

FORCYTE: A COMPUTER SIMULATION APPROACH TO EVALUATING THE EFFECT OF WHOLE-TREE HARVESTING ON THE NUTRIENT BUDGET IN NORTHWEST FORESTS

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ABSTRACT

A brief description is given of FORCYTE, an interactive simulation model designed to examine, on a site-specific basis, the long-term effects on nutrient budgets and productivity of various intensive forest management and harvesting practices. There is an input-data file that provides the necessary site and species information and enables the user to dictate various regeneration, spacing, thinning, fertilization, and harvesting options. The model is a hybrid between a process model and an empirical model. It is being designed for use with inventory-type data that can be obtained in one year of research, from the literature, or both.

INTRODUCTION

As a result of the changing attitude of Third World countries toward their resources, the concept of forests as renewable energy as well as a renewable raw material resources 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 developed countries. For much of the western world, however, 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, result in a greatly increased pressure on the forest resource over the next half century. During this time, world populations are expected to at least double, and possibly triple. Much of this increase will occur in the underdeveloped countries where per capita consumption of forest products is still well below that of the highly developed countries (Table 1). Consequently, this population increase does not necessarily 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. Consequently, 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.

Increases in forest production can be obtained in many ways, including shorter rotations, improved utilization, appropriate postlogging site treatment, better choice of species, use of genetically improved stock, prompt regeneration, optimum stocking control, control of undesirable, noncommercial species, and fertilization. The last is 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.

If we move to stump-root harvesting and the removal of branches and foliage from the site, however, we may reduce the availability of nutrients on the site to the level at which growth is reduced. Where successful fertilization is feasible, both economically and biologically, site nutrient reduction may be of little concern. It is not yet clear, however, that fer-

Table 1. Some world population statistics (Population Reference Bureau 1977).

Region or country	1977 population (millions)	Annual % increase	Years to double population	Projected population in A.D. 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	112.0	2.8	25	205.0
Nigeria	66.6	2.7	26	134.9
India	622.7	2.1	33	1023.7
World	4083.0	1.8	38	6182.0
Canada	23.5	0.8	87	31.6
United States	216.7	0.6	116	262.5
France	53.4	0.4	173	61.7
United Kingdom	56.0	0.1	693	61.9
East Germany	16.7	-0.4		17.7

tilization can always be relied upon to solve such problems, and it would be prudent for foresters to consider conservation of the existing site nutrient capital as a basic component of their management strategy.

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 harvested materials?
2. How frequently will harvest-induced losses occur?
3. What is the magnitude of other harvest-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 losses (from the total or the available pool) 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) are the harvest-induced losses 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 knowledge into a reliable prediction about the long-term effects of intensive biomass harvesting. Such complexity demands that a computer simulation approach be used in conjunction with attempts to answer the above types of questions.

FORCYTE: THE MODEL

Over the past year we have been developing a model with which to synthesize existing information, to guide research needed to fill in information gaps, and to arrive at some predictions about the possible long-term consequences of intensive biomass harvesting (i.e., to give us some foresight into the future consequences of present actions). We have called our model FORCYTE (forest cycling trend evaluator). It differs from the other approaches to modeling this topic that we have seen (e.g., deVries et al. 1975, Mitchell et al. 1975, Waide and Swank 1977, Aber et al. 1978, 1979) in that: (1) it is basically not a process model, (2) it is designed to be applied to a wide variety of forest types, and (3) it is designed to permit the user to examine the consequences of a variety of forest management practices. At the time of this paper the model is the result of 14 mo of activity. A further 18 mo development is planned in order to produce the final version of FORCYTE.

The objective of our modeling activity is to produce a largely empirical model that can be applied on a site-specific basis to examine the possible consequences of various intensive forest management and biomass harvesting scenarios in a variety of forest types. The design requirements of the model are that it have reasonably modest input data requirements with which to make site- and species-specific runs. This precluded using the process model approach, which usually requires many years of intensive scientific research in order to provide the necessary detailed data. Basic ecosystem processes are built into the model, which requires mainly inventory-type data to run it.

The model is designed to have a negative feedback of nutrient availability on plant growth and it assumes that nutrients are a major limiting factor in organic production. Where this is not the case, the model's predictions will be unreliable. Effects of regional climate and local soil moisture availability are dealt with implicitly in the model rather than being explicitly defined. This is done by using local volume-table data as the major driving function of the model. Such data integrate the effects of climate, soil, and biotic factors acting on the stand.

