FORCYTE-11: A FLEXIBLE, USER-CONTROLLED MICROCOMPUTER SIMULATION MODEL WITH WHICH TO EXAMINE BIOMASS YIELDS OF ALTERNATIVE FORESTRY OR AGROFORESTRY MANAGEMENT SYSTEMS

J.P. Kimmins[1], W.A. Kurz[1], K.A. Scoullar[2], M.J. Apps[3], and P.G. Comeau[4]

University of B.C., Vancouver, B.C.[1]; Life Science Programming, Naramata, B.C.[2]; Forestry Canada, Edmonton, Alberta[3]; Ministry of Forests, Victoria, B.C.[4]

The World Commission on Environment and Development has issued a challenge in its report "Our Common Future": to demonstrate that all future developments are consistent with a sustainable environment and sustainable renewable resources. In forestry, this requires projections over at least several rotations (a three-rotation minimum has been suggested by a IUFRO Working Group) concerning the sustainability of yield and site productivity under alternative management strategies. In the absence of empirical experience over such long time spans, interim estimates of sustainability can be obtained by calibrating and using models like FORCYTE-11.

The development of the FORCYTE series of ecosystem management models was a component of the ENFOR program of the Forestry Canada, which was initiated in response to the oil shortages of the mid 1970's. Initially a simple input-output model to examine soil fertility aspects of the sustainability of intensive biomass-for-energy projects, FORCYTE-11 has been developed to become an ecosystem management model with which to simulate the short and long- term effects of a wide variety of rotation-length management strategies on stand-level production, yield, yield sustainability, and economic and energy benefit/cost ratios. Although FORCYTE-11 cannot address questions that relate to climate change (the "greenhouse effect"), it can examine the effects of management on long-term site (i.e. soil) productivity.

INTRODUCTION: ORIGINS OF FORCYTE

The apparently inevitable doubling of world population from the present 5.2 billion to about 10 to 11 billion (Repetto 1987; World Resources Institute and International Institute for Environment and Development 1988), together with the increasingly serious deterioration of the global environment (e.g. Morrison 1984; Shands and Hoffman 1987), led the United Nations to establish the World Commission on Environment and Development. Their report, "Our Common Future" (World Commission on Environment and Development 1987), concluded that while the industrialized nations bear a grave burden of responsibility for current and past environmental deterioration, the greatest long-term threat to the environment comes from poverty in the populous developing countries. The Commission concluded that the long-term survival of the human species on earth depends on the elimination of this poverty, and that this will require the sustainable development of the World's resources. This in turn implies the need for planning tools with which to establish the sustainability of all future resource developments.

The oil crisis of the mid 1970's sent a shock wave through the industrialized nations who vowed to undertake the necessary steps to reduce our dependence on fossil fuels. The International Energy Agency was created, with subprograms to examine the feasibility and sustainability of biomass-for-energy production systems. A parallel activity in Canada, the ENFOR (Energy-from-the-forest) program of the Forestry Canada (funded by Energy, Mines and Resources) also investigated the sustainability of bioenergy production systems in forestry. A small project in this program was to review the soil fertility implications of whole-tree harvesting bioenergy tree plantations on short rotations, and to prepare a simple nutrient input/output model by which to establish the site nutrient budget for such harvesting systems. This was to become the basis for speculations about the sustainability of yield in energy plantations. Initial work on this input/output model revealed that such a simplistic model would tend to give simplistic answers. The significant questions could only be answered in a significant and believable manner by a much more complex approach. It was therefore concluded that a mechanistic, ecosystem-level computer simulation model capable of simulating all the major bioenergy plantation management options was needed.

This conclusion was the genesis of the FORCYTE (the FOrest nutrient Cycling and Yield Trend Evaluator) series of models. Credit for the genesis of the model must go to the pioneering work of the late Dr. Peter Rennie (Rennie 1955, 1957) and Dr. A. (Jock) Carlisle, whose tireless insistence on the need for such an evaluation tool made the development of FORCYTE possible.

A BRIEF HISTORY OF MODEL DEVELOPMENT

FORCYTE developed out of a 1977/78 ENFOR contract.

