Growth simulation of eastern cottonwood (*Populus deltoides*) using LIGNUM model incorporating real weather data

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Introduction

The model LIGNUM is a functional-structural tree model, which simulates annual development of tree biomass and structure based on carbon balance (Perttunen *et al.*, 1996; 1998; 2001). LIGNUM represents the tree architecture with simple structural units called tree segment, branching point and bud. The metabolic processes of the tree are associated directly to these elementary model building blocks. The model calculates the shading relationships between tree compartments within the 3D structure, and computes the annual interception of solar irradiance in each compartment. Intercepted irradiance is used for estimating leaf photosynthesis, and net primary production (NPP) is obtained by deducting the respiration losses in each tree compartment from the whole tree photosynthesis. Carbon allocation within the tree is estimated following the pipe model principles (Shinozaki *et al.*, 1964), i.e. according to the relationships between the growth of foliage and water conducting and supporting organs - branches and stem - needed to support it. Tree structure is updated according to the carbon allocation.

In this paper, we report application of LIGNUM model for simulating the growth and yield of eastern cottonwood (*Populus deltoides* Bart. ex. Marsh.) in a dense short-rotation plantation and a wide-spaced agroforestry system. In the cottonwood application of LIGNUM, there are also several new modelling developments including use of real weather data and a biochemically derived photosynthesis model (Le Roux *et al.*, 1999; von Caemmerer and Farquhar, 1981). We also apply different time steps for physiological processes and structure update (Sievänen *et al.*, this volume), and voxel space for estimating the interception of photon flux (Perttunen *et al.*, this volume).

The model

The previous LIGNUM versions (Perttunen *et al.*, 1996; 1998; 2001) use the annual integral of photosynthetic irradiance, and divide it over the sky using the standard overcast distribution (Ross, 1981). The cottonwood application uses real weather data, i.e. photon flux density and air temperature (T_a) recorded according to real solar time (RST) every ten minutes in the field site of the two model systems simulated (New Franklin, Missouri, USA 39°1' N, 92°46' W). The measured photon flux density is divided into diffuse (Q_d) and direct (Q_b) component using the relationship between the measured and potential global radiation (Nygren *et al.*, 1996; Weiss and Norman, 1985). The direction of Q_b is computed as a function of latitude, Julian day and RST (Gates, 1980; Ross, 1981). Photosynthesis and leaf respiration are accumulated according to the time step of weather data. The short time step of weather data improves the accuracy of simulation, especially for a fast-growing tree like cottonwood. Tree structure is updated within a cycle of weeks rather than a year. In each update time step, the model calculates and allocates NPP into tree compartments and updates tree structure. The work for defining computationally efficient yet accurate time steps for physiological processes (a fraction of day) and structure update (a fraction of growing season) is under way.

Abbreviations: Qb, incident direct photon flux density (µmol m-2 s-1); Qd, incident diffuse photon flux density (µmol m-2 s-1); Qi, intercepted global photon flux (µmol m-2 s-1); Ta, ambient temperature (°C); NPP, net primary production (kg); Al(n), projection of the leaf area in a voxel on a plane perpendicular to photon flux from sky region n (m2); Av(n), projection area of a voxel on a plane perpendicular to photon flux from sky region n (m2)

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Interception of Q_b and Q_d by leaves is determined by incident photon flux and mutual shading of leaves. The 3D growing space is divided into small volume elements, voxels. The 3D tree structure generated by LIGNUM defines the position of each leaf within the voxel space. Interception of Q_b and Q_d is calculated for the integrated leaf area in each voxel. The sky is divided into n regions. Each region has a direction and a proportion of total Q_d. The sum of the proportional values over all regions is unity. The direct flux, Q_b, is emitted from the apparent direction of the sun.

