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PLANT ARCHITECTURE, GROWTH AND RADIATIVE TRANSFER  
FOR TERRESTRIAL AND SPACE ENVIRONMENTS

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# PLANT ARCHITECTURE, GROWTH AND RADIATIVE TRANSFER FOR TERRESTRIAL AND SPACE ENVIRONMENTS

## INTRODUCTION

The overall objective of this research was to develop a hardware implemented model that would incorporate realistic and dynamic descriptions of canopy architecture in physiologically-based models of plant growth and functioning, with an emphasis on radiative transfer while accommodating other environmental constraints.

The general approach has five parts: (a) A realistic mathematical treatment of canopy architecture, (b) a methodology for combining this general canopy architectural description with a general radiative transfer model, (c) the inclusion of physiological and environmental aspects of plant growth, (d) inclusion of plant phenology, and (e) integration of (a) - (d).

The research activities to accomplish the overall objective were divided between Professor Naren Goel, who currently is Head of the Department of Computer Science at Wayne State University, Detroit, MI but was at SUNY-Binghamton, NY when the research began, and Professor John Norman from the Department of Soil Science at the University of Wisconsin. Goel concentrated on the description of canopy architecture and radiative transfer modeling, and Norman emphasized physiological and phenological aspects of plant functioning and integration of all the parts into an overall model.

## SUMMARY OF ACCOMPLISHMENTS

This has been one of the most difficult and complex research projects that we have undertaken, and although all of the final results are not yet in the journal literature, we have been successful in all aspects of the project; A general L-Systems canopy architecture model has been developed and published by Goel, A remarkable radiosity model that is an order of magnitude faster than other attempts has been developed and published by Goel, a plant growth model that includes photosynthesis, nutrient uptake and biomass partitioning has been developed and reported on by Norman, a phenological model for corn has been modified and linked with the growth model, and all the components of this project have been integrated together and run on Goel's computer for a 70-day simulation.

The L-Systems description of canopy architecture is being increasingly widely used for various kinds of vegetation and the L-Systems compiler that Goel and Knox developed for the PC (approximately 10,000 lines of code) is a powerful tool for adapting L-Systems to various kinds of canopies. Goel has begun to use L-Systems to describe the architecture of forest canopies, which are much more complex than crop canopies, and is continuing his work with NASA on the BOREAS experiment. Goel's combination of L-Systems architecture with radiosity is exceedingly powerful in forest canopy exchange because existing forest models are clearly inadequate; furthermore the radiosity approach would not have been developed without this grant.

The integrated code for the four modules that comprise this project, namely canopy architecture, radiative transfer, plant growth and phenology, is more than 25,000 lines. Furthermore, video technology was developed to display the plant architecture with appropriate radiative illumination to visualize the model and be able to examine its faithfulness to reality.

We had hoped to include with this report a video tape of a 70-day simulation based on actual weather data, and have delayed this report for that purpose; however that tape is not yet ready so we will send it when it is completed. We also are nearly finished with a paper a comparison of photosynthesis models based on random architecture versus realistic architecture in corn.

Overall, we believe that this project has been extremely successful for a high-risk proposal, both in terms of productivity during the project as well as future impact of the developments.

## **REPORT OF ACTIVITIES**

### **A. Mathematical Treatment of Canopy Architecture**

The basic approach for generating the canopy architecture is based on the so called L-systems. L-systems are parallel rewriting systems introduced by Aristid Lindenmayer (1968) for describing the development and growth of living systems. They are particularly well suited to represent the branching structures of plants. The potential of L-systems to generate realistic-looking plants was first realized by Alvy Smith (of Lucasfilm Ltd.) in 1978. His subsequent paper (Smith, 1984) and that of Aono and Kunii (1984) established L-systems as a modeling tool for computer imagery. More recently, Prusinkiewicz (1986, 1987) pushed further their use for generating realistic looking plants (Prusinkiewicz et al., 1988) and general computer imagery.

We used an L-systems based approach to generate the canopy architecture. The most basic one, the OL-systems, consists of an alphabet (a set of symbols or letters), a non-empty word (a sequence of letters out of the alphabet) called the axiom (initial string of alphabet characters which act like a seed), and a finite set of productions which define how a letter in the alphabet is replaced by a word (string of letters). L-systems are parallel rewriting systems in a sense that each letter in the axiom is replaced in parallel by a string of letters according to the production rules. The new string undergoes the same replacement process, resulting in a rapidly increasing length of string. The process of replacement stops after a predefined number of iterations (replacement steps). The alphabets in the final string are interpreted graphically to obtain plant-like structures on a computer display monitor.

To model the evolution of plant architecture associated with the growth of a plant, we introduce "growth profiles" to change the size, geometry and color of plant elements (leaves, stalks etc.). In such profiles the x-axis shows the age of the plant, while the y-axis shows a growth parameter in arbitrary units. These parameters can be used to link the plant architecture to the phenological age of the plant.

