# FORCYTE - A COMPUTER SIMILATION APPROACH TO EVALUATING THE EFFECT OF WHOLE TREE HARVESTING ON NUTRIENT BUDGETS AND FUTURE FOREST PRODUCTIVITY

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## ABSTRACT

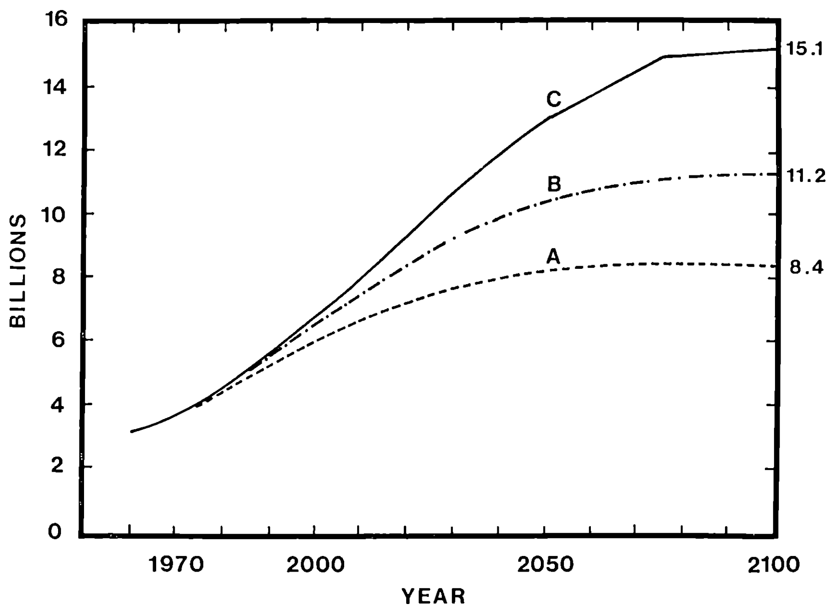
The continuing growth of human populations, the steady decline in the world's forests, and the increased interest in forests as a renewable energy resource will cause a relentless trend towards more complete utilization of forest biomass. This has implications for soil organic matter content and site fertility. FORCYTE is a mathematical model of plant biomass production and decomposition, complete with nutrient cycling and nutrient limitation on growth. Implemented on a computer it permits the user to investigate the probability that soil organic matter, site nutrient capital and forest stand productivity will decline with shortened rotations, increased biomass utilization, and increased intensity of management (thinnings and fertilization). While the model is not yet in final form, its present stage of development permits some useful analyses to be made. Results of applying FORCYTE to a set of management scenarios are presented, together with a brief description of a field study designed to provide data for model calibration.

Simulations of a medium site Douglas-fir forest predicted that changing from harvest to harvest-plus- thinning, to harvest-plus-thinning- plus-fertilization would increase total yield with either stems-only or complete-tree harvest; that 80-year rotations would give a greater mean annual total biomass yield over 240 years than either 120- or 30-year rotations; and that the reduction in yield with the 30-year rotation would be greater for stemwood than for total biomass. In the two longer rotations there would be little reduction in yield from one rotation to the next, but with the 30-year rotation coupled with complete tree harvesting, there would be a rapid drop in mean annual yield over the first three rotations, to a level of about 46% of the first managed rotation. The 120-year rotation would not result in any reduction in forest floor biomass and nitrogen content, whereas these parameters would decline by 89% and 85%, respectively, under complete tree harvesting with thinning and fertilization after 8 successive 30-year rotations. The majority of the drop would occur in the first two rotations. Because these simulations were made with an un-calibrated and un-validated model, they should not be accepted as quantitative predictions.

## INTRODUCTION

As a result of the changing attitude of Third World countries towards their resources, the concept of forests as a renewable energy as well as a renewable raw material resource is moving from the academic to the real world. There is nothing new about the use of forests for energy, of course: underdeveloped countries have been doing it all along, and it is only a few decades since wood and sawdust burners were a common source of domestic heat in many developed countries. However, for much of the western world, it has been one or two centuries since wood was an important industrial source of energy.

Changes in the energy situation together with an impending timber famine in many parts of the world will, we believe, cause increased pressure on the forest resource around the world over the next half century. During this time, world populations are expected to at least double, and possibly triple (Figure 1).




| IF THE WORLD ATTAINED REPLACEMENT FERTILITY IN | WORLD POPULATION WOULD THEN STAND AT | AND WORLD POPULATION COULD BE EXPECTED EVENTUALLY TO STABALIZE AT |
|---|---|---|
| A. 2000 - 05 | 5.9 BILLION (2000) | 8.4 BILLION |
| B. 2020 - 25 | 8.4 BILLION (2020) | 11.2 BILLION |
| C. 2040 - 45 | 12.0 BILLION (2040) | 15.1 BILLION |

Figure 1: Projected growth of the human population according to optimistic (A) and pessimistic (C) assumptions about the future trends in human fertility (Population Reference Bureau 1977).

Much of this increase will occur in the underdeveloped countries (Table 1) where per capita consumption of forest products is still well below that of the highly developed countries. Consequently, this population increase does not neccessarily mean a doubling of the demands for forest products. However, there can be no question that the demand on the forest for raw materials and biomass for energy will continue to increase for the foreseeable future. As a result, foresters must conduct their activities on the basis that loss of productivity is quite unacceptable and that, within social and environmental limitations, every effort must be made to increase production.

