Annual 87'

DOE/ER/60490--T4

PROGRESS REPORT: Grant DE-FG03-86ER60490

"The development of a generic ecosystem model for assessing the effects of elevated carbon dioxide on ecosystems."

Period Covered: 9/1/86 to 5/18/87

Submitted to: Dr. Roger C. Dahlman
Carbon Dioxide Research Division
Office of Energy Research
Washington, D. C. 20545

Submitted by: Dr. James F. Reynolds, P.I.
Dr. J. W. Skiles, Co-P.I.
Dr. Robert L. Dougherty, Co-P.I.
Systems Ecology Research Group,
San Diego State University

Date: May 19, 1987

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

db
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

T4

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

This report consists of three major sections: (1) progress made on the development of a generic plant growth model, (2) progress made on the holistic ecosystem model, and (3) a summary outlining future directions of our modeling efforts.

I. GENERIC PLANT GROWTH MODEL

The major accomplishments for the plant growth modeling have been the identification and implementation of components for the photosynthesis module, development of a plant canopy module, and further refinement of the various modules that make up the basic structure for a generic plant growth model. Results of this work will be presented at the ESA meetings in August (see abstract: Dougherty *et al.* 1987). A summary of these activities is given below.

Farquar-Harley-Tenhunen Photosynthesis Model

Following our research reported in Greenbook #028, we examined several implementations of a leaf-based, CO₂ responsive, photosynthesis model that incorporates information at the enzyme-kinetics level. We have identified the Harley *et al.* (1985)/ Tenhunen *et al.* (1980) photosynthesis model as a good potential foundation for the photosynthesis module of our generic plant growth model. We now have working versions of the photosynthesis model in FORTRAN and have translated the model equations into a LOTUS 1-2-3 spreadsheet for interactive analysis. In cooperation with J. Tenhunen, we have also developed preliminary models for CO₂-sensitive stomatal response as part of this photosynthesis module. Our plans are to incorporate this photosynthesis model in a canopy module (described below).

Caldwell Canopy Model

A canopy model is required for implementation of the photosynthesis and transpiration modules in the context of whole plant responses to elevated CO₂. In Greenbook 028, we stated our plans to simulate whole-plant photosynthesis by iterating a leaf-based photosynthesis model through a simulated canopy. A canopy model allows the calculation of light interception and heat balance at all levels in a plant canopy, and passes these driving variables to the photosynthesis module. Thus, the model's photosynthesis predictions are sensitive to a number of characteristics of canopy architecture, including, for example, leaf sizes and internode distances. Since these attributes are themselves influenced by CO₂ concentration, it is critical that our model incorporate these effects of whole plant canopies on photosynthesis.

We have identified a suitable canopy model (Caldwell *et al.* 1986). Our interactions with Martyn Caldwell (Utah State Univ.) have included a series of meetings between him and Reynolds in Wurzburg, Germany and a subsequent visit by Caldwell to our offices in San Diego, where he assisted with 2 days of intensive examination of the logic and computer code of the canopy model. We now have this model running on our computers and are preparing a package of documentation materials for the model. Further collaboration with Caldwell on this phase of the modeling is anticipated.

Gutschick Canopy Model

The examination of alternative canopy models is important so that we can identify potential data bases for parameterizing and validating these models. Consequently, we examined another canopy model

(Gutschick, unpublished) that we found to be potentially useful to our efforts. Vince Gutschick (New Mexico St. Univ.) recently visited our lab at our invitation so that we could examine his model in detail and begin implementing these canopy programs on our computer system. In some ways Gutschick's model is less attractive than Caldwell's because it is not in the form of a simulation model; however, data requirements for his model are more modest than those of Caldwell's. Also, Gutschick's model already includes a well-developed photosynthesis module that is responsive to elevated CO₂. Our plans for Gutschick's model are to embody it in a skeletal simulation framework and compare its predictions to those of Caldwell's model. At the very least, we will be able to validate one model with the other, but we hope to incorporate some of Gutschick's analytical approaches into Caldwell's model. This would allow us to simulate canopy processes with less intensive data requirements.

