HIERARCHICAL, PARALLEL COMPUTING STRATEGIES USING COMPONENT OBJECT MODEL FOR PROCESS MODELLING RESPONSES OF FOREST PLANTATIONS TO INTERACTING MULTIPLE STRESSES

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Abstract

Process models are powerful research tools for assessing the effects of multiple environmental stresses on forest plantations. These models are driven by interacting environmental variables and often include genetic factors necessary for assessing forest plantation growth over a range of different site, climate, and silvicultural conditions. However, process models are usually detailed and present complex modelling challenges that require innovative computing approaches. The authors have developed a hierarchical, parallel computing strategy for modelling forest plantations growing under multiple stresses. The strategy utilizes object-oriented programming to achieve computational efficiencies through distributed processing within a parallel computing network using the Microsoft Component Object Model (COM). The authors present this strategy as an alternative for process modelling of forest plantations.

Introduction

Forest plantations experience an onslaught of interacting multiple stresses that affect their growth and productivity. These stressors often include both natural, and human-caused environmental disturbances such as global climate change

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(Isebrands *et al.*, 1999b). Assessing the effects of multiple interacting stressors on forest plantations is an exceedingly complex task and is virtually impossible to accomplish experimentally. Therefore, forest managers and scientists are increasingly making use of process models to help understand and predict the growth of trees in a changing environment (Isebrands *et al.*, 1990; Landsberg & Gower, 1997; Isebrands *et al.*, 1999a). Process models are driven by interacting environmental variables, and often include genetic factors to assess growth over a range of different sites, climate, and silvicultural conditions (Isebrands & Burk, 1992). Because process models are driven by physiological processes rather than empirical relationships, they can be used to extrapolate model results beyond the data used to develop the model, as well as to larger spatial and temporal scales (Jarvis, 1993; Host *et al.*, 1994, 1996; Isebrands *et al.*, 1996). However, a major constraint to detailed process modelling is the computational demands required to integrate complex processes occurring at multiple temporal and spatial scales (Field & Ehleringer, 1993) across large numbers of individual processing elements (Fig. 1). In trees, individual leaves are the primary receptors of environmental stress (Dickson & Isebrands, 1991); leaves within the canopy vary in photosynthetic rates, light interception ability, nitrogen content, and numerous other attributes. Similarly, individual tree roots exist in a heterogeneous soil matrix, each exposed to differing moisture and nutrient regimes, as well as to fine-scale variation in soil texture and structural properties. Moreover, complex interactions and feedbacks occur between the aboveground and belowground portions of the plant: these relate to the carbon demand of roots, the ability of the root system to differentially supply nitrogen to leaves in different portions of the canopy, or the control of whole-plant transpiration by plant water potential and stomatal regulation. The task of modelling these interactions is further amplified when questions are asked at a higher scale, *i.e.*, the higher order interactions of individual trees competing in a patch stand (Host *et al.*, 1996).

We have developed a detailed whole-tree growth process model for the genus *Populus*, known as ECOPHYS (Rauscher *et al.*, 1990; Natural Resource Research

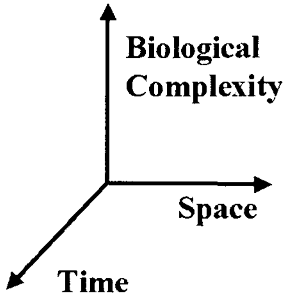

Fig. 1. Prediction and analysis of forest plantation's response to multiple stresses involves scaling a biological complex system both spatially and temporally.

