THE FORCYTE EXPERIENCE: A DECADE OF MODEL DEVELOPMENT

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ABSTRACT

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 an 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 Forestry Canada, which was initiated in response to the Arab oil embargo of the mid-1970s. Initially a simple input-output model to examine soil fertility aspects of the sustainability of intensive biomass-for-energy, FORCYTE 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 this version of the model 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 the world population from the present 5.2 billion to about 10-11 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 although 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 so-called developed western nations have become hopelessly addicted to the use and annually increasing use of fossil fuel energy. Our current standard of living, lifestyle, and entire economics are so fossil-fuel energy-dependent that the prospect of major reductions in the availability and use of fossil fuels is as threatening to current developed societies as the impending withdrawal of supplies of heroin must be for a heroin addict.

The Arab oil embargo of the mid-1970s sent a shock wave through the industrialized nations, who vowed to undertake the necessary steps to reduce their 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 Forestry Canada (funded by Energy, Mines and Resources Canada) 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 end 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 FORCYTE: the FORest nutrient Cycling and Yield Trend Evaluator. Credit for this genesis 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, this volume, or 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 next 5 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, a simulation of site quality change, various management activities, tabular as well as graphical output, energy analysis, and economic analysis). FORCYTE-10 has been field tested in Oregon (Sachs and Sollins 1986), Finland (Kellomaki and Seppala 1987), Alaska (Yarie 1986), Canada (Feller et al. 1983), and the southern pine region of the United States (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 limited its use as a more quantitative decision support tool. Consequently, another 5 years was invested in the development of 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 modeling approach of the model. FORCYTE-11 is a modeling 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 MODELING APPROACH

The development of FORCYTE-11 has been guided by a list of design criteria. These are as follows:

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 bioenergy), or agroforestry management systems. It should be a modeling 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 mathematical surrogates for an ecologically and biologically sound description wherever possible.

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, and laboratory measurements of the rates of some processes is unavoidable, inventory-type data should be employed wherever it is possible. This design criterion depends on the combination of a field-measured outcome of some process (e.g., annual growth of plants; annual weight loss of a decomposing log) with an understanding of the 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 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 usable basis for model (or individual module) rejection.

7. Wherever possible, the user should have the option to switch off or alter the simulation of individual processes where he or 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.

8. 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.

9. The modeling 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.

10. The use of the model by resource managers should be made as user-friendly as possible by the development of supervisory computer software that facilitates the user of the model in multiple comparison runs and the presentation and interpretation of the output of these runs.

Details of the modeling approach will not be presented here as they have been presented in Kimmins (1985, 1986, 1988) and Kimmins and Scoullar (1990).

STRUCTURE AND PROCESSES REPRESENTED

Details of the structure and processes of FORCYTE-11 can be found in the user's manual (Kimmins and Scoullar 1990). The structure of this version of the model is summarized in Figure 1, and 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. Some of these representations may be modified or improved upon in future versions.

Planned Future Developments

The benchmark version of FORCYTE-11 marks the end of the second phase of FORCYTE develop-