FORCYTE-1 was a simple historical bioassay (see Kimmins 1985, 1986, 1988) mathematical model of forest growth including herbs, shrubs and trees, with simulated nutrient cycling, but no feedback between nutrient availability and forest growth. This initial model was a foundation from which a useful model could be developed, but it could not be used to address the critical questions. Over the subsequent five years, the model was developed to FORCYTE-10 (Kimmins and Scoullar 1983). The various intermediate versions of the model (FORCYTE-2 to FORCYTE-9) represented significant stages in the development of this benchmark version: addition of nutrient feedback, of a simulation of site quality change, of various management activities, of tabular as well as graphical output, of energy analysis, and of economic analysis. FORCYTE-10 has been field tested in British-Columbia (Feller et al. 1983), Newfoundland (Meades 1987, Moore and Meades 1987), Oregon (Sachs and Sollins 1986), Finland (Kellomaki and Seppala 1987), Alaska (Yarie 1986), and the southern pine region of the US (Fox et al. 1984).

Useful as a teaching and research tool, and suitable for use as a qualitative decision support tool in some aspects of bioenergy plantation management or conventional forest management, FORCYTE-10 proved to have several shortcomings that limit its use as a more quantitative management decision support tool. Consequently, a further five years were supported by Forestry Canda (ENFOR) to develop its successor, FORCYTE-11. Whereas the series FORCYTE-1 to FORCYTE-10 constituted the definable stages in development of the benchmark FORCYTE-10, development of FORCYTE-11 involved a major restructuring of the model. This was necessary to overcome those unacceptable limitations of FORCYTE-10 that were the result of the modelling approach of that model. FORCYTE-11 is a modelling framework rather than an individual model, and it permits the user to simulate a much wider range of bioenergy, forestry, or agroforestry management systems than was possible with FORCYTE-10.

DESIGN CRITERIA AND MODELLING APPROACH

A number of design criteria guided the development of:

FORCYTE-11:

1. The model should have a sufficiently generalized structure that it can be applied to a wide variety of even-aged stands managed under monoculture, mixed species, or alternating species forest crop (traditional or bioenegy) or agroforestry management systems. It should provide a modelling framework that can be "customized" for a wide variety of uses, rather than a single, fixed-structure model.

2. The model should have a modular structure that separates the calibration and testing of individual ecosystem component modules from the evaluation and use of the ecosystem management simulator. This structure also keeps the size of the management simulator within reasonable limits, and reduces the problem of model size and complexity that normally limits the amount of detail that can usefully be added to an ecosystem-level model.

3. The model should provide the user with the opportunity to simulate the effects of all the major management treatments on nutrient cycling, soil nutrient availability, and competition for nutrients and light. The effects of these site resources on plant growth and the relative competitive abilities of different species should be simulated explicitly.

4. Ecological processes that determine growth should be simulated as mechanistically as possible, avoiding the use of artificial mathematical surrogates which do not have an ecologically or biologically sound theoretical basis.

5. The model should, wherever possible, be driven by empirical, inventory-type data, rather than by data on process rates that require prolonged and detailed scientific measurement. Although the requirement for field, growth chamber, or laboratory measurements of the rates of some processes is unavoidable, inventory- type data should be employed wherever it is possible. Achievement of this design criterion depends on the combination of a field-measurement of the outcome of some process (e.g. annual growth of plants; annual weight loss of a decomposing log) with an understanding of that process. This combination is used to infer the rate at which the process must have occurred. Thus, many process rate estimates are obtained indirectly from field inventory-type data.

6. The modelling approach should be that of hybrid simulation: the presentation of the historical patterns of plant growth and

ecosystem function, and an evaluation of the repeatability of these patterns when the rates of certain processes are changed by the simulation of altered management practices.

7. The model should produce sufficient diagnostic output to permit the user to identify errors in data entry, "bad" data, or unacceptable model performance. This diagnostic output should be produced by each of the model's subcomponents, and should provide a useable basis for model (or individual module) rejection.

8. Wherever possible, the user should have the option to switch off or alter the simulation of individual processes where he/she does not accept the way these processes have been simulated. This provides the user with a means of modifying many of the model's assumptions. The user must have control over all process rates by way of input data files.