Institute, 1999). ECOPHYS operates at the individual leaf level on an hourly time step. Photosynthates produced at the individual leaf level as a function of hourly light and temperature serve as inputs to a photosynthate production model. The interception of direct beam solar radiation is calculated geometrically by accounting for the position of a leaf in three-dimensional space, the position of the sun in a given hour, and the mutual shading from their leaves. As the tree grows, shading becomes increasingly complex. The photosynthate model parameters are genetically determined and vary with leaf age (Host *et al.*, 1990). The model implements both a hyperbolic model of the light response curve, as well as a RUBISCO-based model of the light-CO_2 response surface. Photosynthates are transported upwards to younger leaves and internodes, and downward to lower stem internodes and roots using a detailed experimentally derived carbon allocation matrix (Rauscher *et al.*, 1990). The net photosynthate allocated from multiple leaves is used to increase dimensional growth and biomass of leaves, stem internodes, and roots. The growth process continues on an hourly basis, accounting for temperature effects and respiratory losses. ECOPHYS also has a belowground component that simulates movement of water and nutrients in three-dimensional space as a function of soil water potential, and allows for differential uptake by a heterogeneous three-dimensional root growth submodel (Theseira *et al.*, 1999). Root architecture is based on a relaxed fractal algorithm for carbon allocation coupled with genetically determined branching rules; roots are tracked by position and order using a tree structure (Host *et al.*, 1996). Outputs of the model include cumulative whole-tree photosynthate production, leaf area development, biomass by component, and other mensurational variables.

Initially, ECOPHYS operated as an aboveground, branchless tree in its establishment year (Rauscher *et al.*, 1990). To scale the original ECOPHYS model to a multi-year branched tree, we translated the model from the original compiled BASIC and C programming languages into C++, an object-oriented language (Host *et al.*, 1996, 1999; Isebrands *et al.*, 1999a). These changes allow the model to run at larger spatial and temporal scales. Unlike the array-based structures of traditional programming languages, object-oriented data structures can be organized hierarchically, and relate to the biological organization of trees. Object-oriented program (OOP) languages integrate the data and the procedures for a given structure into a single entity (Isebrands & Burk, 1992). The use of OOP allows us to encapsulate the properties and behaviors of individual plant components (leaves, internodes, roots, branches) in self-contained 'objects', which simplifies programming, allows us to emulate the natural hierarchical organization of plants (leaves within branches, branches within the tree, trees within a patch) in the programming approach (Fig. 2), and allows us to extend the model in time and space (Host *et al.*, 1996). A detailed account of the object-oriented version of ECOPHYS is given by Host *et al.* (1999). OOP approaches are currently being used for modelling large-scale complex forest ecosystems (Vaisanen *et al.*, 1994).

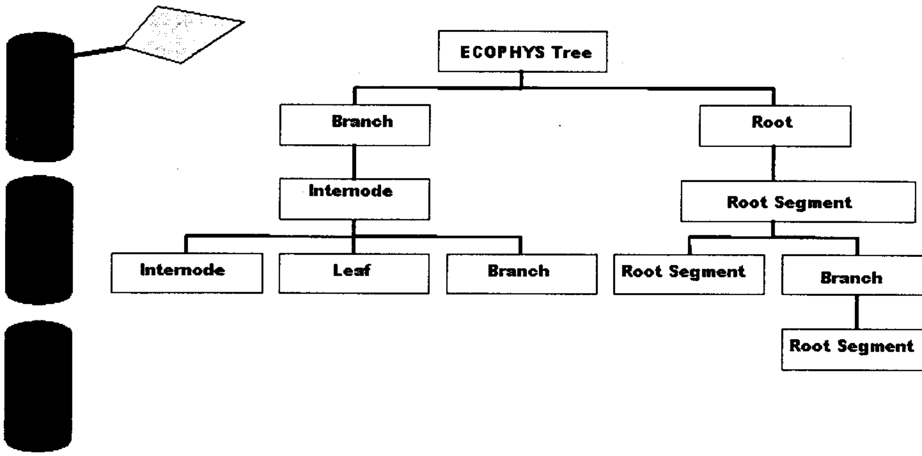

Fig. 2. Organization of ECOPHYS objects showing aboveground and belowground tree with leaves, internodes, branches, and roots. (Reproduced from Host *et al.*, 1999, by courtesy of the publisher.)