ARTUS model

In February, we conducted an intensive 3-day workshop to determine the suitability of ARTUS, a simulation model of plant production in Arctic tundra, for the current modeling objectives of the CO₂ program. This study included an analysis of the utility of the CO₂-sensitive mechanisms in ARTUS for our own modeling effort. We concluded that the level of resolution of ARTUS, especially its use of empirically-oriented scalar functions for CO₂ sensitivity, is too coarse for the objectives of the CO₂ program. These conclusions are contained in a report to the DOE R4D Scientific Coordinating Committee (Dougherty *et al.* 1987).

Further Development of Modular Scheme

In Greenbook #028 we outlined our initial efforts to identify appropriate modules for inclusion in a plant growth model. Many of these initial ideas have been further developed in collaboration with Basil Acock of the USDA-ARS Model and Database Coordination Laboratory. Acock is currently scheduled to visit our lab at San Diego State this summer where further interaction and refinement of ideas can be accomplished.

II. ECOSYSTEM MODEL

For convenience, we refer to our ecosystem model as the SERECO model (Simulation of Ecosystem Response to Elevated CO₂). To date, our ecosystem-level modeling efforts have focused on the evaluation of extant models for use in the CO₂ modeling effort. Our philosophy is that the model we develop for systems-level responses should be the least complex and the least data-intensive model possible. Our initial ecosystem-level modeling activities have revolved around modification of the SPUR model (Wight and Skiles, in press) and questions of model scale and extrapolation.

The SPUR model

A model for the Simulation of Production and Utilization on Rangelands (SPUR) has been under development for the past seven years by the Agricultural Research Service of the U.S. Department of Agriculture. It is ready for release sometime later this year (Wight and Skiles, in press). Skiles, who now is working on this CO₂ modeling project, is the former senior modeler of the SPUR Project. Since his arrival at San Diego State last October, the SPUR model has been brought up on our Apollo computer network system and is now fully operational. We have also imported the SPUR climate generator (Skiles *et al.*, in press). In the absence of an actual climate record, this generic program provides the daily driving variables necessary to run the SPUR model for any given rangeland ecosystem.

The SPUR model was designed to be a rangeland management tool. It has major modules which simulate rangeland hydrology, plant growth, and steer growth. There are two versions: Basin Scale Version (BSV) and Field Scale Version (FSV). We are working with the FSV in the development of the SERECO model. FSV operates on a daily time step, accomodates up to seven plant species on up to nine sites, and plant growth is modeled based on one square meter areas. The generic plant growth model will eventually be substituted into the modified SPUR model, eventually leading to the formulation of the SERECO model.

SPUR explicitly models soil water content in soil layers, percolation, overland and subsurface flow, runoff, evaporation, and transpiration (coupled with the plant component). The Basin-Scale Version of the model also simulates erosion and sedimentation, ponding and streamflow. The hydrology component has been tested and validated for various rangelands in Idaho (Springer *et al.*, 1984), Arizona (Renard *et al.*, in press; Lane, in press), and Nevada (Springer, personal communication). These features make the hydrology components of SPUR attractive as a starting point for the CO₂ modeling project. Coupled with the CO₂ plant response model described in Part I above, SPUR hydrology offers a generic soil abiotic simulation tool. The evaluation of the suitability of SPUR will continue as the development of the generic plant model proceeds.

A new phase of the SPUR modeling project has already begun. Skiles is a member of the SPUR modeling team and an advisor in the overall SPUR project. In February, Skiles attended a SPUR modeling team meeting and a coordinating committee meeting in Boise, Idaho. By prior agreement between our lab and the ARS, Skiles' participation in the SPUR project will enable us to use new hydrology routines and other parts of the new SPUR as they are developed.