Table 1: Some World Population Statistics (Population Reference Bureau 1977)

| Region or Country | 1977 Population (millions) | Annual Percent Increase | No. of years to double Population | Projected Population in 2000 (millions) |
|---|---|---|---|---|
| Libya | 2.7 | 3.9 | 18 | 5.2 |
| Mexico | 64.4 | 3.5 | 20 | 134.6 |
| Iraq | 11.8 | 3.2 | 22 | 24.3 |
| Brazil | 112. | 2.8 | 25 | 205. |
| Nigeria | 66.6 | 2.7 | 26 | 134.9 |
| India | 622.7 | 2.1 | 33 | 1,023.7 |
| World | 4,083. | 1.8 | 38 | 6,182. |
| Canada | 23.5 | 0.8 | 87 | 31.6 |
| U.S.A. | 216.7 | 0.6 | 116 | 262.5 |
| France | 53.4 | 0.4 | 173 | 61.7 |
| United Kingdom | 56. | 0.1 | 693 | 61.9 |
| East Germany | 16.7 | -0.4 | - | 17.7 |

In spite of the fact that much of our country is forested the situation in Canada is not much different from elsewhere in the world. Decades of exploitation in old-growth forest, coupled with inadequate investment in regeneration, protection, research and forestry education at the technical, undergraduate and graduate level has left much of Canada's forests in a serious condition (Reed et al. 1978). In British Columbia we can look forward to declining yields for many decades, and even the most intensive management imaginable will only reduce and not prevent an impending yield "fall-down". To reduce the undesirable socio-econimic effects of this yield reduction to a minimum, there will be great pressure to increase the rate of biomass harvest in our forests.

Short-term increases in harvested biomass can be obtained in many ways, including shorter rotations, intensive utilization, appropriate post- logging site treatment, better choice of species, use of genetically improved stock, prompt regeneration, optimum stocking control, control of non-commerical species, and fertilization. The latter may be essential for sustained high production on many sites because of nutrient withdrawals in harvested materials. Increasing the proportion of the stem that is harvested may not pose a major problem of nutrient withdrawals unless it is coupled with very short rotations and high stocking density.

However, if we move to complete-tree harvesting, including the stump-root and crown, we may reduce the availability of nutrients on the site to the level at which future growth is reduced. Where successful fertilization is economically and biologically feasible, withdrawals of nutrients in harvested materials may be of little concern. However, it is not yet clear that fertilization can always be relied upon to solve such problems, at the loss of forest floor biomass and soil organic matter may ultimately prove to be more serious than the loss of nutrients. It may be possible to replace lost nutrients by fertilization, whereas soil organic matter cannot be replaced by the manager. It would be prudent for foresters to consider conservation of the existing site capital of nurtients and organic matter as a basic objective of their management.

Evaluation of the long-term effects of intensive biomass harvesting is complex, requiring answers to several questions (Kimmins 1977):

1. What proportion of the site nutrient capital, total and "available", is removed in havested materials?
2. How frequently will harvest-induced losses occur?
3. What is the magnitude of other harest-induced losses such as erosion and soil leaching?
4. How rapidly does the remaining site nutrient capital cycle? How "available" are the nutrients to the plant?
5. How rapidly are the nutrient losses replaced by natural processes, and what are the processes?
   How are the processes of replacement affected by harvesting and stand treatments?
6. What is the nutrient demand of the next crop? How does the nutrient demand on the soil vary during the life of the crop?
7. What is the nutrient cycling "strategy" of the crop species? How efficiently can it conserve and accumulate nutrients?
8. How important is availability of nutrients in regulating production of the crop species? To what extent can the species modify its internal cycling of nutrients to compensate for reduced uptake from the environment?
9. How easily (economically and ecologically) can the harvest-induced losses be replaced by fertilization or other means?

For most situations we do not yet know the answers to these and other pertinent questions, and even if we did, it would be difficult to synthesize this diversity of knownledge into reliable predictions about the long-term effects of intensive biomass harvesting. Such complexity demands that a computer simulation approach be used in attempts to answer the above types of questions.

## Objectives of the Modelling Activity

The past decade has witnessed much activity in computer simulation of nutrient cycling in forest ecosystems. This activity has produced many models of forest growth, the development of which has been justified in terms of advancing our understanding of forest ecosystems through synthesis of existing knowledge, identification of gaps in our knowledge, and providing a guide for future research. Most of the models that have been produced have been specific to the forest types that they describe, have involved detailed simulation of biological processes and generally they have not proven useful as management tools. Their value has been more to forest science than to forest management.

In developing this simulation model, our objectives were somewhat different. We wanted a model that:

1. could be used to predict the long-term consequences (in terms of biomass production, ecosystem organic matter and nutrient capitals, and economic and energy cost (benefit ratios) of switching from conventional long-rotation, low utilization to short-rotation, high utilization forestry;
2. would have broad generality, so that it could be used as a management-gaming tool for many different forest conditions;
3. would produce output in a graphical as well as a tabular form to give the user confidence of the biological reality of its predictions;
4. would permit the user to examine all the major types of intensive forest management treatments, including thinning (commercial and non-commercial), pruning, fertilizing, clearcutting, controlling brush with herbicides, and varying regeneration delay, on a site-specific basis;
5. has a feedback between the availability of nutrients and plant growth. We wanted the model to respond, within defined limits, to either site improvement or site degradation;
6. would run on inventory-type input data rather than requiring detailed process information that would involve many years of scientific work to prepare.

(Mitchell et al. 1975, Penning de Vries et al. 1975, Waide et al. 1977, Aber et al. 1978 and Aber et al. 1979) but none satisfy all of them. Consequently, we undertook to develop a new model, named FORCYTE (FORest nutrient CYcling Trend Evaluator). To date we have invested two years work in our efforts to achieve these objectives. The present edition of the model is called FORCYTE-9.