We developed software for generating the string for a given L-system and a specified number of iterations, and for interpreting the string on a IBM PC, using turtle graphics. We also purchased hardware and developed software which allows computer controlled recording of a sequence of computer generated images (animation) on a 3/4" (SONY VO-5850) video casset recorder. This hardware uses an IBM PS/2 Model 30 computer, equipped with a TARGA-16 graphics board as the host computer, a Lyon-Lamb encoder and a Lyon-Lamb MiniVas controller.

The results of this L-systems application to a corn crop is contained in Goel et al. (1990).

## **B. Canopy Architecture And Radiative Transfer**

We had originally planned to use a radiosity-based approach for solving the radiative transfer problem for general canopy architectures. Appropriate architectures would be generated by the L-systems and then radiative exchange among the canopy elements would be obtained using hardware-assisted radiosity calculations on the Hewlett-Packard 9000/835 Turbo SRX minicomputer. We generated a simple test canopy to determine whether Hewlett-Packard actually had the capability that they advertised and found out that they did not. During the second year, we simultaneously considered two approaches to the general radiative transfer problem; namely, a) Monte Carlo methods and b) radiosity approaches. Although Monte Carlo methods were acceptable for solving the remote sensing problem of canopy bidirectional reflectance, they require too much computer time to obtain the required precision in light distribution over leaves for the calculation of photosynthesis. Therefore, after a year of exploring various methods for solving the three-dimensional radiative transfer problem, we decided to concentrate on the radiosity approach that did not require the Hewlett-Packard computer. The result of this effort is the model "Diana".

The model "Diana" has four basic components: a) Generation of the reflecting and transmitting objects, which consist of 3000 to 30,000 three- and four-sided polygons, using L systems; b) determination of visibility of a facet (2 per polygon) by direct rays from the sun to define sunlit leaf area; c) determination of the fraction of energy flux leaving a facet that reaches another facet using the radiosity approach to estimate multiple scattering effects; and d) rendering the canopy with a three-dimensional perspective, with the brightness of a facet indicating the amount of scattered light reaching an observer, and the calculation of measurable quantities such as bidirectional reflectance factors and albedo.

The "Diana" model has been written up and is in the journal literature (Goel et al., 1991).

## **C. Physiological Considerations of Plant Growth and Photosynthesis**

The canopy architecture (L-System) and radiative transfer (Radiosity) routines described above will provide the absorbed photosynthetically active radiation on each of the polygons that represent portions of leaves in the corn canopy. We calculate the photosynthesis and stomatal conductance on each of these leaf polygons using a general set of equations that consider light, temperature, carbon dioxide concentration, wind speed, humidity of the air and specific species characteristics.

The photosynthesis routines provide a calculation of the amount of carbon dioxide that is taken up by the leaves and fixed into carbohydrates based on the amount of light each leaf is receiving. A growth model combines these carbohydrates with nutrients taken up from the root system to produce dry matter that can be distributed to leaves, tassels, ears, roots or stems depending on the phenological stage of development. The Growth model considers the architecture of the root system in some detail along with chemical and hydraulic properties of the soil. The growth model partitions the newly formed dry matter into above-ground plant parts (leaves, stems, sheaths, tassels and ears) and below-ground parts (roots). A phenological submodel controls allocation of above-ground dry matter to leaves, stems, sheaths, tassels and ears and is linked to the L-systems parameters that define the size and shape of the various plant parts. A new canopy architecture is computed from the combination of phenological and physiological models and the process continues.

Figure 1 contains a diagram of how the various parts of this research problem will fit together; namely, canopy and root architecture (L-Systems), Radiosity, photosynthesis, plant growth and phenological development.

A 70-day simulation of corn growth and development has been done using the combination of models illustrated in Figure 1. This took 4 days of computer time on the SUN 4/360 computer and we are in the process of preparing a video tape showing the growth of this corn canopy. Further we are comparing the light interception and photosynthesis predictions from the realistic L-systems model with simpler random models and have a paper in preparation for publication (Norman et al., 1994).