Scaling the ECOPHYS model in time and space, however, presents problems that are not easily resolved, even through OOP. First, while processes such as light interception, photosynthesis, and carbon allocation are concurrent throughout the plant, a single-processor approach requires that these process calculations be done in a serial fashion. As the number of branch and root orders increases exponentially (Fig. 2), this not only results in slow run-times, but also generates problems related to processing order. For example, many roots can occupy an individual soil cell. If roots are extracting available soil moisture based on their position in an array, those at the end of the array may occupy soil that is at the wilting point. The approach of progressively dividing operations to accommodate serial processing problems is not only computationally inefficient, but is counter to the biological organization of the plant; a parallel computing approach to individual-based models would be more realistic and expedient (Isebrands *et al.*, 1999a). Moreover, at larger spatial and temporal scales, such as simulating interactions among individual trees, a parallel approach could explain process dynamics not evident when individual model components are aggregated.

To extend the ECOPHYS model to larger trees growing in plantations, we have developed a hierarchical, scalable computing strategy for running object-oriented models in parallel across a distributed network of workstations. Our approach is based on a Component Object Model (COM) specification (Microsoft Corp., 1999; Smith, 1999). We created a suite of modular, object-oriented applications that allow different tasks of the plant growth simulation to be accomplished in parallel over a network of microcomputers, substantially reducing processing time. This approach is new to the forest growth process modelling community. In this paper we outline a parallel computing strategy using COM for process modelling responses of forest plantations to interacting multiple stresses.

Approach

What is COM?

Component Object Model (COM) is a new Microsoft Corp. component technology (Microsoft Corp. 1999) that allows the modeller to create customized modular, object-oriented, computer applications (Smith, 1999). With COM, it is possible to implement parallel and distributed computation over a multiple computer network. COM supports distributed objects, allowing a single computer application to be divided into a number of different component objects that are run on an ensemble of parallel computers. Thus, the modeller can decompose a complex system (*i.e.*, forest plantation) into interacting objects with clearly defined boundaries. The decomposition of the system being modeled allows one to separate the internal dynamics within a particular system object (*e.g.*, leaf) from dynamics external to that object. One important characteristic of COM is location transparency. This transparency allows modellers to use objects in precisely the same manner, regardless of whether they are being processed locally or remotely (*i.e.*, kilometers away). Thus, COM overcomes some of the aforementioned limitations of OOP and provides a means to use and integrate existing models without concerns of computer language and operation system dependency. For more details on COM, the reader should see Microsoft Corp. (1999) and Smith (1999).

We are using COM to extend the ECOPHYS model the first three years of a tree growing under multiple stresses (Fig. 3). We have developed a hierarchical, scalable strategy for running object-oriented models in parallel across a distributed network of workstations. We also have an initial implementation for a plant growth regulatory system, and mechanisms for evaluating and distributing model results (Isebrands *et al.*, 1999).

Applying COM to ECOPHYS

Our present object-oriented version of ECOPHYS enables us to model a patch of individual *Populus* trees growing under ideal conditions (Host *et al.*, 1999). Our motivation for applying COM to ECOPHYS was to adapt it to address a multitude of constraints and feedbacks resulting from interacting multiple stressors distributed over a complex temporal and spatial system (Fig. 1). By utilizing COM, we were able to: *1.* boost the re-usability of our model components; *2.* insert useful modular model components (*i.e.*, weather generator); *3.* extend our object-oriented approach (*i.e.*, C++ links); *4.* encapsulate our model implementation within a standard set of interfaces; and *5.* develop a distributed processing system with multiple parallel processors. Based on the COM specification, we created a suite of modular, object-oriented applications that allow different tasks of ECOPHYS growth simulation to be accomplished in parallel over a network of microcomputers, substantially reducing processing time (Fig. 4).