9. The number of calibration "twiddle knobs" should be kept to an absolute minimum, and where these are inevitable, they should be controlled by the user in the input file. They should not be "hidden" in the code. As few assumptions as possible should be embedded in the computer code: wherever possible, assumptions should be controlled by the user via the input data files.

Details of the modelling approach will not be presented here as they have been presented in Kimmins (1985, 1986 and 1988) and Kimmins and Scoullar (1989). Details of the supervisory software package PROBE that facilitates the use of the model in multiple comparison runs (Kurz et al. 1987), and the presentation and interpretation of the output of these runs (Apps et al. 1988, McIsaac et al. 1989) have been presented elsewhere.

STRUCTURE AND PROCESSES REPRESENTED

Details of the structure and processes of FORCYTE-11 can be found in the User's Manual (Kimmins and Scoullar 1989). By way of summary, the structure of this version of the model is presented in Figure 1, while the major compartments and processes that are simulated are shown in Figure 2. The simulation options and processes that are represented in the benchmark version of FORCYTE-11 are listed in Table 1.

A. Management Options Available to the User of the Benchmark Version of FORCYTE-11.

- Site preparation: manual weeding, broadcast slashburning.
- Regeneration: planting, natural seeding, vegetative reproduction (root suckering or coppice sprouting); regeneration of single or multiple-species crops.
- Weed control - manual.
- Stocking control - precommercial thinning (spacing).
- Nurse crops - Nitrogen-fixing herbs, shrubs or trees.
- Stand maintenance - control of non-crop species. - control of species composition.
- Fertilization - single or multiple nutrients.
- Commercial thinning - high, low or random thinning. Any utilization level.
- Final harvest - clearcutting, shelterwood, or seed tree method with any utilization level.
- Utilization level: stem only, "whole tree" (above-ground), or "complete tree" (above- plus below-ground), or any intermediate level.

B. Natural Disturbance Events That Can Be Simulated.

- Wildfire - effects of wildfire on ecosystem organic matter and nutrients.
- Herbivory - insect defoliation of canopies, wildlife browsing of seedlings, domestic livestock grazing of competing vegetation.

C. Processes That Can Be Simulated.

- Photosynthesis and "foliage nitrogen efficiency".
- Plant growth and biomass accumulation.
- Nutrient limitation of growth.
- Litterfall - above-ground and below-ground.
- Foliar leaching.
- Plant competition for light and nutrients.
- Effects of shading on photosynthesis: sun and shade foliage.
- Effect of shading on height growth.
- Plant mortality - density-dependent mortality (stand self-thinning, or shading by competitors) and density-independent mortality. - Winter photosynthesis - evergreen photosynthesis when deciduous competitors are leafless.
- Geochemical cycle - inputs and outputs of nutrients to and from the ecosystem: precipitation, weathering, nitrogen fixation, fertilization, soil leaching, harvest removals.
- Biogeochemical cycle - uptake, litterfall, foliar leaching, decomposition (mineralization/immobilization).
- Internal cycling - retranslocation of nutrients at the time of tissue senescence.

- Decomposition - loss of organic matter and nutrient mineralization and immobilization.
- Effect of clearcutting on decomposition.
- Soil leaching.
- Soil exchange capacities.

CONCLUDING STATEMENT

Although the capabilities of FORCYTE-11 have expanded the scope of the original project, the objective of the model has not changed: to be able to make short, medium, and long-term predictions concerning the yield, the sustainability of yield, the economics, and the energy efficiency of a wide range of alternative bioenergy management strategies. Initially a main-frame model, FORCYTE now runs on 386-based microcomputers making the model more accessible.

A model is limited by its performance and ease of use. Major improvements have been made in the latter by the development of the PROBE package of software (Figure 1), and further development in this area is progress (McIsaac et al. 1989). Verification and validation projects are planned or in progress (Grewal et al. 1989, Peterson and Apps 1989, Pike and Meades 1989, Sachs et al. 1989), and a group of cooperators willing to field test the benchmark version of FORCYTE-11 has been identified. It is planned to report on the results of this activity in both 1990 and 1991.

