Leaves to landscapes: using high performance computing to assess patch-scale forest response to regional temperature and trace gas gradients

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Keywords: Photosynthesis, process model, ozone, patch model

Introduction

ECOPHYS is one of the early FSTM's that integrated plant physiological and tree architectural models to assess the relative importance of genetic traits in tree growth, and explore the growth response to interacting environmental stresses (Host et al 1999, Isebrands et al 1999, Martin et al 2001). This paper will describe extensions of the ECOPHYS individual tree model to the scale of tree patches distributed across a regional landscape. The complexity of quantifying hourly light interception within the patch canopy has required the use of various high-performance computing platforms. Additional extensions include advances in photosynthesis modeling, strategies for simulating photosynthetic response to increased atmospheric ozone, and validation of tree growth characteristics with experimental data on *Populus tremuloides* from the Aspen FACE experiment (Rhinelander, WI, USA; Karnosky et al 2003). These advances have led to the ability to use the patch model to simulating changes in forest productivity under 20 and 40 year ozone forecasts across the north central United States.

Parallel Computing

We have implemented a parallel modeling strategy to run simultaneous individual tree models across an N x N patch of trees. The patch consists of "core" trees, which are individually-simulated instances of trees with varied physiological and phenological characteristics, surrounded by rings of "neighbor trees", with canopies created as translates of the core trees. The patch thus represents a 'closed canopy' in which interactions among trees with different attributes and environmental sensitivities, and resulting patch-level responses, can be assessed.

The parallel routines use the standard Message Passing Interface (MPI) Library, and run on 1 to *n* number of computer processors. In the current implementation, a cluster of computer processors collaborates on each simulation, with individual computer processors exchanging canopy information daily. Direct and diffuse radiation are derived from measured weather traces in conjunction with hourly temperature, relative humidity, and atmospheric CO_2 and O_3 concentrations to predict individual leaf photosynthate production and respiratory loss. At the end of each day, photosynthates are distributed via a carbon allocation model (Martin et al 2001, Laconite et al 2002) and used for growth of leaves and branches. Updated canopy information from each processor is then distributed to other processors in the cluster, and the process is repeated for the duration of the simulation.

The code has been tested on patches with core sizes up to 6 x 6, and with simulation lengths of up to 6 years. Code testing has been performed on a small "Beowulf" class cluster located at the University of Minnesota Duluth Visualization and Digital Imaging Laboratory. The model is numerically tractable even on "clusters" consisting of a single Linux computer possessing only two processors. Simulations have also been performed on the high-performance facilities of the Minnesota Supercomputer Institute (MSI), as well as a heterogeneous cluster of networked Linux workstations. Simulating a 6x6 core patch (36 individual trees; 324 trees in full canopy) for three years takes approximately six minutes on our cluster of networked Linux workstations, and one minute using the BladeCenter supercomputing cluster at MSI. A 6x6 patch run for five years at MSI requires approximately eight minutes. The diversity of tree architectures resulting from different clonal attributes and inter-tree interactions are shown in Figure 1.