## Overall Description of FORCYTE-9

FORCYTE-9 is a model of plant biomass production and decomposition, complete with nutrient cycling, nutrient limitation on growth, and management interventions. It has been designed for even-aged plantation forests that are clear-cut harvested at or before reaching maturity. The present driving functions for plant growth are site-specific volume/age equations of the Chapman-Richards type (Pienaar & Turnbull 1977), but the predicted growth is modified according to the availability of nutrients to the plants.

To date, the model has been run only for nitrogen, but any element for which the necessary input data are available can be used in the model. The model does not simulate the effects of water availability and climate explicitly; these effects are implicit in the driving-function (site-specific volume/age equations). However, we recognize that the model's predictions will be less reliable where extremes of climate and moisture are the major constraints on biomass production. They will be most accurate in more moderate environments in which nutrient availability plays a major role in determining tree growth.

Figure 2 presents a simplified flow chart of the model. Site-specific growth equations are used to simulate the development of stemwood biomass for the particular type of site being considered. Age-specific ratios of foliage, branch, stembark, and root biomass to stemwood biomass are applied to the age-sequence of stemwood biomass to simulate the development of these biomass components over time. Growth in the model occurs to replace ephemeral litterfall, to replace natural tree mortality, and to produce the increase in net biomass expected according to the growth equations.

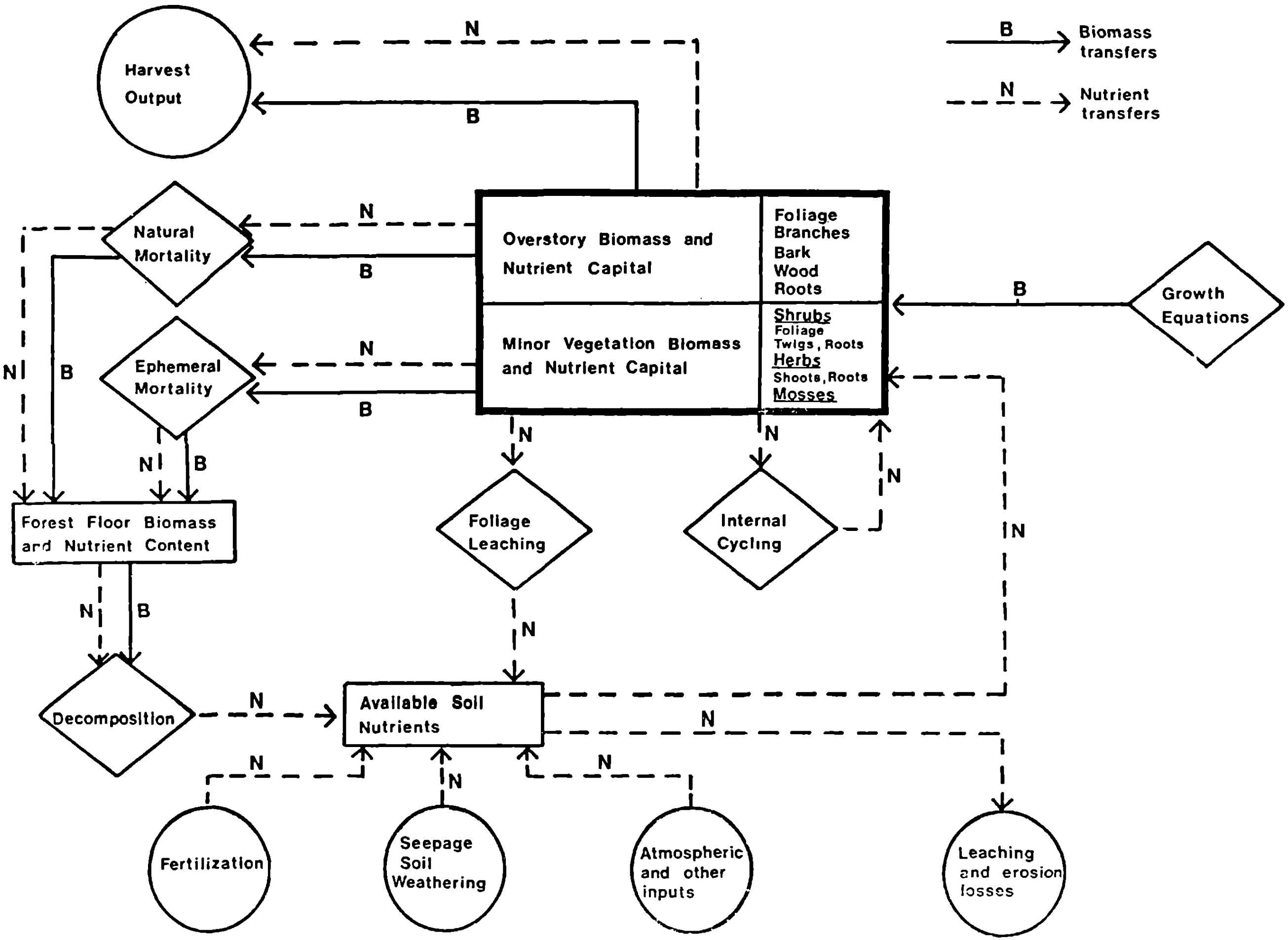
Ephemeral litterfall is produced as follows. The model keeps a record of the bark, foliage and branches produced each year, and transfers the oldest cohort of these components to litterfall when they reach an age that is dictated in the input data file. The proportion of small roots becoming litterfall each year is the same as the proportion of foliage that becomes litterfall. This is an oversimplified assumption that requires change in a future edition of the model. The fixed age at which tree components become litterfall, regardless of site fertility or tree stocking density, is another of the several weaknesses in FORCYTE-9 that will be removed in FORCYTE-10 (due to be completed by 1981).