ACKNOWLEDGEMENT

This work has been supported (in part) by the Federal Panel on Energy R&D (PERD) through the ENFOR (Energy from the Forest) Program of Forestry Canada.

REFERENCES

Apps, M.J., W.A. Kurz, J.P. Kimmins and K.A. Scoullar. 1988. User friendly applications of the FORCYTE ecosystem model on a microcomputer. pp. 263-269. In: Forest Growth Modelling and Prediction, A.R. Ek, S.R. Shifley and T.E. Burk (eds.) USDA For. Service, North Central Forest Experiment Station, Gen. Tech. Rep. NC-120.

Feller, M.C., J.P. Kimmins and K.A. Scoullar. 1983. FORCYTE-10: Calibration data and simulation of potential long-term effects of intensive forest management on site productivity, economic performance, and energy benefit/cost ratio. pp. 179-200. In: R. Ballard and S.P. Gessel, (eds.) Forest Site and Continuous Productivity. Proc. IUFRO Symp. USDA For. Serv. For. Range Expt. Stn., Portland Ore., Gen. Tech. Rep. PNW-163.

Fox, T.R., J.P. Kimmins and H.L. Allen. 1984. Adaptation of the forest nutrient cycling trend evaluator (FORCYTE) for loblolly pine plantations. pp. 203-211. In: E. Shoulders (ed.), Proc. 3rd Biennial S. Silvic. Res. Conf., Atlanta, Georgia.

Grewal, H., M.J. Apps, and D.A. MacIsaac. 1989. Using the STEMS and FORCYTE-11 computer models for mixedwood forest management. 7th Canadian Bioenergy R & D Seminar, Apr. 24-26, 1989, Ottawa, Ont., this volume.

Kellomaki, S. and M. Seppala. 1987. Simulations on the effect of timber harvesting and forest management on the nutrient cycle and productivity of Scots pine stands. Silva Fennica 21(2):203-236.

Kimmins, J.P. 1985. Future shock in forest yield forecasting: the need for a new approach. Forestry Chronicle 61(6):503-513.

Kimmins, J.P. 1986. FORCYTE in forestry: the need for a systems approach in forest education, yield prediction and management. pp. 1-25 In: The E.B. Eddy Distinguished Lecture Series. Faculty of Forestry, Univ. of Toronto, Ontario.

Kimmins, J.P. 1988. Community organization: Methods of study and prediction of the productivity and yield of forest ecosystems. Can. J. Bot. 66:2654-2672.

Kimmins, J.P. and K.A. Scoullar. 1983. FORCYTE-10. A User's Manual for the Tenth Version of the FORest nutrient Cycling and Yield Trend Evaluator. 2nd Approximation. Contract Report to Canadian Forestry Service, Ottawa, Unpubl. 116 pp. + app.

Kimmins, J.P. and K.A. Scoullar. 1989. FORCYTE-11 User's Manual. Forestry Canada. Northern Forest Research Station. Edmonton, Alberta. In Press.

Kurz, W.A., M.J. Apps and Y.-H. Chan. 1987. PROBE: A program to facilitate user-friendly gaming with FORCYTE, pp. 160-164 In: Granger, C. (ed.) Proceedings of the Sixth Canadian Bioenergy R & D Seminar, Richmond B.C., February 16-18, 1987. B.C. Research, Vancouver.

MacIsaac, D.A., M.J. Apps, and W.A. Kurz. 1989. Updated PROBE utilities for evaluation of forest management strategies using FORCYTE-11. 7th Canadian Bioenergy R & D Seminar, Apr. 24-26, 1989, Ottawa, Ont., this volume.

Meades, W.J. 1987. The integration of forest site classification and FORCYTE-10 calibration in western Newfoundland. Pp. 29-40 In: T.M. Williams and C.A. Gresham (eds.): Predicting consequences of intensive forest harvesting on long-term productivity by site classification. IEA/BE Workshop. Georgetown, N.C., US, October 2-9, 1987.

Moore, J.P., and W.J. Meades. 1987. Calibration of the FORCYTE growth model in Western Newfoundland. Pp. 155-159 In: Granger, C. (ed.) Proceedings of the Sixth Canadian Bioenergy R & D Seminar, Richmond B.C., February 16-18, 1987. B.C. Research, Vancouver.