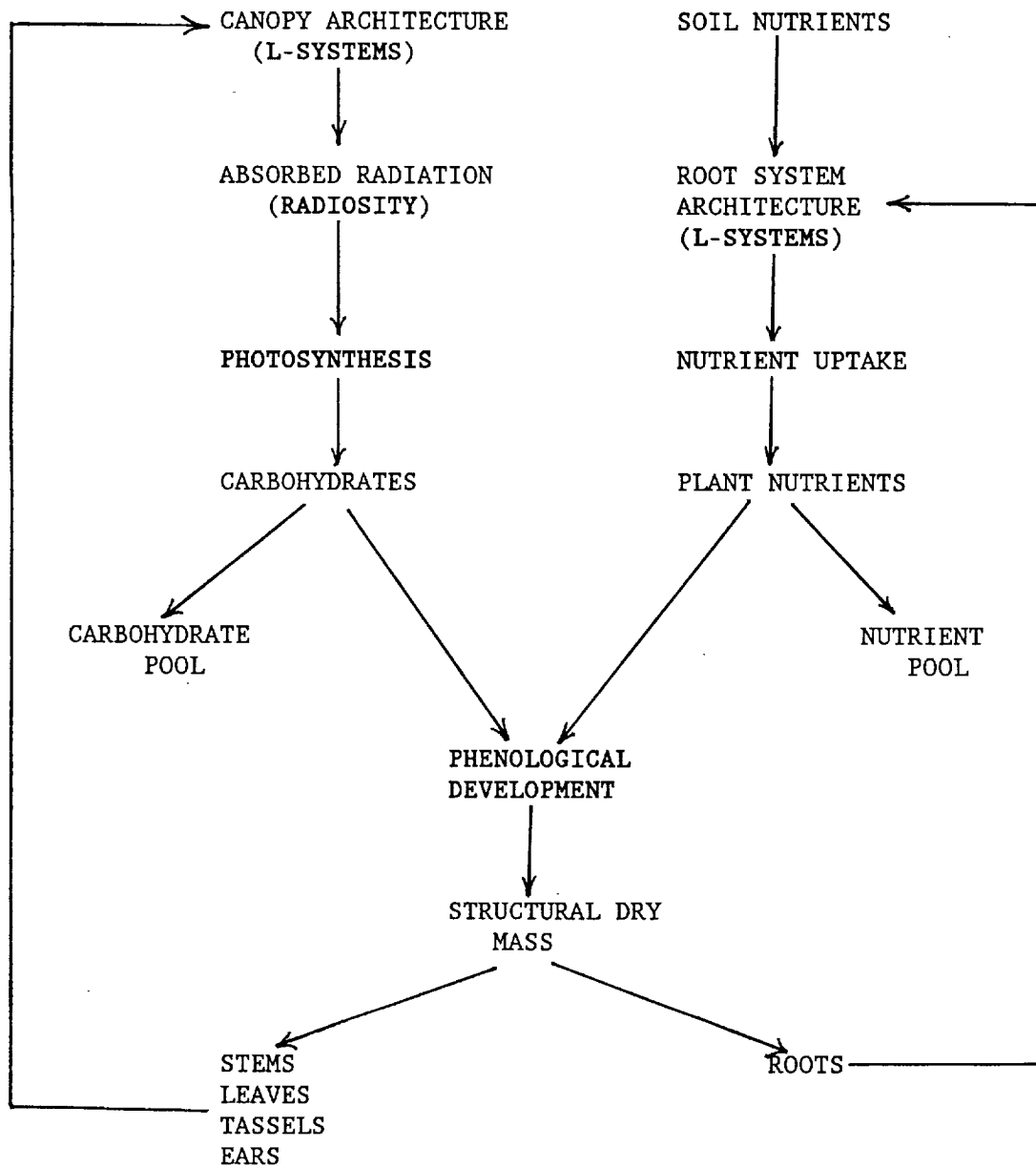


Figure 1. Structure of the overall model. Radiosity, L-Systems, photosynthesis and phenological development are in bold type because they are individual components. The remaining elements are the Growth model.

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## **PUBLICATIONS FROM THIS GRANT**

### **Refereed Publications**

Goel, N.S., L.B. Knox and J.M. Norman. 1990. From Artificial life to real life: computer simulation of plant growth. *International J. General Systems*, 18:291-319.

Goel, N.S. and I. Rozehnal. 1990. Some non-biological applications of L-systems. *International J. General Systems*, 18:321-405.

Goel, N.S. and J.M. Norman. 1992. Biospheric models, measurements and remote sensing of vegetation. *ISPRS J. Photogrammetry and Remote Sensing*, 47:163-188.

Goel, N.S., I. Rozehnal and R.L. thompson. 1991. A computer graphics based model for scattering from objects of arbitrary shapes in the optical region. *Remote Sensing Environ.* 36:73-104.

Norman, J.M., N.S. Goel, Z. Ko and L. Murdock. 1994. Modeling corn photosynthesis and light interception using random and realistic canopy architectures. In preparation for *Agronomy Journal*.

### **Non-Refereed Publications**

Goel, N.S., L.B. Knox and J.M. Norman. 1990. Computer simulation of plant growth dynamics. *Proc. 10th Annual Geoscience and Remote Sensing Symp., IEEE Cat. No. 90CH2825-8, IEEE*, 445 Hoes Lane, Piscataway, NJ 08854, pp. 1765.

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## PRESENTATIONS

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