Tree mortality occurs according to natural mortality curves (stems per hectare/stand age) for each site type given in an input data file. As the age of the stand increases, the expected number of stems declines, and any trees in excess of the expected number are added to litterfall.

FORCYTE-9 only deals with average sized trees. In FORCYTE-10, where a distribution of tree sizes will be simulated, mortality will be applied to the smaller trees.

As each annual litterfall component reaches the forest floor it experiences changes in weight and chemical concentrations according to instructions given in the input data file. For each type of litter, the decay coefficient changes over a decay period that varies for different litterfall components. Rate of decay increases initially and then declines as the remaining material approaches the humus condition. The chemical concentrations in the litter may change linearly with time, may change more rapidly at

Figure 2: Simplified FORCYTE Flow Chart (FORCYTE-9 does not have foliar leaching or mosses included in the simulation)



first or may change more slowly at first, ultimately attaining the concentration found in humus. The pattern of change for each litterfall component is controlled in the input file.

The combination of biomass changes and chemical concentration changes in decomposing litterfall results in either an increase (immobilization) or a decrease (mineralization) in the total amount of the chemical in that litter. Mineralization adds nutrients to an "available soil nutrient pool" and immobilization removes nutrients from this pool. The pool also receives inputs from precipitation, canopy leaching, soil weathering, slope seepage and fertilization, and loses nutrients to soil leaching and uptake by plants.

The input data file defines the chemical composition of various biomass components, and this permits calculation of the amount of nutrients required for the expected new growth (including that to replace ephemeral litterfall and tree mortality), and to replace nutrient losses in foliar leaching (not included in FORCYTE-9). These nutrients may be provided by redistribution within the plant, or by uptake. Internal cycling in trees is simulated by comparing the differences in chemical content in young and old components, and in old and dead (litterfall) components. The remaining nutrients required for new growth are designated as the nutrient demand that must be satisfied through uptake. Where the supply of nutrients from the soil available pool fails to provide the uptake demand, growth is reduced. Where the supply exceeds demand, growth is increased towards an upper limit that is defined in the model.

FORCYTE grows a population of herbs following clearcut harvesting. These are shaded out as shrub foliage biomass develops, and the shrubs are in turn shaded out as tree foliage biomass develops. Shrub and herb growth, internal cycling and nutrient uptake are simulated in the same manner as for trees, except fewer components are included: shoots and roots for herbs,and twigs, foliage and roots for shrubs. Shrub and herb growth are both site-dependent, as is tree growth.

Soil leaching of nitrogen depends upon the form of nitrogen. Mineralized nitrogen is allocated to nitrate and ammonium forms depending upon the site quality, the biomass of herbs and the biomass of tree fine roots. Nitrate nitrogen is leached if it is not taken up by plants or immobilized in the process of litter decomposition. Ammonium nitrogen is retained even in the absence of plant uptake; it is assumed to be adsorbed on cation exchange sites.

As the model simulates over time, site quality can change according to whether or not tree demand for nutrients is satisfied. Where the demand is not satisfied, site quality is lowered, growth is reduced and there is a change in a wide variety of other variables, such as internal cycling, chemical concentrations in new biomass, and decomposition rates. Additions of nutrients improve the site quality while losses or withdrawals of nutrients reduce site quality.

This is a very brief description of a rather complex model. A more detailed description of the model (FORWRITE-9) is available.

## Type of Output from FORCYTE-9

Because of the complexity of the model, FORCYTE provides a variety of types of output. Most of these are merely to provide the user with a detailed understanding of annual changes in various parameters and processes in the simulated forest. This is important to give the user confidence in the biological realism of the model. For example, values of up to 120 parameters can be printed out annually in a series of 12 graphs for runs of up to 500 years. Two diagnostic files can be printed out, as desired. One of these describes the state of every parameter at the end of each run, while the other presents details of the annual net immobilization or release of nutrients from each of the decomposing biomass categories identified in the forest floor. Finally, the model can print out a series of tables summarizing the biomass and nutrient budgets for the entire run, for each rotation in the run, and for each thinning or fertilization within the rotation. Table 2 presents a summary of the type of information included in the output.

## Example of the Use of FORCYTE-9

FORCYTE-9 is still a stage of development of FORCYTE, and its predictions should be less reliable than those of future versions. However, the known inadequacies of the model do not prevent us from making qualitative predictions concerning the effects of intensive biomass harvesting on site nutrient and organic matter budgets. As an illustration of the potential uses of the model, Figures 3, 4, 5, and 6 show the results of a series of simulations for a west coast Douglas-fir forest growing on a medium site in which rotation length was varied. Figure 3 shows the stem and total biomass harvested in eight successive 30-year rotations under two management regimes: stems-only harvest with no stand management, and complete tree harvest with a 50% commercial thinning at age 20 years and fertilizing with 150 kg $N.ha^{-1}$ two years after the thinning. The simulation shows an increase in the total biomass harvested as the intensity of management and utilization increase, but a decline in stemwood biomass harvested with complete tree utilization. Complete tree utilization produced a much more marked decline in yield in successive rotations than did stem-only harvesting, and this is reflected in a progressively greater loss of forest floor biomass and nitrogen as rotations are reduced and as the intensity of management and utilization is increased (Figure 4). The short rotation intensive management appears to be "mining" the capital of biomass and nutrients accumulated in the forest floor by the old-growth, unmanaged forest that existed prior to the institution of the intensive management.