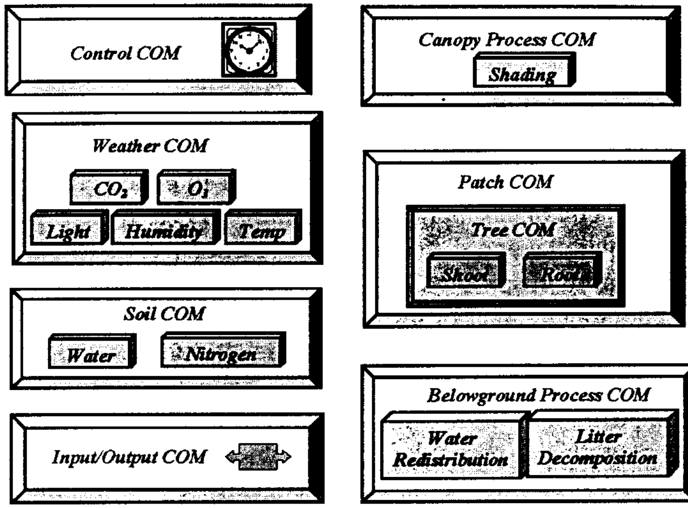

Fig. 3. Schematic diagram of distributed ECOPHYS using Component Object Model (COM) structure.

An example: ECOPHYS shading

The greatest improvements in ECOPHYS model efficiency have been made by allowing for the simultaneous calculation of leaf shading in each hour of the day. Growth in the model is driven by photosynthates produced at the individual leaf level as a function of hourly light temperature, humidity, and CO_2 concentration. Leaf-level photosynthate production depends on interception of direct beam and diffuse solar radiation that is calculated based on the orientation of leaves in three-dimensional space, the position of the sun in a given hour, and the mutual shading from other leaves (Host *et al.*, 1990). Because the numbers of branch orders and leaves increase geometrically with tree age, the individual-leaf shading calculations provide the greatest computational load in the simulation, accounting for over 70% of the seasonal computational run time. Assuming leaf orientation and size are relatively constant from hour to hour, the amount of light intercepted by the tree is independent of light intercepted in the previous hours in a day, allowing light interception for each hour to be processed in parallel. Consequently, we developed an out-of-process shading COM object that calculates the shaded and sunlight proportions of an array of leaves, and have deployed this object across a microcomputer network (Fig. 4).

To illustrate the use of COM in the distribution of the more computationally demanding aspects of ECOPHYS, Table 1 describes the allocation of leaf shading calculations to an ensemble of remote processors. The hardware ensemble for

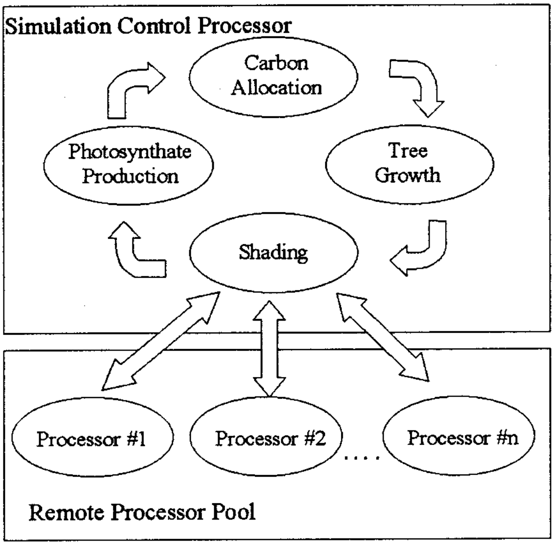

Fig. 4. Flow diagram of daily ECOPHYS cycles to the control and remote processor pool. The shade processors are dedicated to hourly shading tasks, and the control processor assists in shading, as well as in performing all other simulation activities.

these numerical exercises consisted of five personal computers running the Microsoft NT 4.0 operating system. All machines had Pentium II processors running at 300-350 MHZ, with 64-128MB RAM and various cache sizes. Inter-processor communication is done via the TCP/IP protocol. The independence of shading calculations at different times within a day allows for a temporal subdivision of these computations. Table 1 describes how 14 hourly shading tasks for a mid-third-year growth tree are distributed among one to five processors. Row T (k) gives the number of seconds required for the completion of the k^{th} task, with the number in parentheses identifying the processor assigned the task. The bottom row gives the time required for a full day of shading tasks as measured by the master processor. Note the subsequent decrease in shading task time when more processors are added.