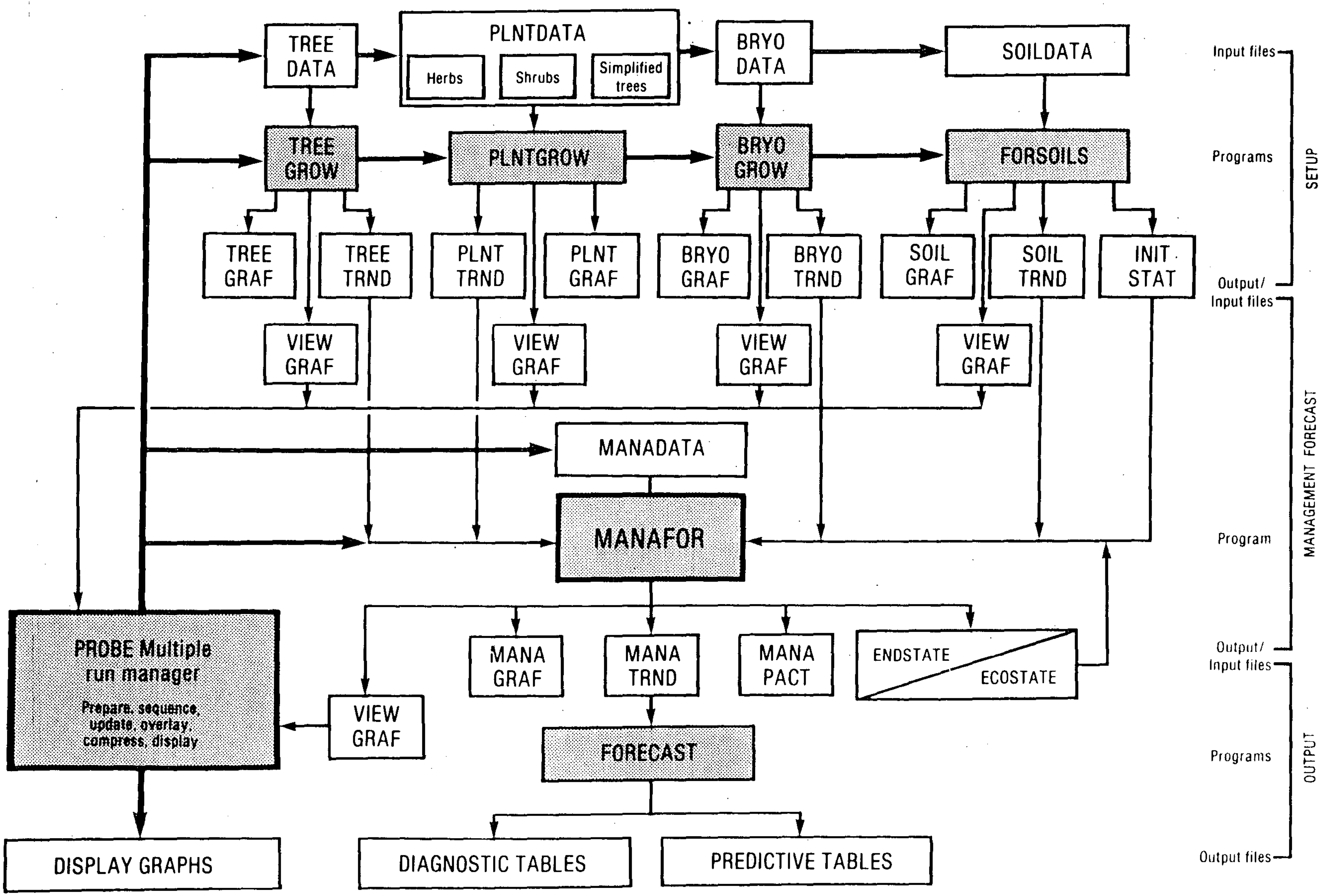

Figure 1. The overall file and program structure of the FORCYTE-11 modeling framework. Users can assemble the appropriate set-up modules to produce a simulation of any particular forest or agroforestry ecosystem. The relationship between the PROBE supervisory software and the FORCYTE framework can be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