Figures 5 and 6 present a summary of comparable simulations for three intensities of management and two intensities of utilization with 120-year, 80-year and 30-year rotations over a 240-year period. The progressive increase in total biomass yield and decrease in forest floor biomass and nitrogen capital as the intensity of management and utilization increase is seen in all three rotations. Stemwood biomass yield is increased by going from 120- to 80-year rotations, but it is decreased by a 30-year

Table 2: Summary of some predictions of FORCYTE based on input data for a medium Douglas-fir site in southwestern British Columbia. The predictions should not be treated quantitatively since the model was not accurately calibrated for these runs and the model is not yet in final form. The table is merely presented to illustrate part of the output capabilities of the model. The run assumed a commercial thinning at 20 and 40 years and a whole tree harvest at 80 years.

BIOMASS AND NUTRIENT CONTENT IN HARVESTED TREES AND SLASH (kg.ha$^{-1}$)

| Rotation | Treatment | Stand Age | Parameter | Stem Wood | Stem Bark | Branches | Foliage | Roots | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Thinning 1 | | Biomass removed | 23,871 | 9,103 | 24,976 | 14,216 | 9,610 | 81,776 |
| | | | Biomass slash | 241 | 92 | 252 | 3,554 | 9,038 | 13,177 |
| | | | Nitrogen removed | 24 | 36 | 63 | 175 | 17 | 315 |
| | | | Nitrogen slash | 0 | 0 | 1 | 44 | 88 | 133 |
| | | | Biomass removed | 39,797 | 9,465 | 17,881 | 5,962 | 21,108 | 94,214 |
| | | | Biomass slash | 402 | 96 | 181 | 1,491 | 11,169 | 13,338 |
| | | | Nitrogen removed | 30 | 29 | 35 | 58 | 33 | 184 |
| | | | Nitrogen slash | 0 | 0 | 0 | 14 | 82 | 98 |
| | Harvest 1 | | Biomass removed | 193,588 | 33,509 | 45,607 | 17,709 | 110,176 | 400,588 |
| | | | Biomass slash | 1,955 | 338 | 461 | 4,427 | 48,781 | 55,963 |
| | | | Nitrogen removed | 117 | 96 | 81 | 165 | 133 | 592 |
| | | | Nitrogen slash | 1 | 1 | 1 | 41 | 326 | 370 |
| Summation for the rotation | | | Biomass removed | 257,256 | 52,076 | 88,464 | 37,887 | 140,894 | 576,578 |
| | | | Biomass slash | 2,599 | 526 | 894 | 9,472 | 68,988 | 82,478 |
| | | | Nitrogen removed | 170 | 161 | 179 | 398 | 183 | 1,092 |
| | | | Nitrogen slash | 2 | 2 | 2 | 99 | 496 | 600 |

| | At Start | At End | % Change |
|---|---|---|---|
| Total Site Nitrogen | 2,632 | 1,598 | -39.28 |
| Total Site Biomass | 478,718 | 213,108 | -55.48 |
| Forest Floor Nitrogen | 2,602 | 1,579 | -39.32 |
| Forest Floor Biomass | 478,717 | 211,769 | -55.76 |

BIOMASS AND NITROGEN IN ECOSYSTEM PROCESSES (kg.ha$^{-1}$)

| Parameter | Trees Rotation | Trees Annual | Shrubs Rotation | Shrubs Annual | Herbs Rotation | Herbs Annual |
|---|---|---|---|---|---|---|
| **Biomass:** | | | | | | |
| Total Production | 1,791,761 | 22,397.01 | 56,730 | 709.13 | 7,716 | 96.45 |
| Total Litterfall | 1,105,460 | 13,818.25 | 55,941 | 699.26 | 7,720 | 96.51 |
| Litter as % of production | 67.7 | | 98.6 | | 100 | |
| **Nitrogen:** | | | | | | |
| Total uptake | 6,733 | 84.16 | 413 | 5.16 | 51 | 0.64 |
| Total litterfall | 5,078 | 63.48 | 408 | 5.10 | 51 | 0.64 |
| Total internal cycling | 5,241 | 65.51 | 305 | 3.81 | 58 | 0.73 |
| Biomass Production/N Uptake | 266 | | 138 | | 150 | |
| **Nitrogen Inputs and Losses:** | | | | | | |
| Precipitation input | 400 | 5 | | | | |
| Soil weathering input | 80 | 1 | | | | |
| Biol. fixation input | 80 | 1 | | | | |
| Fertilization input | 0 | 0 | | | | |
| Soil leaching input | 554 | 6.8 | | | | |
| Harvesting output | 1,092 | 13.7 | | | | |

Figure 3: Simulated mean annual stemwood biomass yield and total biomass yield for Douglas-fir on a medium-quality site in coastal British Columbia over 8 successive 30-year rotations. The figures on the left are for stems-only harvest with no management. The figures on the right are for complete-tree harvest with a 50% thinning at 20 years and a fertilization (150 N kg.ha$^{-1}$) at 22 years.