The set of 14 shading tasks is made available to both the control processor and a pool of remote processors (Fig. 4). When a processor returns the result of a particular shading task, it accepts another task, should any remain. In this way faster processors perform more shading tasks than slower processors, providing a coarse degree of load balancing that responds to varying network loads and processing capabilities. The first shading task for a processor includes the network overhead and computational time associated with the definition of the leaf canopy structure. This canopy structure can then be reused for other shading tasks during that day. Therefore, subsequent shading tasks assigned to that processor are performed more quickly and efficiently.

Table 1. Shading task time allocation for 14 daily ECOPHYS light interception measurements of a three-year-old poplar tree with five parallel computers using COM

	Number of processors				
Shading tasks	*1*	*2*	*3*	*4*	*5*
T1 (6 am)	2.02	2.11(1)	2.20(1)	2.16(1)	2.28(1)
T2	2.27	3.63(2)	4.83(2)	7.06(2)	5.64(2)
T3	2.22	2.14(1)	4.63(3)	6.30(3)	6.34(3)
T4	2.52	2.70(2)	2.53(1)	6.73(4)	5.91(4)
T5	2.84	2.78(1)	3.06(3)	2.86(1)	3.81(5)
T6	2.77	2.95(2)	2.72(1)	2.73(1)	2.77(1)
T7 (noon)	2.72	2.66(1)	3.05(2)	2.83(2)	2.61(5)
T8	2.94	2.81(2)	2.61(1)	3.28(3)	2.63(1)
T9	2.69	2.70(1)	2.97(3)	2.94(4)	2.89(2)
T10	2.31	2.56(2)	2.56(2)	2.42(1)	2.53(4)
T11	2.19	2.19(1)	2.16(1)	2.33(2)	2.56(3)
T12	2.28	2.30(1)	2.56(2)	2.58(3)	2.27(5)
T13	2.11	2.31(2)	2.34(3)	2.30(4)	2.11(1)
T14 (7 pm)	1.97	2.00(1)	1.97(1)	1.97(1)	2.20(4)
Daily shading time (sec)	35.5	19.0	15.5	12.0	10.5

Yearly ECOPHYS simulations with COM

ECOPHYS simulations of older trees require considerable run time because of the complexity of the ECOPHYS object-oriented process model (Fig. 5). This complexity is due to increased branch orders and increased number of leaves (Fig. 6). The processing performance of a three-year-old ECOPHYS tree with five parallel processors and COM is given in Table 2. ECOPHYS calculations are subdivided into control program (including the control of the daily growth cycle, and root growth), canopy processes (photosynthate production, carbon allocation, shoot and canopy growth), and interleaf shading (Fig. 3). Distributed processing decreased the total run time from 107 to 59 minutes for a three-year ECOPHYS simulation. The performance time of the control processor was stable at ca. 19-20 minutes, as was the branch object processing time at ca. 14 minutes. However, the shading processing time was the highest in all parallel processing configurations from n = 1 to 5. The processing efficiency advantages in decreasing the total run time for the three-year-old tree clearly came with the addition of multiple parallel processors (Fig. 7). Note that non-shading calculations, that are currently performed serially, remained about the same with increased numbers of processors. Adding additional processors, as expected, increased the network communication time, but remained a low portion of the overall run time. A graphical view of the three-year-old branched tree with both an aboveground and belowground system simulated with multiple processors is shown in Figure 8.