Extrapolation and Quality of Data

A major consideration in our modeling work is that of extrapolation. In February, a 3-day workshop was held at Pennsylvania State University on this topic. Skiles attended this workshop and gave a short presentation on how extrapolation was accomplished in the SPUR model development.

In April, Skiles attended a workshop on climatology and hydrology at the University of Alaska, Fairbanks. Our objective in having a representative at this meeting was to ascertain the types and quality of data gathered in other current research projects, such as the DOE R4D, for use in the modeling of CO₂ effects on arctic tundra ecosystems.

Results of our activity in extrapolation to date will be presented at the ISEM meetings in August (see abstract: Skiles *et al.* 1987).

III. FUTURE DIRECTIONS

The DOE CO₂ Research Plan for examining the effect of elevated CO₂ on ecosystems requires an integrated research strategy. One of our major objectives has been to develop the modeling component in such a way as to provide a logical foundation for an integrated experimental and modeling approach. During these first 9 months of funding, we have attempted to further refine these ideas to accomplish this goal. Our initial attempts at such "refinement" have been specifically outlined in the unsolicited proposal "INTEGRATION OF EXPERIMENTAL AND MODELING APPROACHES IN THE UNMANAGED ECOSYSTEM RESEARCH PLAN." Further refinement

with regard to this integration will continue during the last quarter of this first year's effort and will be one of our major deliverables.

As indicated above, we have made progress on the development of the generic plant growth model and have developed collaborative ties with the A.R.S. in further development of the SPUR model. We are continuing these efforts and plan to present the details of our proposed model scheme at the CO₂ ecology meeting next fall. It is our intention that these details will be distributed to all participants of this meeting beforehand in the form of a "Greenbook" report.

To improve communication and provide integrative enhancement between the modeling and experimental components of the DOE CO₂ Program, we plan to introduce two new tools to the program: (1) structured systems analysis and design and (2) expert systems.

Structured Systems Analysis and Design

Simulation models are often constructed, tested, and disseminated without being documented. Or, equally bad, documentation is written after the model is built. This leads to confusion in the groups using the models and even for the model builders themselves. Furthermore, if the models are to be continually developed and improved, it is extremely important that experimentalists have insights into the conceptual framework at each level of detail in the model. We have addressed these two issues by employing a relatively new technique for model construction which is called Structured Systems Analysis and Design (SSAD) (Gane and Sarson, 1981).

Briefly, the SSAD technique calls for identifying the least resolved or coarsest level of conceptualization in the proposed model. A data flow diagram (DFD) is then drawn which shows the main processes involved at this level, e.g. water balance, plant growth, etc. Next, the data and information flows between processes (e.g., soil water content, leaf area index) are illustrated and those data sets required at that level are identified. This top level is then broken sequentially into new DFD's for each new level of finer resolution.

We have purchased *Prokit Analyst*, a software package for constructing DFD's. This software package is now running on a microcomputer in our lab and is being utilized to structure our generic plant growth and ecosystem models. Prokit draws the data flow diagrams and keeps track of data stores at each level. Data stores and process names are placed in dictionaries for each level and that information may be retrieved by the user when needed. Data flow diagrams of the modeled system can be produced for any desired level of resolution (an example of LEVEL 1 structure for the SERECO model is shown in Figure 1.) Data dictionaries and data flow diagrams can easily be printed at each stage of the modeling effort, forming the basis for model documentation. At the moment we do not have a tool equivalent to Prokit for our Apollo computer network. We are therefore, starting to evaluate other SSAD packages for the Apollos. Among these is *Teamwork* from Cadre Technologies. We anticipate that this SSAD method will greatly enhance the communication between our modeling efforts and the experimentalists in the program. Hence, this will be the basis of forthcoming presentations of our models at future DOE CO₂ meetings and Greenbook reports.

Expert Systems Development

We anticipate development of an expert system which will accompany the construction of the SERECO model. This expert system will eventually be used to create parameter sets, utilize expert knowledge, etc., to examine the range of potential effects of elevated CO₂ on ecosystems.

