complexity when calculating radiative fluxes on each plant part.

We have developed three alternative approaches to calculate light climate of the forest canopy in the model LIGNUM. The first two are based on turbid medium approach and the third is surface based. In addition, we simplify the approximation of radiative fluxes by considering photosynthetically active radiation (PAR) only, i.e. we assume no reflection of light from foliage but the light is absorbed and transmitted. The objective is to study consequences of using different light models for the development of tree stand when a common growth allocation method is used.

Material and Methods

Here we describe the assessment of the light environment for coniferous trees in three different ways to overcome the computational complexity for the calculation of the canopy light climate due to multiple directions of light sources and large number of shading elements causing a need for exploding number of pairwise comparison of tree segments when the number of segments becomes large (several thousands). The time step for simulations is 1 year.

Common to all methods, a model sky has been implemented where the hemisphere is divided into sectors of approximately solid angles. The incoming radiation originates from the midpoint of each sector applying the standard overcast sky radiation (SOC) distribution (Ross, 1981).

We have implemented the division of the growth space of a tree or forest stand into equal size cubic volume elements and the fast voxel traversal algorithm (Amanatides and Woo, 1987) that finds the entry and exit points of the light ray between adjacent voxels before crossing the voxel boundaries.

Method 1

The first method follows our previous work (Perttunen et. al., 2005) and ignores the geometry of the shading and shaded segments and uses the mean characteristics of foliage instead. First, the voxels each shading segment belongs to is determined by the user defined equally spaced points on the segment cylinder and the proportions of the foliage areas of the shading segments is assigned into their respective voxels. The woody parts of the segments are ignored. Secondly, incoming and absorbed radiation is assessed to the center point of each voxel using the fast voxel traversal algorithm to follow the routes of the light rays (Amanatides and Woo, 1987).

First, define the transmission $h1$, proportion of radiation going through one voxel as:

$$h1 = \mathrm{e}^{0.14 L \frac{A_f}{V_{box}}} \qquad \text{(Eq. 1)}$$

where L is the path length of the ray in the voxel, A_f the foliage area of the segments in the voxel, V_{box} the volume of the voxel and 0.14 is assumed to be the mean shoot silhouette to total area ratio or $\overline{STAR}$ (Oker-Blom and Smolander, 1988). The proportion of radiant energy, H, through N shading voxels reaching the target voxel is the production of transmissions $h1_j$ in each shading voxel:

$$H = \prod_N h1_j \qquad \text{(Eq. 2)}$$

The incoming radiant energy, I_{c_i}, reaching the target voxel from the ith sky sector is:

$$I_{c_i} = HI_0 \qquad \text{(Eq. 3)}$$

where I_0 represents the irradiance (both direct and diffuse) from the ith sky sector. The total radiant energy, I_{TOT}, reaching the voxel is the sum of the irradiances from every sector of the model sky:

$$I_{TOT} = \sum I_{c_i} \qquad \text{(Eq. 4)}$$

Finally, the total absorbed radiation, I_a^{TOT}, on one segment depends on the $\overline{STAR}$ and on the foliage area of the segment:

$$I_a^{TOT} = 0.14 A_f I_{TOT} \qquad \text{(Eq. 5)}$$

Method 2

The second method recovers the geometry of the shaded segment as in Perttunen et. al., 1998. The fast voxel traversal algorithm (Amanatides and Woo, 1987) starts from the center of the shaded segment and assesses the incoming radiation as in the first method (Eq. 1 – Eq. 3).

The amount of radiation, I_a^i, the shaded segments absorbs from the *i*th sector is then given by Perttunen et. al., 1998:

$$I_a^i = (1 - \mathrm{e}^{-K(\phi) A_f / A_C}) A_c I_0 \qquad \text{(Eq. 6)}$$

where A_f is the foliage area of the shaded segment, $K(\phi)$ defines the light beam extinction as a function of the angle ϕ between the direction (axis) of shaded segment and the direction of the light beam (Oker-Blom and Smolander, 1988). The A_C is the projection area of the segment cylinder in the direction of the light beam:

$$A_C = 2LR\cos(\phi) + \pi R^2 \sin(\phi) \qquad \text{(Eq. 7)}$$

where *L* and *R* are the segment length and radius including foliage respectively.

The total radiant energy absorbed by the shaded segment is the sum of absorbed radiation from all sectors of the sky:

$$I_a^{TOT} = \sum I_a^i \qquad \text{(Eq. 8)}$$

Method 3

The third method recovers the geometry of the shading segments (Perttunen et. al., 1998). This is achieved by caching the geometric information of the tree segments into voxels where they belong. This allows us to compute the distance light beam traverses through segment foliage along the route in the voxel space defined by the fast voxel traversal algorithm (Amanatides and Woo, 1987). The transmission *h*3 of the light beam through one segment is (Perttunen et. al., 1998):

$$h3 = \mathrm{e}^{-K(\phi)(A_f / V_f) l} \qquad \text{(Eq. 9)}$$

where V_f is the volume occupied by the foliage in the segment and *l* the length the light beam traverses in the foliage of the segment defined by the entry and exit points of the beam on the surface of the foliage cylinder. If the light beam hits the woody part of the shading segment the transmission is 0 from that sector of the sky. The proportion of radiant energy, H, through N shading segments on the path of one light beam is:

$$H = \prod_{N} h3_j \quad \text{(Eq. 10)}$$

and the radiant energy reaching the shaded segment from the ith sector is then:

$$I_{c_i} = HI_0 \quad \text{(Eq. 11)}$$

The total incoming radiation is the sum of the irradiances from all sectors of the model sky (Method 1, Eq. 4). The absorbed radiation for the shaded segment is as in the Method 2 (Eq. 6 – Eq. 8).