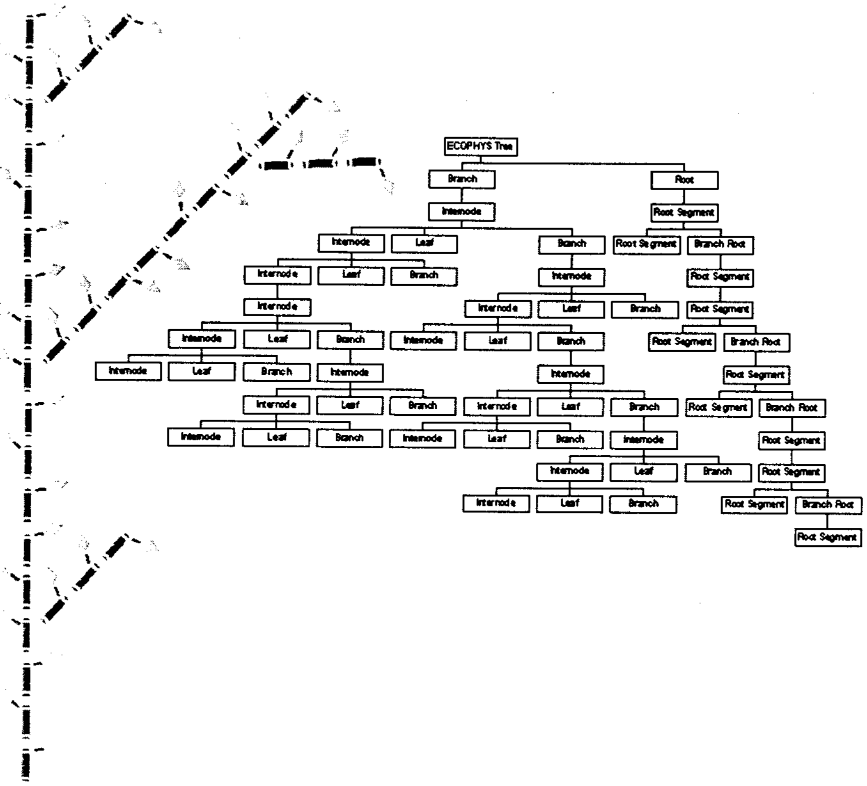

Fig. 5. Schematic of an object-oriented three-year-old ECOPHYS tree with multiple branch orders aboveground and belowground that increase modelling complexity.

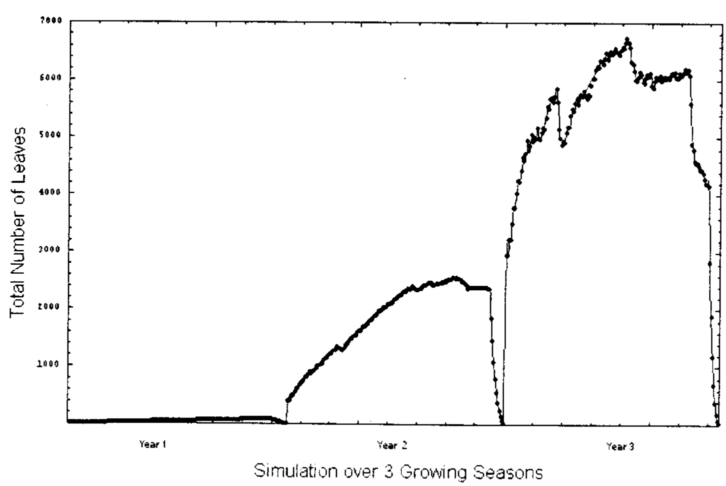

Fig. 6. Total number of leaves on ECOPHYS tree over three growing seasons simulated with multiple parallel processors using COM.

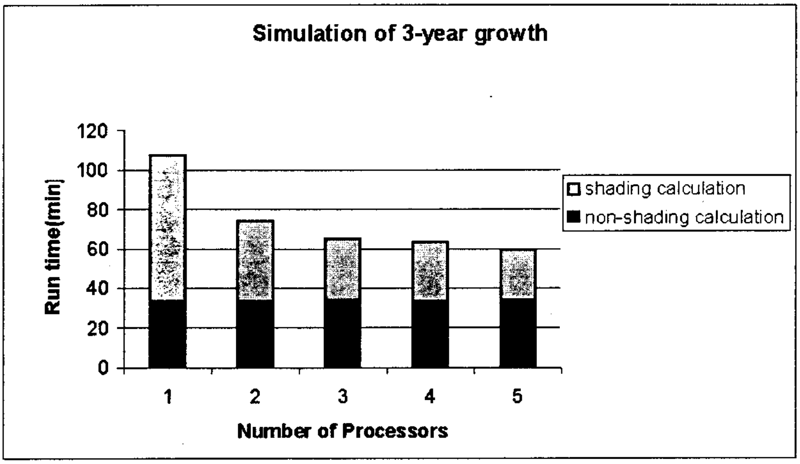

Fig. 7. Run times of three-year-old ECOPHYS tree with up to five parallel computer processors showing the high percentage of calculation time in leaf shading.

