Mechanistically-based functional-structural tree models for simulating forest patch response to interacting environmental stresses

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The number of interactions among environmental factors and plant genetic constraints makes an assessment of plant responses to global change factors difficult to solve by experimentation alone. Mechanistically-based Functional-Structural Plant Models (FSPMs) however, have the potential to predict the effects of subtle interactions among environmental driving variables on key physiological processes, and consequently, growth and response to environmental stress.

To further our understanding of interacting environmental effects on plant systems, we developed a simulation modeling approach that extends ECOPHYS, an established detailed physiological model of *Populus*, to the complex branch and root architectures and carbon allocation patterns that develop over multiple years under interacting environmental stresses. To achieve this extension of the model we have developed a scalable strategy for running object-oriented submodels in parallel across a distributed network of workstations and, more recently, a small "Beowulf"-class cluster of networked Linux computers. These models incorporate several components of global change, including sensitivity to atmospheric trace gasses such as ozone. Our work is closely coupled with the Aspen FACE experiment, a large-scale experimental facility assessing the interacting effects of elevated ozone and carbon dioxide on aspen forest ecosystems (Dickson et al. 2000). Here we detail recent developments in this modeling approach as they relate to modeling tree architecture, light interception, ozone response, carbon transport processes, and ultimately, tree growth under different stress scenarios.

Light Interception

One of the significant challenges of modeling photosynthetic response is quantification of the light environment at the individual leaf level an appropriate time scale. There have been a variety of methods for simulating light attenuation through the canopy, from the individual leaf shading calculations found in ECOPHYS to voxel-based calculations found in CANLIP, to simple applications of Beer's Law. Selection of appropriate model involves the balance between the desired level of precision and the computational complexity of the model. However, it is apparent that the nonlinearities found in most photosynthetic models make them sensitive to errors in the input variables.

Recent advances in computer hardware and alternative approaches to shading calculations have made the calculations of light interception in dense tree canopies a much more tractable problem. The widespread use of OpenGL, and the concomitant development of graphics cards designed to process OpenGL code provides a means to draw and then query graphics images. For example, using OpenGL one can assign unique colors to individual leaves, project them onto a plane, and then query the image to determine how many pixels of individual colors were displayed. This lead to the development of OpenGL-based shading algorithm that accepts leaf coordinates and solar position as inputs and returns the shaded area of each leaf as an output; using code processed within the CPU and memory of a graphics card. The algorithm proved to be quite accurate on the development platform, however, results were inconsistent across different graphics cards. Thus, OpenGL 'standards' are not consistent across platforms, reducing the utility of this technique as a general solution to leaf shading. (Tordsen 2003). A Dynamic Canvas-Building Algorithm (DCBA) now incorporated into ECOPHYS has dramatically improved the speed and accuracy of shading calculations (Guan 2002), and we have adapted image analysis techniques to allow for testing and calibration of light interception models (Stech et al. this session).

Carbon Allocation and Tree Architecture

The simulated architecture of trees is based on a number of genetically-defined routines which cover factors such as initial branch angles and angles of curvature, in combination with branch-level carbon allocation routines and modified by branch productivity. Branch productivity is used to calculate a probability of bud or branch mortality. These probabilistic submodels allow for the development of realistic canopy architectures, in that the shaded portions of the canopy will experience more branch mortality, and subsequently be more open compared with more sunlit parts of the canopy. We are currently working with C14 radiotracer data to determine how branches in different parts of the canopy allocate carbon to various sinks. Additionally, we have partnered with other researchers to evaluate alternative means of simulating carbon transport (Laconite, Isebrands, and Host 2002).

Plant Ozone Response

Plant ozone responses are genotypically specific, and consequently, the ability to predict ozone effects at a stand level requires an understanding of species-specific ozone responses. We have created a process-based ozone response model that incorporates the effects of ozone on the photosynthetic parameter V_{cmax} after a threshold exposure level is exceeded. We have evaluated this process model against the response of an ozone-sensitive aspen clone subjected to a square-wave ozone treatment (Martin et al. 2003). Ozone effects included a greater effect on stem diameter than on stem height, earlier leaf abscission, and reduced stem and leaf dry matter production at the end of the growing season.

Simulation Modeling

Growth and phenological data from 1998-2000 have been used to parameterize various submodels within ECOPHYS. Early results calibrated against 3rd yr control data show a significant height growth response to elevated CO_2 that was damped with ozone (Roskoski et al. 2002; Figure 1). The FACE data from 1998 do not show a significant response, but these trees were subjected to a *Venturia* infection that caused terminal dieback (W. Mattson, personal communication). The CO_2 trees also experienced dieback due to a delayed budset.