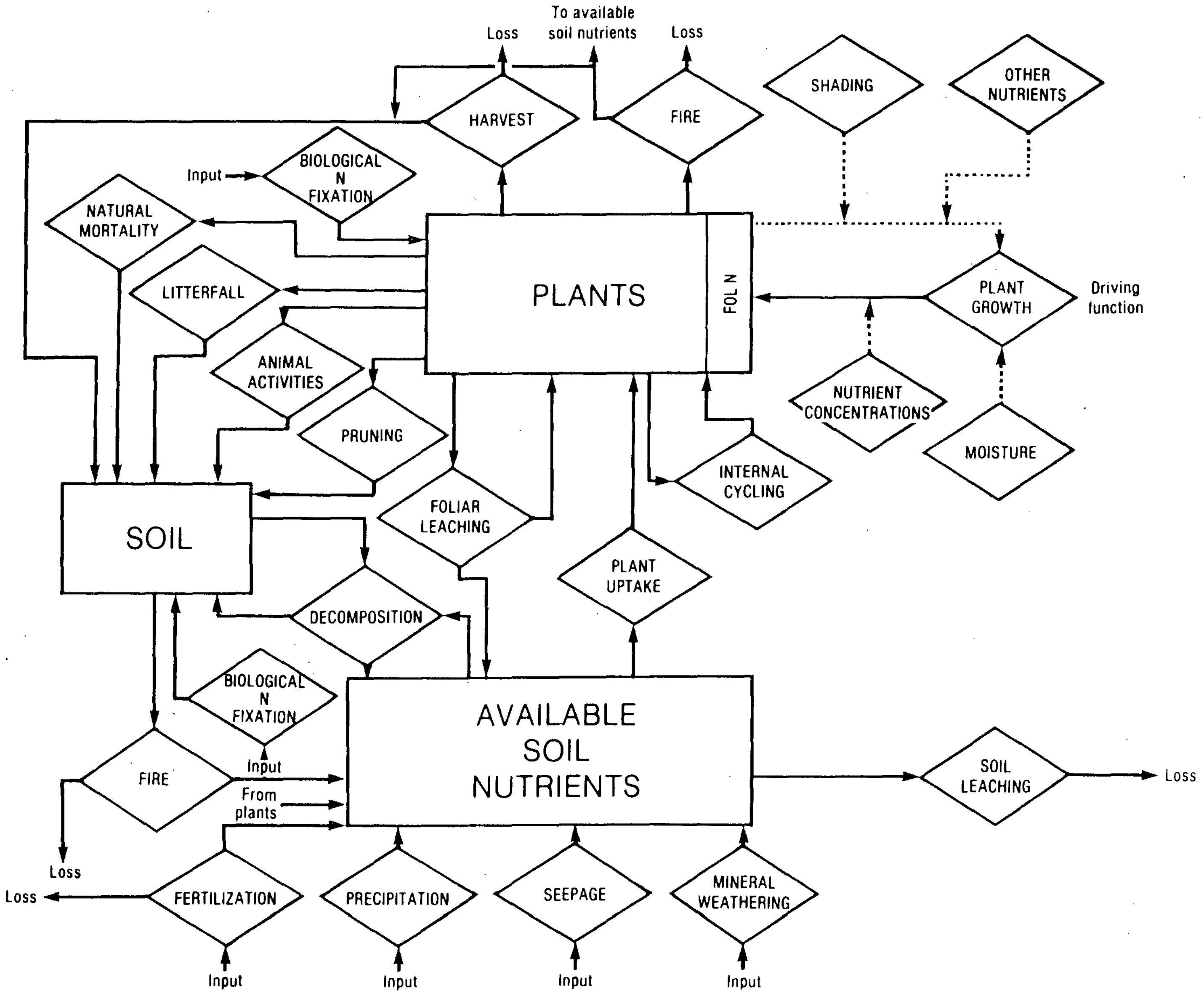

Figure 2. Major compartments and processes that are operational in the benchmark version of FORCYTE-11. Some of the processes shown in earlier published versions of this diagram are not available in this benchmark version but are expected to be available in future versions.

Table 1. Simulated options and processes represented in FORCYTE 11

A. Management options available

- 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)
- Nurser crops—Nitrogen-fixing herbs, shrubs, or trees
- Stand maintenance—control of noncrop species
  —control of species composition
- Fertilization—single or multiple nutrients
- Commercial thinning—high, low, or row thinning. Any utilization level
- Final harvest—clearcutting, shelterwood, or seed tree method (the model can simulate multi-age, selection cut stands, but not as well as its simulation of even-aged clearcut systems) 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, litter fall, foliar leaching, decomposition (mineralization/immobilization).
- Internal cycling—retranslocation of nutrients at the time of tissue senescence
- Decomposition—loss of organic matter and mineralization and immobilization
- Effect of clearcutting on decomposition
- Soil leaching
- Soil exchange capacities

ment, as FORCYTE-10 was the end of the initial period of development. As time and resources permit, a number of further developments are planned.

1. The benchmark FORCYTE-11 will be extended to add a variety of new capabilities. These will include an explicit representation of temperature and moisture in the simulation to permit the model to be used for climate change research and yield prediction. Mechanical site preparation (piling or windrowing, with or without burning), erosion, compaction, phosphorus sorption-desorption, soil mixing by animals or mechanically, some degree of horizontal spatial representation, and a simulation of canopy shape will be added. This model will be called FORCCAST (FORestry and Climate Change ASsessmenT).

2. A variety of improvements will be made to FORCYTE-11 to render it suitable for use in either tropical or temperate agroforestry or in agriculture. The resulting model will be called AGRICYTE (AGRICultural Yield Trend Evaluator).

3. FORCYTE-11 will be modified to make it more suitable for use in mined land reclamation research and the model will be called MINESYTE (MINed EcoSYstem Trend Evaluator). The planned modifications could render the model more useful for acid rain and air pollution research applications.