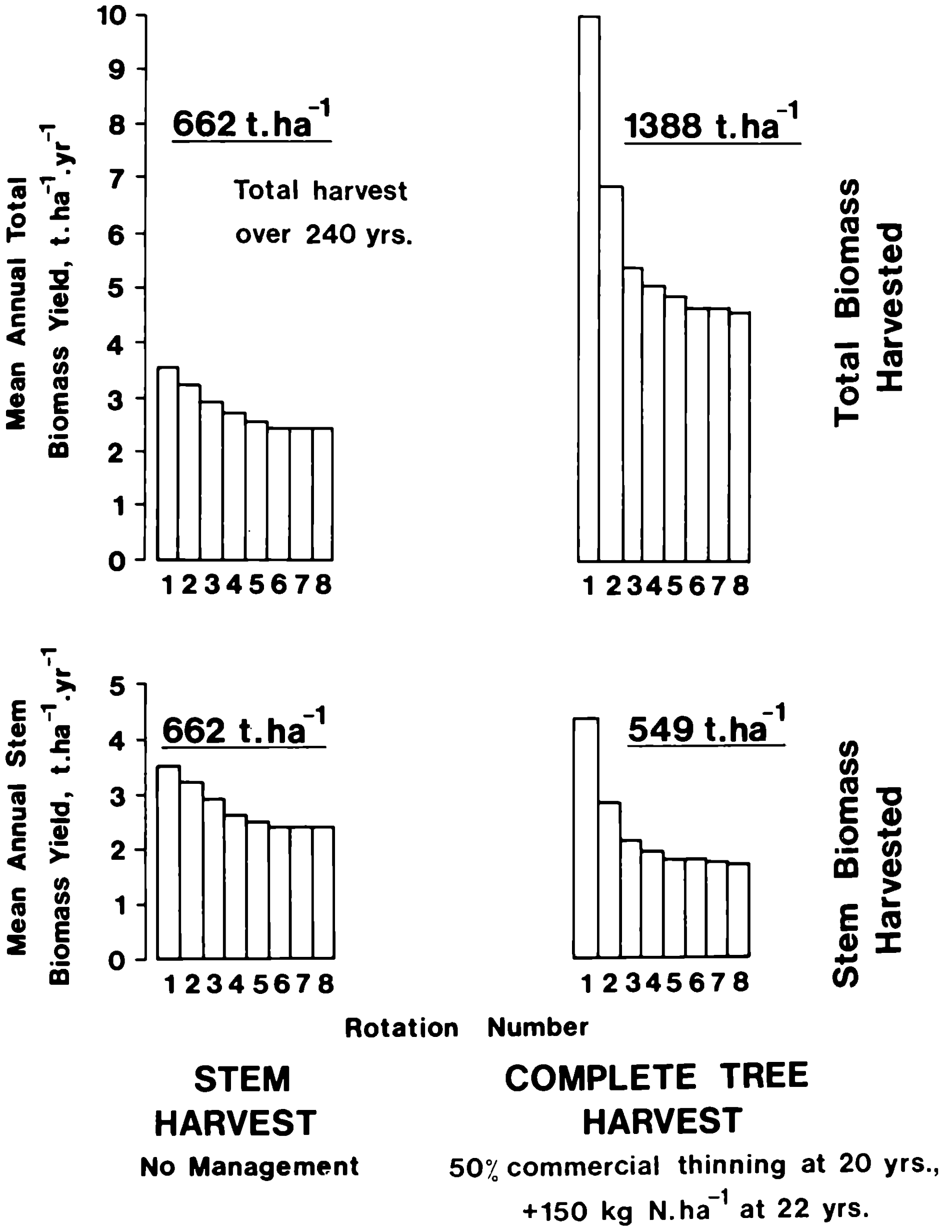


Figure 4: Simulated changes in the biomass and nitrogen content of the forest floor under the management and harvesting regimes described in Figure 3. The value at the beginning of each graph (marked with a +) indicates the condition following clearcut harvesting of a mature, old-growth stand.