The calculation of the intercepted total photon flux, Q_i, follows the steps:

1) For each voxel, a path is traced towards each sky region and a list of voxels that are on the path is generated. Each path is used to calculate a part of Q_d from each sky region.
2) Solar position determines the direction of Q_b. A list of voxels between the sky region, where the apparent solar disc is situated, and each voxel containing leaves is generated.
3) Along each path, Q_b or directional Q_d flux components may undergo one of three transformations: (a) may be intercepted by shading voxels, which are the voxels before the current voxel in the list; (b) may be intercepted by the current voxel; or (c) may pass through the current voxel. The photon flux intercepted by a voxel is the sum of Q_b and Q_d that it intercepts from all paths.
4) A "Monte Carlo voxel" approach is used in the cottonwood model for determining flux interception. The leaf area and voxel surface area projection perpendicular to flux direction from each sky region n, $A_l(n)$ and $A_v(n)$, respectively, are calculated. The probability, (p), of the directional flux interception within the voxel is the ratio $A_l(n)/A_v(n)$. The Bernoulli process is used to determine whether the flux is intercepted by the voxel i with probability p_i:

$$\mathrm{Bernoulli}(p_i) = \begin{cases} 1 & \text{probability of 1 is } p_i \\ 0 & \text{probability of 0 is } (1 - p_i) \end{cases}$$

where 1 denotes interception and 0 is non-interception.

5) An "average" green leaf (Monteith, 1965; Ross, 1981) is used for estimating interception; in the case of interception, 80% of the flux is intercepted and 10% is transmitted through the leaf to next voxel. Reflected flux and scattering in the canopy are not considered in the current model version. In the case of non-interception, the whole flux goes through the voxel.

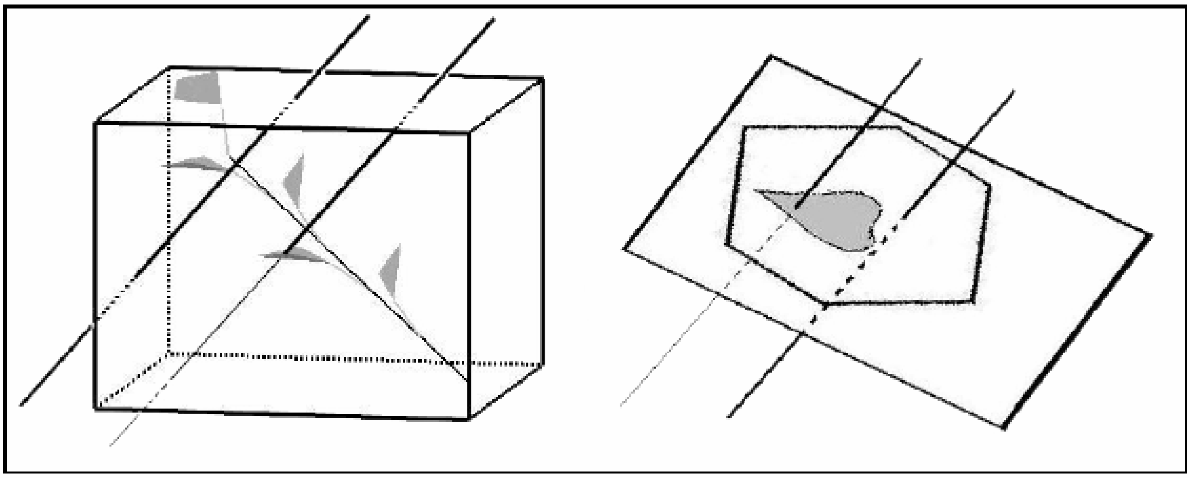

Fig. 1 Left: A voxel with a tree segment and leaves. Photon flux entering to the voxel from a sky region may pass through the voxel (thick line) or be intercepted by a leaf (thick line turning thin). Right: Projection of the voxel (polygon) and leaf area (shaded area in polygon) to the plane perpendicular to photon flux from the sky region.

Model parameterisation

Leaf photosynthesis (P) is modelled as a function of Q_i and T_a according to the Farquhar's approach (Le Roux *et al.*, 1999; von Caemmerer and Farquhar, 1981). The model parameters were determined under controlled environment at 25°C ambient temperature. The photosynthesis data were measured with an infrared gas analyser (LI-6400, Li-Cor, Inc., Lincoln, NE, USA) on cottonwood saplings in a growth chamber (Pallardy, unpublished) and analyzed with "Photosyn Assistant" software (Dundee Scientific, Dundee, Scotland, U.K.). The temperature dependence of the parameters is modelled according to Long (1991). Farquhar's model gives the instantaneous photosynthetic rate per unit leaf area per unit time. Leaf respiration rate is subtracted from photosynthetic rate to get the net C uptake. The leaf respiration rate is adjusted by T_a. Net C uptake is integrated over the leaf area of the whole tree, and NPP is estimated as the difference between foliar net C uptake and respiration by woody parts of the tree.