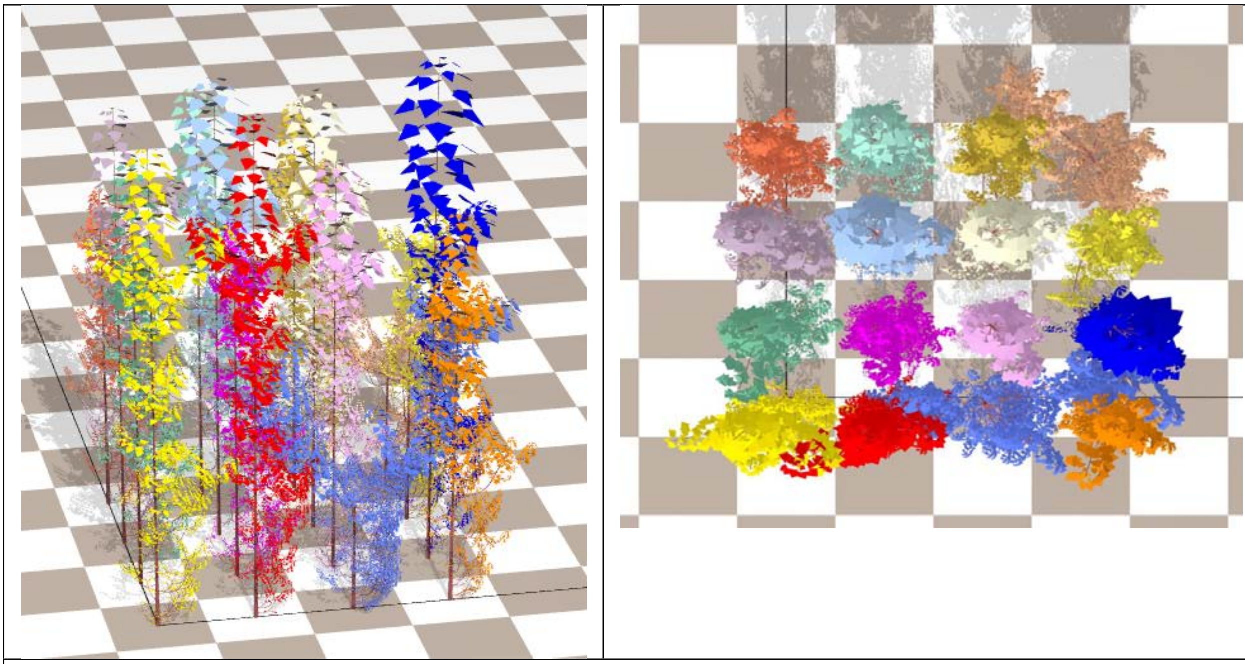

Figure 1. Side and top views of the canopies of a 4x4 patch during the third season of growth. Images are rendered using POV-RAY, a public domain visualization and animation package.

The ability to simulate multiple trees provides the opportunity to assess the sensitivity of the model to key tree and patch scale attributes. Patch attributes include tree spacing patterns, the size of the core patch, and the number of shade rings. These attributes were evaluated under different environmental conditions and with different species characteristics to quantify the relative importance of individual variables and identify interactions among variables; we have employed a fractional factorial design to identify the most sensitive combinations of patch, environmental and tree variables. Tree spacing, parameters of the random leaf drop algorithm and weather year were among the most influential factors; the size of the core patch did not strongly impact growth response variables.

Ozone Modeling

We have developed a model of ozone damage that adds new elements to the model of Martin et. al. (2001); the model views leaf photosynthetic health as an aggregate, dynamic quantity that is reduced by the presence of ozone-produced reactive oxygen species (ROS), but may improve due to various leaf repair mechanisms. The revised model allows for scavenging of ROS as well as repair or recovery of photosynthetic tissues. The resulting ozone damage/leaf recovery model was integrated with a photosynthesis production model. The augmented system couples stomatal conductance, internal CO_2 concentration, the rate of CO_2 fixation, leaf photosynthetic mechanism "health" and leaf (aggregate) ROS concentration. The system has been shown to be numerically solvable using the mathematical package *Mathematica,* and has been validated by comparing model simulations to a variety of chamber studies taken from the literature – it is currently being calibrated with leaf gas exchange data from *Populus tremuloides* published by Noormets et. al. (2001).

Landscape-scale modeling

The patch model has been applied to regional ozone concentrations projected to 2020 and 2040, under warm/dry (1999) and cool/wet (2001) seasonal weather traces (Fast and Heilman 2005). Ozone concentrations were projected over a 12 x 12 km grid, which was resampled to approximately 40 x 40 km cells, resulting in ~1500 data points distributed across the north central United States. The underlying photosynthesis model in ECOPHYS was modified to simulate water stress effects, following Wang et al. (2001). Water stress (fw) is derived from soil moisture content (θs) relative to the wilting point (θmin), and the field capacity (θmax). Soil moisture content values were obtained from the US National Data Climate Center; we used a linear interpolation between monthly points to determine a value for soil moisture content each day. The fw value reduces photosynthate produced by scaling the Vcmax and the Jmax values within the photosynthesis model. A series of approximately 1500 patch runs across a three-state region of the northern United States showed significant variation related to weather gradients, soil moisture characteristics and regional seasonal trends in ozone exposure (Figure 2).