Ideally, a user will sit at a computer terminal and interact with an expert system which will ask questions and make judgements in order to formulate a parameter set for the model. The user may not know, for example, the photosynthetic rate of a particular plant species. The expert system data base should have that information as well as other data for that plant species. Thus, if a user wants to simulate a pasture seeded with crested wheatgrass, the expert system will produce parameters for photosynthetic rate, temperature response curves, and whether or not the pasture is in the geographical range for the plant species. We anticipate that this type of information (the "knowledge base" component of expert systems) will be contributed by the various experimentalists in the program over the next several years.

We have initiated the construction of an expert system in the context of our CO₂ modeling effort. We have obtained the XLISP programming language, ESIE (expert system inference engine), and EXPERT, an expert system development shell, for use on our microcomputers. We are evaluating expert systems development tools for use on our Apollos. Among these are "Quintus" from Quintus Computer Systems, which is a development tool based on the LISP language. We are also evaluating the literature on the new Apollo workstation which comes with 8 megabytes of RAM and a hard disk. This machine, hooked into the existing network, may be ideal for expert system development and application.

Lastly, another potential benefit of expert systems is the actual implementation of our models at other research labs. Once models are built, verified and validated, they are distributed to various users. However, such users are often at a loss as to how to parameterize and use the model since they have not had the experience of model-building nor of previous use of the model. Such quandaries may be remedied by extensive training in the use of the model (which is both expensive and time consuming), site visits by model builders (also expensive and often not feasible), or the use of a specially designed expert system. Our hope is that through the use of an expert system, the models we develop can be transferred to other interested users with a minimum of misunderstanding, misinterpretation, and time.

IV. LITERATURE CITED

- Caldwell, M.M., H.-P. Meister, J.D. Tenhunen and O.L. Lange. 1986. Canopy structure, light microclimate and leaf gas exchange of *Quercus coccifera* L. in a Portuguese macchia: measurements in different canopy layers and simulations with a canopy model. *Trees* 1:25-41.
- Dougherty, R.L., J.D. Tenhunen, and J.F. Reynolds. 1987 Simulation of plant production: report on ARTUS workshop. Dept. of Energy, R4D Program unpublished report.
- Gane, C. and T. Sarson. 1981. Structured Systems Analysis: Tools and Techniques. McDonnell Douglas Professional Services Company, Saint Louis, Missouri. 373p.
- Harley, P.C., J.A. Weber and D.M. Gates. 1985. Interactive effects of light, leaf temperature, CO₂ and O₂ on photosynthesis in soybean. *Planta* 165:249-263.
- Lane, L.J. in press. Chapter A5. Hydrology Component: Water Routing and Sedimentation. In - see Wight and Skiles below.
- Renard, K.G., E.D. Shirley, J.R. Williams, and A.D. Nicks. in press. Chapter A3. Hydrology Component: Upland Phases. In - see Wight and Skiles Below.

Skiles, J.W., E.P. Springer and C.W. Richardson. in press. Chapter B4. User guide for the climate generator. In - see Wight and Skiles below.

Springer, E.P., C.W. Johnson, K.R. Cooley, and D.C. Robertson 1984. Testing the SPUR hydrology component on rangeland watersheds in southwest Idaho. Trans ASEA 27:1040-1046 & 1054.

Tenhunen, J.D., O.L. Lange, P.C. Harley, A. Meyer and D.M. Gates. 1980. The diurnal time course of net photosynthesis of soybean leaves: analysis with a physiologically based steady-state photosynthesis model. Oecologia (Berl.) 46:314-321.

Wight, J.R. and J.W. Skiles (eds.). in press. SPUR - Simulation of Production and Utilization on Rangelands: Documentation and User Guide. U. S. Government Printing Office (draft 950p.).

CO₂ Research Seminars/Papers Presented at Scientific Meetings

Dougherty, R.L., J.F. Reynolds, and J.D. Tenhunen. "A modular structure for simulating plant growth under elevated carbon dioxide concentrations." Paper accepted for presentation to the Ecological Society of America, Ohio State University, August 1987.