Morrison, I.K. 1984. Acid rain. A review of literature on acid deposition effects in forest ecosystems. For. Abstr. 45:483-506.

Peterson, E.B., and M.J. Apps. 1989. Do ecosystem models such as FORCYTE-11 have a role in boreal mixedwood management? 7th Canadian Bioenergy R & D Seminar, Apr. 24-26, 1989, Ottawa, Ont., this volume.

Pike, D.B., and W.J. Meades. 1989. A preliminary evaluation of FORCYTE-11 using western Newfoundland balsam fir stands. 7th Canadian Bioenergy R & D Seminar, Apr. 24-26, 1989, Ottawa, Ont., this volume.

Rennie, P.J. 1955. Uptake of nutrients by mature forest growth. Plant & Soil 7:49-95.

Rennie, P.J. 1957. The uptake of nutrients by timber forest and its importance to timber production in Britain. Quart. J. For. 51:101-115.

Repetto, R. 1987. Population, resources, environment: an uncertain future. Population Bulletin 42(2)44pp.

Sachs, D. and P. Sollins. 1986. Potential effects of management practices on nitrogen nutrition and long-term productivity of western hemlock stands. For. Ecol. Manage. 17:25-36.

Sachs, D., J.P. Kimmins, and M.J. Apps. 1989. Using FORCYTE- 11 to examine the potential effects of intensive management and increased utilization on the long-term productivity of Douglas fir forests. 7th Canadian Bioenergy R & D Seminar, Apr. 24-26, 1989, Ottawa, Ont., this volume.

Shands, W.E. and J.S. Hoffman (eds.). 1987. The Greenhouse Effect, Climate Change, and U.S. Forests. The Conservation Foundation, Wash., D.C. 304 pp.

World Commission on Environment and Development. 1987. Our Common Future. Oxford University Press. Oxford. 383 pp.

World Resources Institute and International Institute for Environment and Development. 1988. World Resources 1988-89. An Assessment of the Resource that Supports the Global Economy. Basic Books, Inc., N.Y. 377 pp.

Yarie, J. 1986. FORCYTE - Extension of a stand level growth and yield model utilizing nitrogen dynamics to taiga white spruce forests. pp. 190-204. In: K. van Cleve et al. (eds.), Forest Ecosystems in the Alaskan Taiga. A Synthesis of Structure and Function. Springer-Verlag, NY.