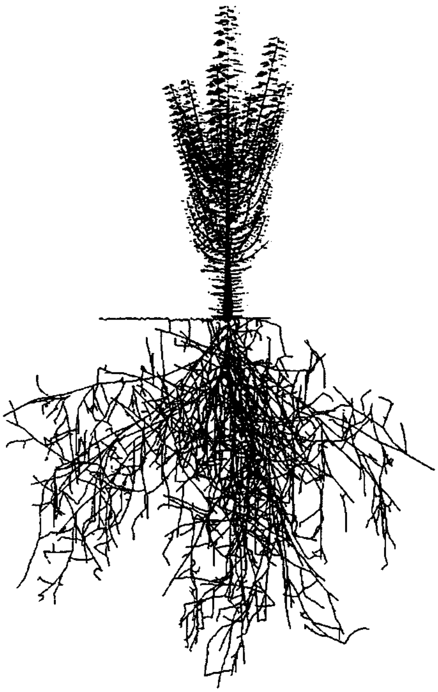

Fig. 8. Graphic display of branched three-year-old ECOPHYS tree with aboveground and belowground system, simulated with multiple, parallel processors. (Reproduced from Isebrands *et al.*, 1999a, by courtesy of the publisher.)

Table 2. Distributed processing performance of ECOPHYS three-year simulation with COM

No. of processors	*Control tasks* *min*	*Shading tasks* *min*	*Branch tasks* *min*	*Network communication time* *min*	*Total time* *min*
1	19.4	73.9	13.7	0.00	107
2	19.2	39.8	13.8	1.20	74
3	19.7	30.8	13.8	1.70	66
4	19.6	27.1	13.7	2.60	63
5	19.8	21.6	13.7	3.90	59

The numerical experiments described here can be extended to the situation in which there are the same number of available processors as shading tasks. With even more processors, it can be considered subdividing the canopy spatially, allowing for multiple processors to contribute in the measurement of hourly light interception. However, such a division of computing resources will not likely result in an optimal decrease of simulation run time, because it ignores the fact that the reduction of daily shading times will necessarily increase the relative proportions of all other computational aspects of the ECOPHYS simulator. Photosynthate production, carbon allocation, canopy, root and shoot growth, belowground processes, etc., all must also be re-evaluated and examined for their potential for distributed processing in the future.

Summary and future direction

In this contribution, we outline the potential of using parallel computing strategies with COM for assessing the effects of multiple interacting stresses on forest plantations. The increasing use of object-oriented modelling and protocols such as COM allow for dramatic improvements in computational efficiencies both within individual models and among different types of models. There are many modellers working at the individual tree, stand, or ecosystem scales. The concepts and algorithms outlined here are applicable and available to the modelling community. Moreover, because these algorithms are formulated as COM objects, they represent reusable code (Smith, 1999): they are true binary system object models with one or more well-defined interfaces. Thus, they are reusable in single-system or distributed applications and largely independent of language or platforms. An example is our weather COM object, which is a weather generator that produces diurnal curves of radiation or temperature given daily minimum/maximum values (Host *et al.*, 1999). An alternative interface to this COM object allows the user to access information from actual recorded weather traces. This object can be used by other interested modellers who need to incorporate diurnal weather patterns into their models. Similarly, COM allows the development of scientific visualization and statistical analytical tools that can be used to understand the complex data sets generated through simulation modelling. In this way COM allows for the multi-disciplinary synthesis of knowledge derived from biology, mathematics, and computer science.

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