"We describe a conceptual simulation model of plant growth as influenced by elevated carbon dioxide concentrations. The model is based on current understanding of physiological processes and incorporates effects of carbon dioxide on stomatal opening, light and dark respiration, and photosynthesis. To accomplish generality, the model is organized into modules which represent the processes of phenology, carbon fixation, potential and actual growth, limitations to growth (C, N, and water), tissue loss, and morphology. We discuss model structure with respect to the interdependencies between the process modules, and demonstrate the suitability of the model for inclusion in higher-level ecosystem models."

Skiles, J.W., J.F. Reynolds, and D.W. Hilbert. "Scope, scale, and resolution in modeling the effect of elevated carbon dioxide on ecosystems." Paper accepted for presentation to the International Society for Ecological Modelling, Ohio State University, August 1987.

"The initial response of ecosystems to elevated carbon dioxide is through the direct responses of plants (e.g., photosynthesis). These primary responses may lead directly to higher-order effects, including organism interaction, population adjustments and ecosystem structure. Modeling these responses in homogeneous populations, e.g., crops, is possible, so, the range of operation, or scale of the simulation is not a question; all organisms will have the same response. In an ecosystem composed of heterogeneous populations, this approach is not possible since species may respond differently and knowledge of responses may be fragmentary at best. Using relationships within ecosystem models with different proportions (different units, for example) produces results with different scales. Amalgamating these different scales so that results may be viewed with the same resolution, can introduce errors in the predictions. This paper discusses these problems in view of ambient CO₂ concentration and proposes rules for dealing with them in ecosystem models."

Reynolds, J.F. "Modular generic plant simulators and the new paradigm for ecosystem research." Invited seminar, Cal State - Fullerton, Dept. of Biology. October, 1986.

Reynolds, J.F. "Models for predicting the response of ecosystems to elevated carbon dioxide." Talk presented at SOA Symposium, Carbon Dioxide Research Division, D.O.E., National Academy of Sciences, Washington, D.C., December 1986.

CO₂ Research Papers Fully or Partially Supported by This Grant

Dahlman, R.C., J.F. Reynolds, and B.R. Strain. 1986. Modeling the response of ecosystems to fossil fuel emissions: Carbon dioxide and pollutant interactions. *Air Poll. Contr. Assoc.* 86-9.5, 13 pp.

Leadley, P.W., J.A. Reynolds, J.F. Thomas, and J.F. Reynolds. 1987. Effects of CO₂ enrichment on internal leaf surface area in soybeans. *Botanical Gazette*: IN PRESS.

Leadley, P.W. and J.F. Reynolds. 1987. Effect of carbon dioxide enrichment on mainstem leaf development in soybeans. *Botanical Gazette*: In Review.

Acock, B., J. Reynolds, T. Trent, and R.C. Dahlman. 1987. Generic modular plant simulators and the new paradigm for ecosystem research. *Science*: IN REVIEW.

Lieth, J.H., J.F. Reynolds and H.H. Rogers. 1986. Estimation of leaf area of soybeans grown under elevated carbon dioxide levels. *Field Crops Research* 13: 193-203.

Leadley, P.W. and J.F. Reynolds. 1987. Estimation of leaf area and leaf dry weight of soybeans grown in elevated carbon dioxide environments. *Field Crops Research*: IN REVIEW.

Lieth, J.H. and J.F. Reynolds. 1987. The nonrectangular hyperbola as a photosynthetic light response model: A note on the geometrical interpretation and estimation of θ . *Photosynthetica* 21(3): IN PRESS.

Fig. 1. Ecosystem level model - SERECO - represented in SSAD notation.

Project ID: PROKIT	Date: 05-18-87
Project name: TEST	
Version 6	Level 1 New physical
Diagram name: SERECO	Last Rev. 05/18/87