4. Development of user-friendly, animated color microcomputer games based on one or more of the above models is planned. The intention is to produce these at several levels to serve various purposes:

   a. The high school version will communicate ideas of resource management and environmental sustainability in grade 11 and 12 high school courses. It will also be used for public hearings, openhouses, and other public education applications.

   b. The college-university version will be used for undergraduate teaching in resource ecology or management courses.

   c. The graduate-professional version will be for use in research or as a professional management decision support tool.

All these developments are dependent on securing the necessary research grant support. Other anticipated future activities include the linkage of FORCYTE or other models with a GIS system to change from stand-level to regional prediction and the use of a regional or national modeling framework to permit the model(s) to be used to assess the contribution of Canadian forestry to the greenhouse problem via a national forestry carbon budget analysis.

CONCLUSIONS

Although the capabilities of FORCYTE have developed far beyond 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, sustainability of yield, economics, and energy efficiency of a wide range of alternative management strategies.

Initially a mainframe model, FORCYTE now runs on 386-level microcomputers thanks to the enormous progress made in microcomputer hardware. Until recently, the model's computer requirements were increasing at about the same speed as microcomputer hardware technology, which therefore limited modeling strategy. The hardware developments of 1988 and 1989 have leaped ahead of the model, and it is now anticipated that by 1990 a fairly standard personal computer will be fully capable of running any of the existing or planned model versions.

A model is only as good as its performance and ease of use. Major improvements have been made in the latter by the development of the PROBE package of software (Fig. 1), and further development in this area is anticipated. Verification and validation projects are planned, and a group of cooperators willing to field test the benchmark version of FORCYTE-11 has been identified. A report on the results of this activity is planned for 1990 and 1991.

REFERENCES

Feller, M.C.; Kimmins, J.P.; Scoullar, K.A. 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. Pages 179-200 *in* R.Ballard and S.P. Gessel, eds. Forest site and continuous productivity. Proc. IUFRO Symp. USDA For. Serv., Pac. Northwest For. Range Exp. Stn., Portland, Oreg. Gen. Tech. Rep. PNW-163.

Fox, T.R.; Kimmins, J.P.; Allen, H.L. 1985. Adaptation of the forest nutrient cycling trend evaluator (FORCYTE) for loblolly pine plantations. Pages 203-211 *in* E. Shoulders, ed. Proc. 3rd Bienn. South. Silvic. Res. Conf., Atlanta, Georgia. USDA For. Serv., South. For. Exp. Stn., New Orleans, Louisiana, Gen. Tech. Rep. SO-54.

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

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

Kimmins, J.P. 1986. FORCYTE in forestry: the need for a systems approach in forest education, yield prediction and management. Pages 1-25 *in* The E.B. Eddy Distinguished Lecture Series. Univ. Toronto, Fac. For., Toronto, Ont.

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.; Scoullar, K.A. 1990. FORCYTE-11 user's manual. For. Can., North. For. Cent., Edmonton, Alberta. (In press.)

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

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. Q. J. For. 51:101-115.

Repetto, R. 1987. Population resources, environment: an uncertain future. Popul. Bull. 42(2).

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

Shands, W.E.; Hoffman, J.S., editors. 1987. The greenhouse effect, climate change, and U.S. forests. The Conservation Foundation, Washington, D.C.

World Commission on Environment and Development. 1987. Our common future. Oxford Univ. Press, Oxford, England.

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., New York, N.Y.

Yarie, J. 1986. FORCYTE - extension of a stand level growth and yield model utilizing nitrogen dynamics to taiga white spruce forests. Pages 190-204 *in* K. van Cleve et al., eds. Forest ecosystems in the Alaskan taiga: a synthesis of structure and function. Springer-Verlag, New York, N.Y.

Unpublished report:

Kimmins, J.P.; Scoullar, K.A. 1983. FORCYTE-10. A user's manual for the tenth version of the FORest nutrient Cycling and Yield Trend Evaluator. Second approximation. Prepared for the Canadian Forestry Service, Ottawa, Ont.

FOREST MODELING SYMPOSIUM

Proceedings of a symposium
held March 13-15, 1989, in Saskatoon, Saskatchewan

B.J. Boughton and J.K.Samoil, editors

INFORMATION REPORT NOR-X-308

FORESTRY CANADA
NORTHWEST REGION
NORTHERN FORESTRY CENTRE
1990

*Sponsored by Forestry Canada in cooperation with
the provinces of Alberta, Saskatchewan, and Manitoba
under the auspices of the
Canada-Alberta Forest Resource Development Agreement,
Canada-Saskatchewan Forest Resource Development Agreement, and
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