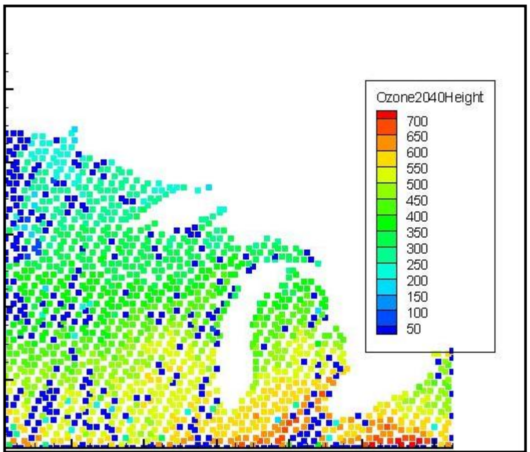

Figure 2. Average height (cm) of a *P. tremuloides* patch under a projected ozone scenario for Yr 2040. Region extends from Minnesota to Ohio, USA.

Acknowledgements

This work was funded in part by the Northern Global Change Program of the USDA Forest Service Award# 05-CA-11242343-036 and the USDA Forest Service North Central Research Station Integrated Program, Agreement 03-JV-11231300-086.

Literature Cited

Fast, J. D and W. Heilman. 2005. Simulated sensitivity of seasonal ozone exposure in the Great Lakes region to changes in anthropogenic emissions in the presence of interannual variability. Atmospheric Environment 39:5291-5306.

Host, G. E., G. W. Theseira, C. Heim, J. G. Isebrands and R. Graham. 1999. EPIC-ECOPHYS: A linkage of empirical and process models for simulating poplar plantation growth. In: (A.

Amaro and M. Tome Eds.) Empirical and Process Models for Forest Tree and Stand Growth Simulation. Edicos Salamandra pp. 419-429.

Isebrands, J. G., G. E. Host, K. McTavish and K. E. Lenz. 1999. Modeling short-rotation forest plantations using hierarchical, parallel computing: A developmental history of ECOPHYS. In: (A. Amaro and M. Tome Eds.) Empirical and Process Models for Forest Tree and Stand Growth Simulation. Edicos Salamandra pp. 537-51.

Karnosky, D.F., D.R. Zak, K.S. Pregitzer, C.S. Awmack, J.G. Bockheim, R.E. Dickson, G.R. Hendrey, G. E. Host, W.S. Jones, J.S. King, B.J. Kopper, E.L. Kruger, M.E. Kubiske, R.L. Lindroth, W.J. Mattson, E.P. McDonald, A. Noormets, E. Oksanen, W.F.J. Parsons, K.E. Percy, G.K. Podila, D.E. Riemenschneider, P. Sharma, A. Sober, J. Sober, S. Anttonen, E. Vapaavuori, and J.G. Isebrands. 2003. Tropospheric O_3 moderates responses of temperate hardwood forests to elevated CO_2: A synthesis of molecular to ecosystem results from the Aspen FACE project. Functional Ecology 17:289-304.

Laconite, A., J. G. Isebrands, and G. E. Host. 2002. A new way to account for the effect of source-sink spatial relationships in whole plant carbon allocation models. Canadian Journal of Forest Research 32:1838-1848.

Martin, M. J., G. E. Host, K. E. Lenz, and J. G. Isebrands. 2001. Simulating the growth response of aspen to elevated ozone: a mechanistic approach to scaling a leaf-level model of ozone effects on photosynthesis to a complex canopy architecture. Environmental Pollution 115: 425-436.

Noormets, A., A. Sober, E.J. Pell, R.E. Dickson, G.K. Podila, J. Sober, J.G. Isebrands, and D.F. Karnosky, 2001. Stomatal and non-stomatal limitation to photosynthesis in two trembling aspen (*Populus tremuloides Michx*.) clones exposed to elevated CO_2 and/or O_3. Plant, Cell and Environment 24:327-336.

Wang, Y.P., R. Leuning, H.A. Cleugh, and P.A. Coppin. 2001. Parameter estimation in surface exchange models using non-linear inversion: how many parameters can we estimate and which measurements are most useful? Global Change Biology 7: 495-510.