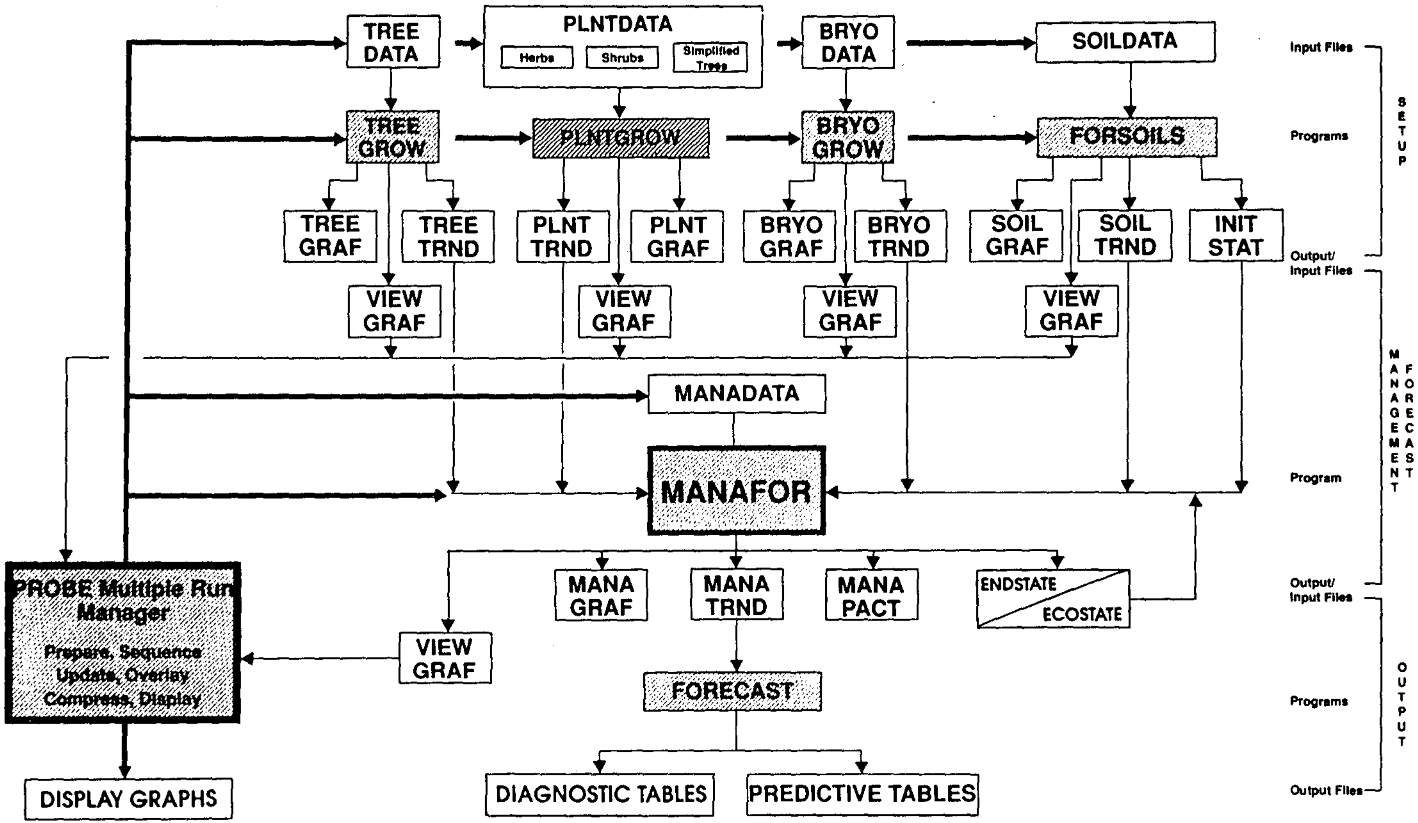


Figure 1.: The overall file and program structure of the FORCYTE- 11 modelling framework. Users can assemble the appropriate "setup" modules to produce a simulation of any particular forest or agroforesty ecosystem. The relationship between the PROBE supervisory software and the FORCYTE framework can be seen.