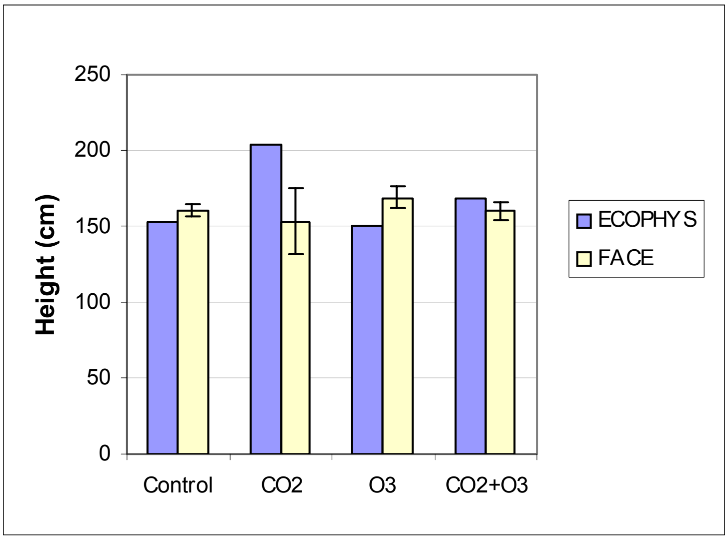

Figure 1. Height growth comparison between simulated and field measurements for two-year-old aspen clone 259. Field data from Isebrands et al. 2001.

Patch Shading Algorithms

We have developed a strategy for delivering multiple tree canopies to the ECOPHYS shade server. The approach allows us to vary the spacing among trees, and simulate aboveground competition for light.

The target spatial extent of the model is an interacting patch of 16-25 trees at approximately 1 m spacing, corresponding to the initial stem density of the Aspen FACE experiment. This initial tree density is also roughly equivalent to densities of native aspen-birch regeneration the first season following disturbance (~10,000 stems/ha). Our target temporal extent is eight years, the age of the FACE experiment at the end of this grant cycle, which represents (i) the degree of canopy complexity and numbers of leaves that we can reasonably expect to simulate under current technologies and (ii) the temporal and spatial scales beyond which stand-scale models will effectively simulate the desired ecosystem response.

We have developed several methods for simulating above-ground competition with varying degrees of precision – these range from replicating with translations and rotations to form a homogeneous patch (easy but imprecise; Figure 2) to growing a population of trees with individual model runs, and access daily 3D leaf files from previous runs as an inputs to a patch model (more precise but computationally intensive). Early results show for two-year old aspen stands, neighbors exert significant effects on overall light interception at low sun angles (Figure 3). We anticipate that as canopy height and complexity increase, this effect will extend to mid-day hours. Global change factors that influence canopy architecture and photosynthesis (i.e. ozone) will likely alter these competitive interactions among clones.

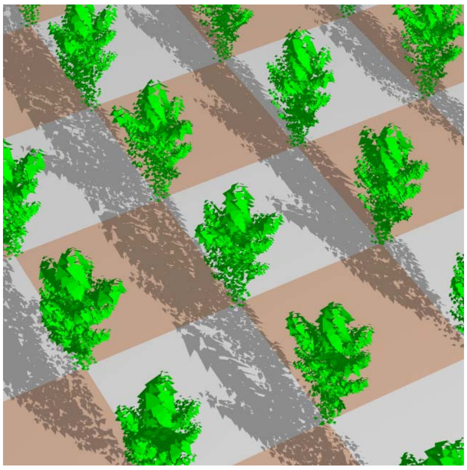

Figure 2. Homogeneous patch of 2-yr old aspen 259 trees at 1 m spacing.; rendered with the POVray ray tracing program by H. Stech.

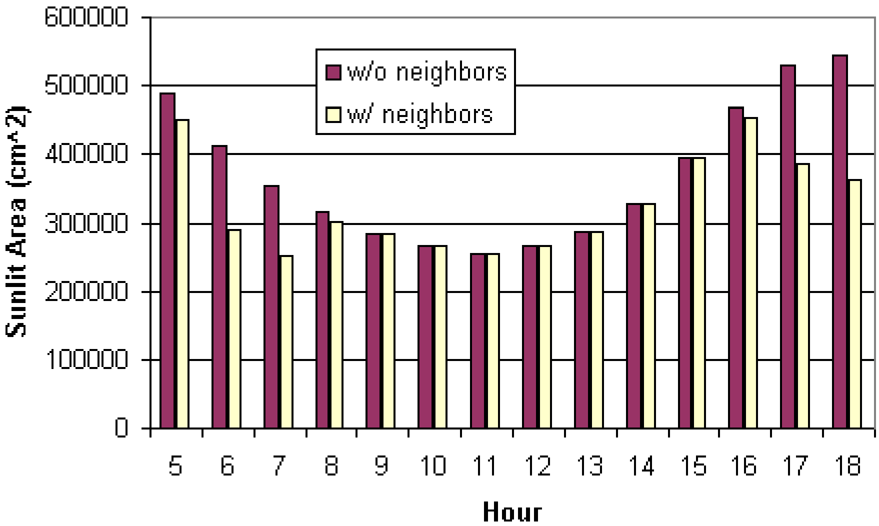

Figure 3. Differences in canopy sunlit area with and without neighboring trees. Two year old aspen, Julian Day 233.

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