Allocation of photosynthates: carbon balance

The metabolism of the tree follows our previous work, assuming that photosynthesis in a segment is assumed to be proportional to absorbed radiation and respiration is proportional to biomass and tissue activity (Perttunen et. al., 1998). New growth in the tree is possible if the production of the photosynthates in the tree, P, exceeds the respiration costs of the tree, M. We assume that all net production is allocated: $P - M = iWn + iWd + iWr$, where iWn is the needle and shoot growth, iWd the secondary wood growth and iWr the root growth.

Results

We compare all three methods and assess their applicability for use in forest simulations. We present simulations of a Scots pine stand using these three methods to assess light environment. For this a 20 m X 20 m X 20 m voxel grid with 0.16 m X 0.16 m X 0.16 m sized voxels. The total amount of unshaded incoming radiant energy of PAR was 1200 MJ/m2 per year including both diffuse and direct radiation corresponding to the conditions in Southern Finland. The physiological parameters for the Scots pine are from our previous work.

To represent the forest stand 87 seven tree locations were randomly created to model initial density of 2100 trees/ha. The tree was initially 30 cm long and it was set to grow at the center of the forest in the opening with 1.0 m radius. Each growth step the tree was copied to the random locations, i.e. the forest consisted of identical trees. When the diameter at breast height (D1.3) of the subject tree exceeded 16 cm the density of the forest was reduced to 800 trees/ha. The tree (forest stand) after simulation was 30 years old.

To study the results we examined in the first instance the appearance and the general shape of the tree representing all trees in the forest stand. Secondly, we collected photosynthesis, P, and the foliage mass, W_f, and the ratio of the two to initially study the model behavior in more detail (Fig. 1).

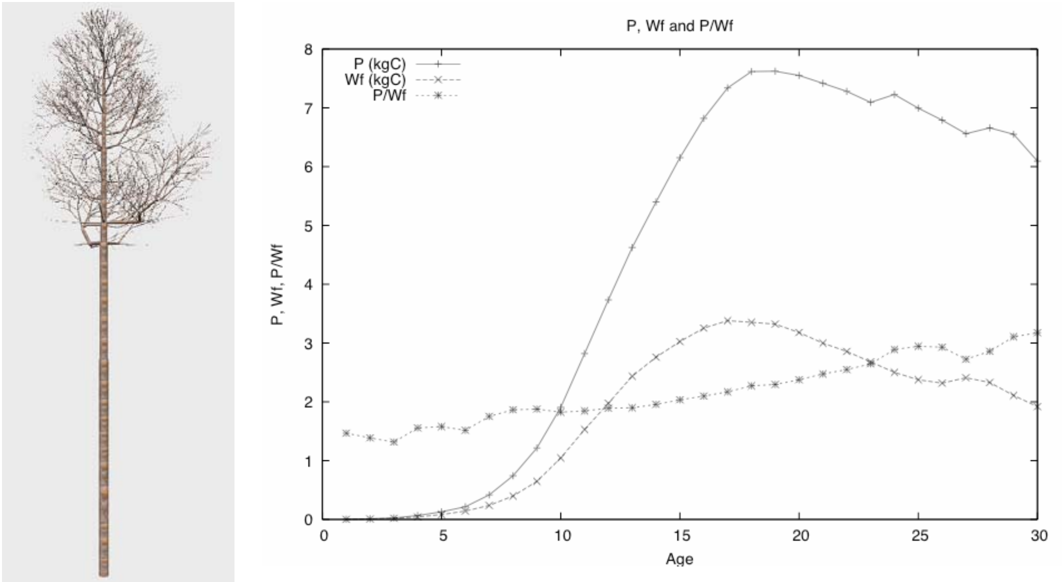

Fig 1. Left: A 30 year old simulated Scots pine with Method 3: Height = 9.4 m, D1.3 = 18 cm. Right: P, W_f and P/W_f.

The overall shape and dimensions of the tree are acceptable. It is also capable to produce the crown rise during the canopy close. The values for P and W_f are realistic. There is a slight increase in P/W_f ratio when the foliage mass in the tree starts to decrease but that too is within acceptable values.

Our work will concentrate in comparing the three methods to assess light climate in a forest stand. We will compare our results with empirical stand models and analyze the results the different light models produce. We aim in the future to develop light calculations in LIGNUM so that it can simulate within computationally reasonable time (e.g., a twenty-four-hour period) a small forest stand representing for example a research plot consisting of different trees and tree species.

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