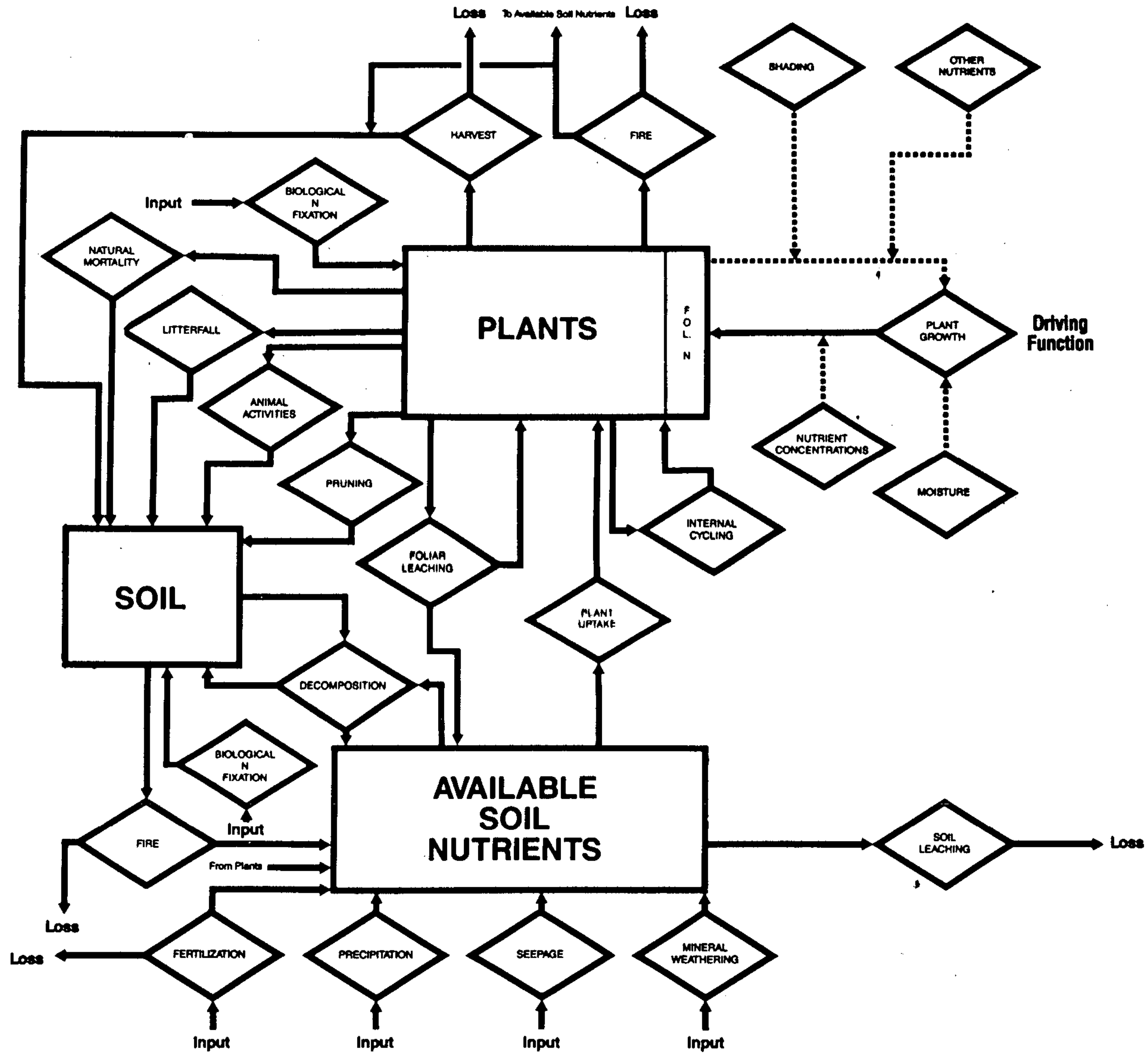
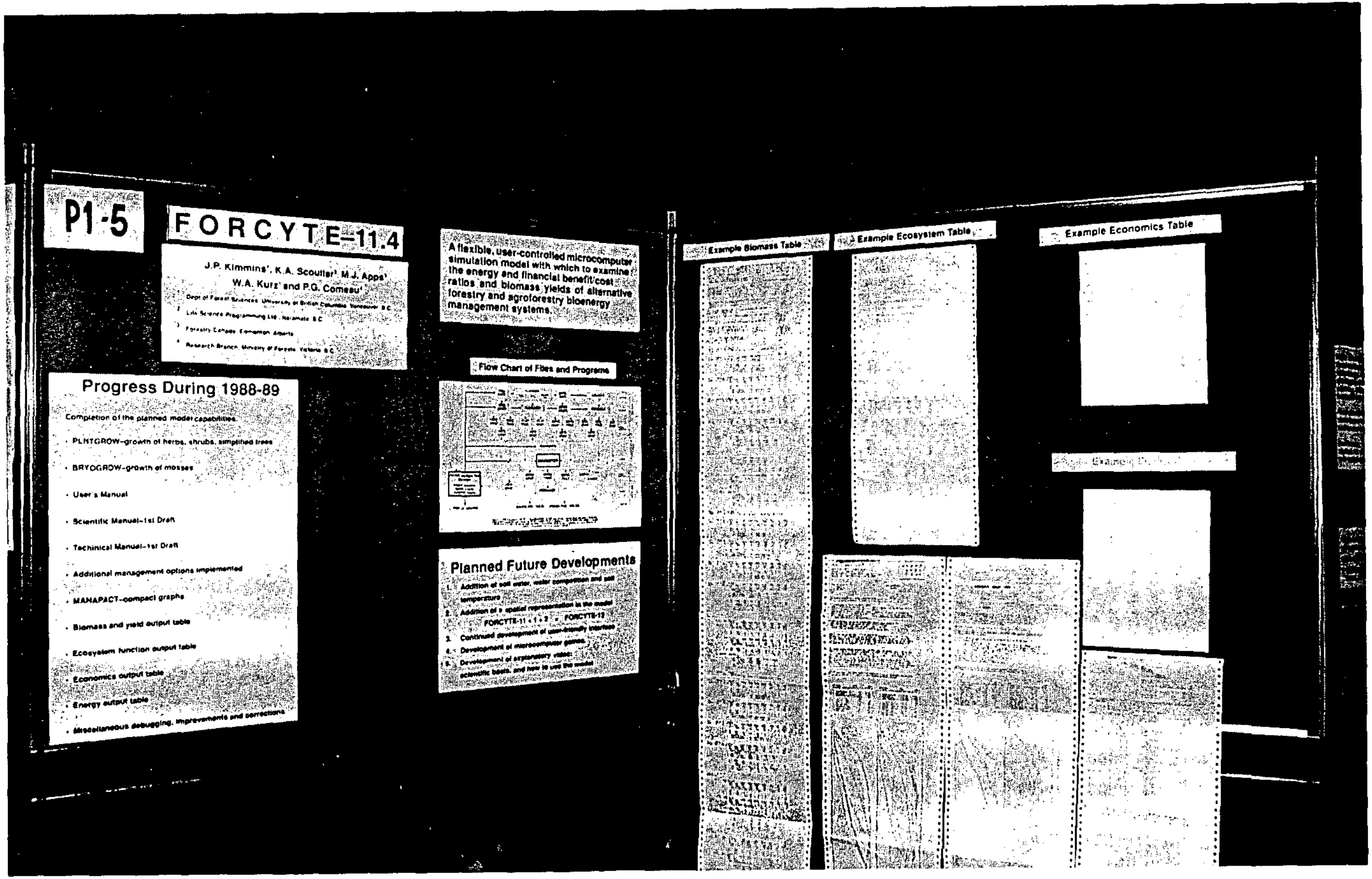