The short-rotation cottonwood plantation for measuring model parameters is described by Pallardy *et al.* (2003). Parameterisation data were also measured in an alley cropping experiment established adjacent to the pure plantation in 2001. Cottonwood was planted in 6 × 18 m spacing in association with white clover (*Trifolium repens* L.). No within-row canopy closure had occurred before the measurements in summer 2002 and 2003.

Results and discussion

The LIGNUM model has been previously applied to several coniferous and broad-leaved tree species. In order to apply LIGNUM to a new species, it is important to capture the essential features of tree growth and to quantitatively measure the structural and physiological parameters for that species.

The cottonwood modelling applies the L-systems (Pruzinkiewicz, 2001; Pruzinkiewicz & Lindenmayer, 1990) combined with the tree segment approach of LIGNUM (Perttunen *et al.*, 2001) for structural development. The branching rules of cottonwood were derived from field data. The cottonwood branches have random azimuth distribution and upwards inclination of 36 ± 13.7° (mean ± std dev.). The LIGNUM default of pipe model theory is used for diameter increment, which provides satisfactory results. The 3D tree structure enables accurate simulation of mutual shading and Q_i in the tree. The physiological processes are used for estimating NPP available for growth.

The new developments in LIGNUM are expected to improve the growth modelling of cottonwood. The Monte Carlo voxel model provides a stochastic method for simulating photon flux interception. In each voxel, the average green leaf is used to determine the likelihood that a voxel intercepts the flux. The area and angle of the average green leaf in the voxel are derived from the observed relationship between segment direction and leaf angle in field data. The average green leaf simplifies the estimation of Q_i. The link to real weather data is expected to provide better convergence of model results with realworld tree growth. The time step of a fraction of growing season for structure update fits well for simulation of fast-growing cottonwood.

The modelled cottonwood structure appears to satisfactorily respond to the differences between the dense plantation and wide-spaced alley cropping (Fig. 2). Self-pruning starts in an early phase of stand development, while branches in alley cropping continue growth in whole canopy length and relatively uniformly in all directions.

The cottonwood version of LIGNUM model is still under development. All necessary submodels are programmed and parameterised, but additional work is needed for improving computational efficiency. While the use of voxel space considerably speeds up estimation of Q_i compared to earlier LIGNUM versions (Perttunen *et al.*, 1996; 1998; 2001), the use of real weather data and short time step for estimating NPP increase the actual computational requirements. The final length of the time steps needs to be defined as a function of result accuracy and available computational resources.

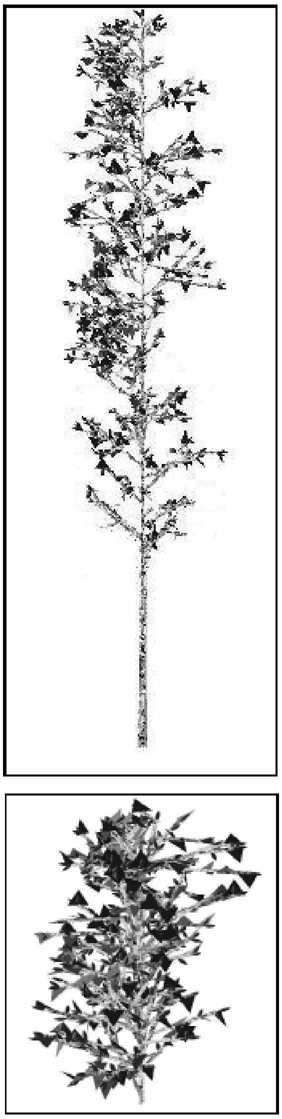

Fig. 2 A cottonwood tree growing in the dense short-rotation plantation (top) and in the wide-spaced alley cropping system (left). The tree in the dense plantation has longer segments than the alley cropping tree. Branch inclination angles are more widely distributed in the alley cropping than in the plantation. Because of mutual shading, the plantation trees develop tall and narrow canopy, while alley cropping trees remain relatively low and branches develop in whole stem length.

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