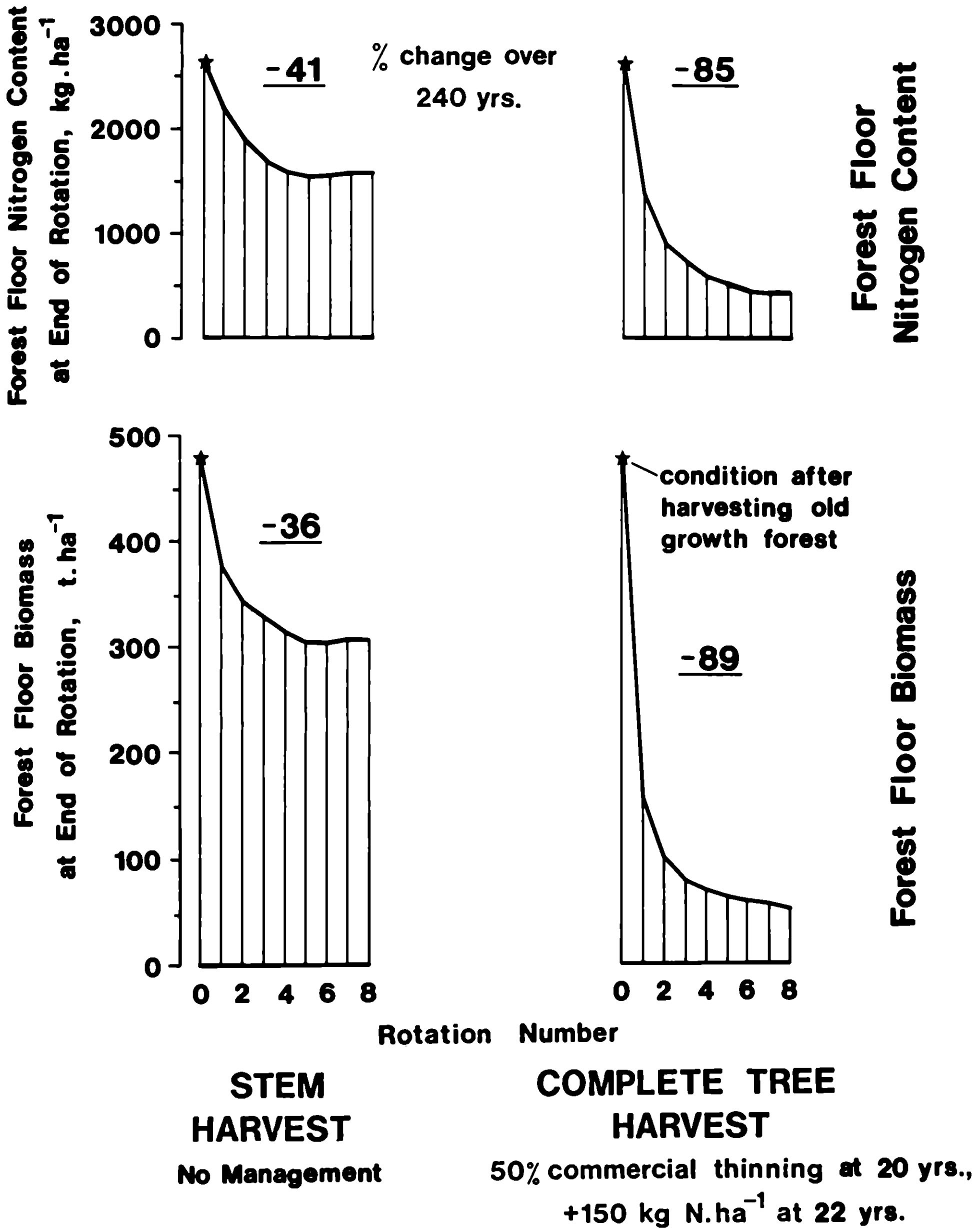


Figure 5: Summary of simulated mean annual harvested biomass for Douglas-fir growing on a medium quality site in coastal British Columbia over a 240-year period. Results of simulations are shown for 1, three different intensities of management (no management-harvesting, thinnings + harvest, and thinnings + fertilization + harvest), 2, two different intensities of utilization (stem-only and complete-tree harvests) and 3, three different rotation lengths (120 yrs, 80 yrs and 30 yrs). The shaded area of the graph indicates stem biomass; the unshaded portion indicates crown, stump and root biomass).

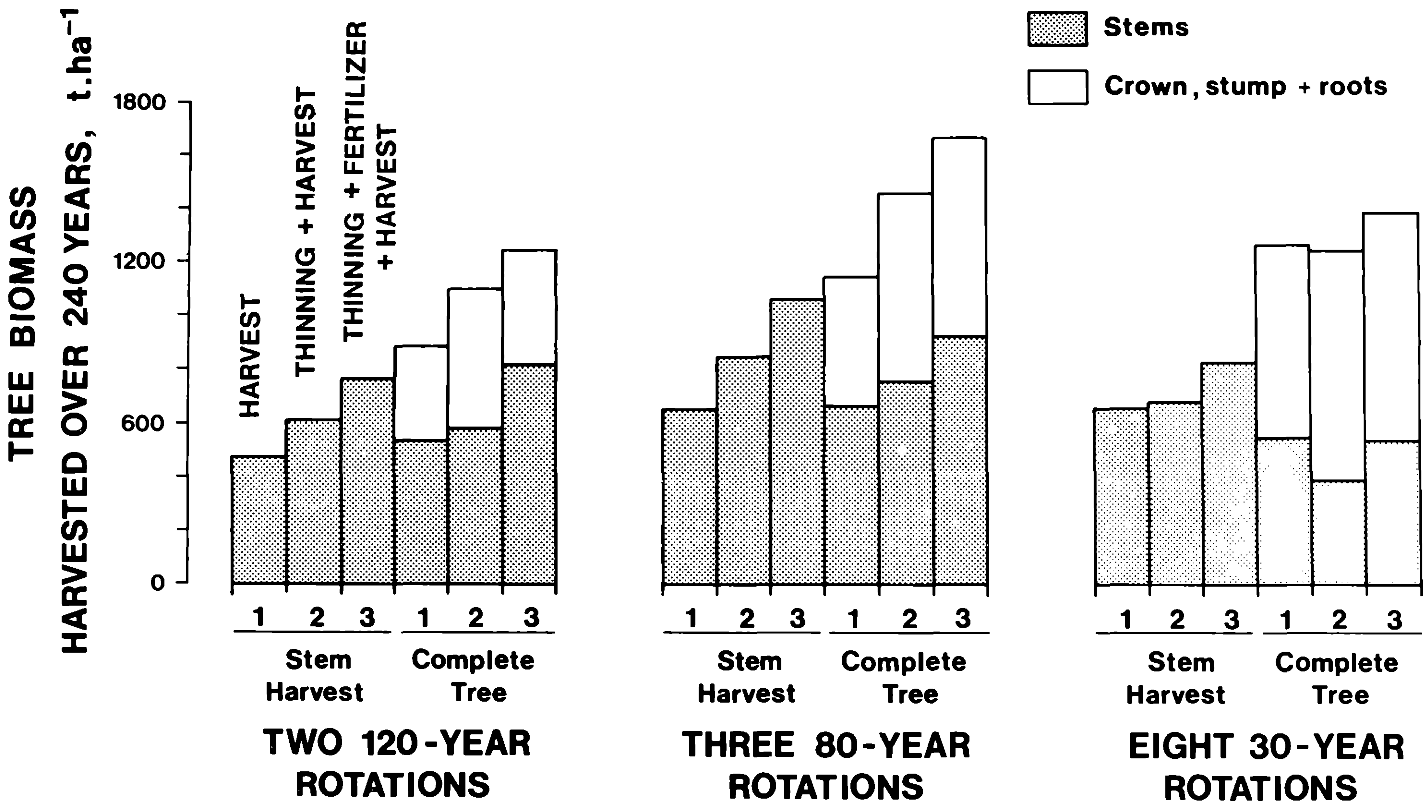
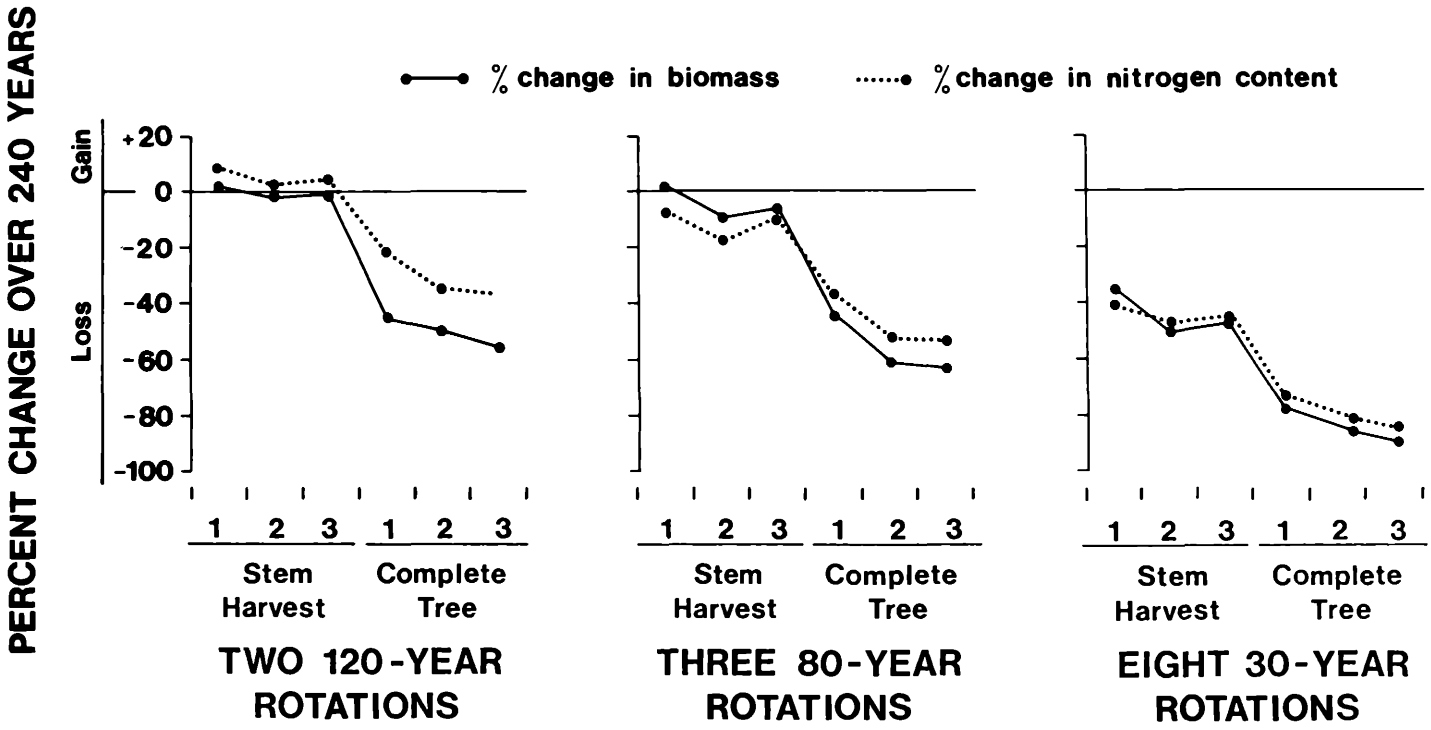