Figure 2. Major compartments and processes that are operational in the benchmark version of FORCYTE-11. Some of the processes shown in earlier published versions of this diagram are not available in this benchmark version, but are expected to be available in future versions.


P1-5
FORCYTE-11.4
J.P. Kimmins, K.A. Scoullar, M.J. Apps
W.A. Kurz and P.G. Comeau
A flexible, user-controlled microcomputer simulation model with which to examine the energy and financial benefit/cost ratios and biomass yields of alternative forestry and agroforestry bioenergy management systems.
Progress During 1988-89
Completion of the planned model capabilities
PLNTGROW-growth of herbs, shrubs, simplified trees
BRYOGROW-growth of mosses
User's Manual
Scientific Manual-1st Draft
Techinical Manual-1st Draft
Additional management options implemented
MANAPACT-compact graphs
Biomass and yield output table
Ecosystem function output table
Economics output table
Energy output table
Miscellaneous debugging, improvements and corrections
Flow Chart of Files and Programs
Planned Future Developments
Example Biomass Table
Example Ecosystem Table
Example Economics Table

SEVENTH CANADIAN BIOENERGY R&D SEMINAR

APRIL 24 - 26, 1989

SKYLINE HOTEL

OTTAWA, ONTARIO

PROCEEDINGS

COMPTE RENDU

SEPTIÈME SÉMINAIRE CANADIEN DE R&D EN BIOÉNERGIE

24 - 26 AVRIL, 1989

HOTEL SKYLINE

OTTAWA, ONTARIO

Sponsored and Organized by:

Bioenergy Development Program
Energy, Mines and Resources Canada

In Cooperation with

Agriculture Canada
Environment Canada
Forestry Canada
National Research Council Canada
Natural Sciences and Engineering Research Council
Office of Energy Research and Development, EMR

Parrainé et organisé dans le cadre du:

Programme de développement de la bioénergie
Énergie, Mines et Ressources Canada

En collaboration avec

Agriculture Canada
Environnement Canada
Forêts Canada
Conseil national de recherches Canada
Conseil de recherches en science naturelles et en génie
Bureau de la recherche et de développement énergétiques, ÉMR