Figure 6: Summary of the simulated changes in forest floor biomass and nitrogen content under the management and harvesting regimes described in Figure 5.



rotation length. Both total and stem biomass yields are greater with an 80-year than with a 30-year rotation, and the rate of loss of forest floor biomass and nitrogen is much less with the former than with the latter rotation length.

The suggestion made by these simulations is that yield can be increased by switching from a 120-year rotation with no management to a shorter rotation with increased management and more intensive utilization, but that there is some point beyond which increasing our demands on the forest will reduce its yield. The intensity of management and utilization at which this occurs will differ on sites of different quality, but could easily be determined by iterative simulations using FORCYTE. This will be done using FORCYTE-10.

The reader is reminded that the predictions in Figures 3, 4, 5 and 6 are qualitative only. They are produced by an un-calibrated and un-validated model. They are merely presented to show the potential of the model. However, we do feel that they are probably qualitatively correct.

## Future Development of the Model: FORCYTE-10

In the coming year, FORCYTE will be modified in a number of ways that will improve its representation of biological and ecological processes and eliminate known deficiencies. In addition, the model will by given the ability to predict log-size at thinning and harvest, and to assign monetary values to harvested biomass and costs to management options. This will permit the addition of an economic cost/benefit analyses for comparisons between selected management regimes. An energy balance analysis will also be added to enable managers to consider the energy cost/benefit rations of different management strategies.

## Field Research to Calibrate FORCYTE

Accompanying the simulation activities, we have a field research project to provide data with which to calibrate the model. Douglas-fir stands of ages varying from 3 years to 80 years old have been selected on both low productivity and high productivity sites on Vancouver Island. Complete biomass inventories have been made and chemical analysis is being undertaken so that we can prepare biomass and nutrient budgets and provide FORCYTE with the necessary input data. Nutrient and biomass turnover is being studied by measuring litterfall, foliar leaching and litter decomposition. Once the model is calibrated to these study sites (i.e. once it can accurately simulate the measured conditions and processes on the study sites) its predictions will be tested using both experimental manipulation of the study sites and a comparison between predictions and British Columbia Forest Service fertilizer-thinning plot data.

## ACKNOWLEDGEMENTS

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