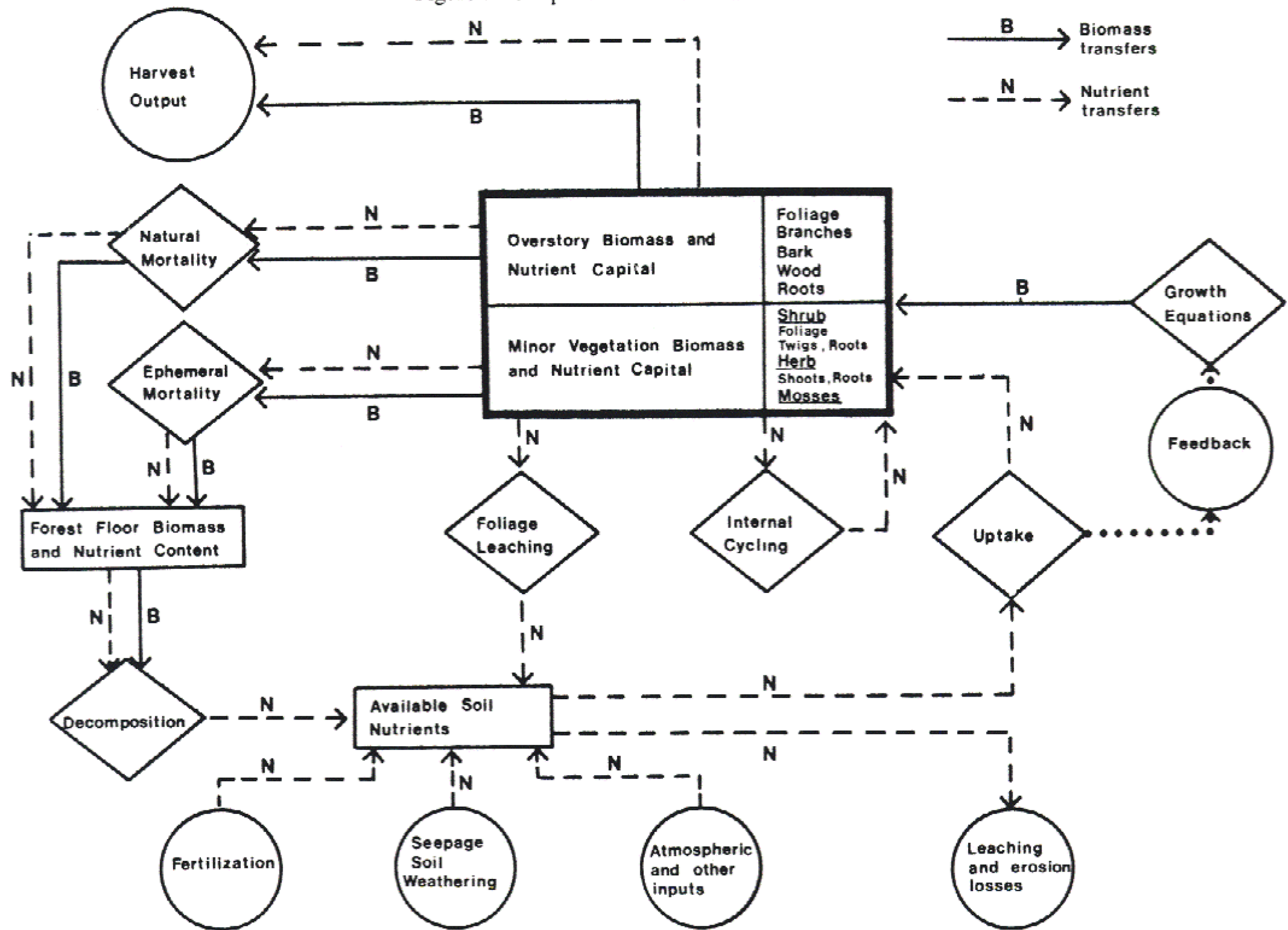
FORCYTE is primarily designed for use by resource managers to examine the possible consequences of various management decisions such as choice of species, stocking density, frequency and intensity of thinnings, fertilization, different intensities of harvesting, different rotation lengths, and certain site treatments (e.g., slash-burning, although this is not yet in the model). The model recognizes three classes of site (good, medium, and poor) but it is able to interpolate between them. It permits either site improvement or site degradation to occur during a run, which can be for up to 500 yr.

The predictions are necessarily qualitative in nature: the model is not intended to make precise scientific predictions and the further into the future one goes, the less reliable the prediction. For example, in 500 yr we could have experienced major changes in world climate that would totally invalidate predictions based on present-day climatic conditions as expressed through the growth equations.

The structure of the model inevitably reflects the senior author's experience, which is mainly with coniferous forests, both plantations and natural. It is not yet clear as to how well it would work for multispecies forests but there is no structural reason to suggest that it would not work. We believe that with minor modifications we could probably make it work for most types of forest. The model has been designed for even-aged forests growing on rotations of less than about 150 yr. The model does not work well if it is run indefinitely without harvest. It is thus first and foremost a management model.

Figure 1 shows the overall structure of FORCYTE. The model grows a forest from some initial starting condition (determined by the use of an "initial states" file that can be adjusted at will) until the run is terminated by the user. The

Figure 1. Simplified FORCYTE flowchart.



major driving function is tree growth, but the model also grows herbs and shrubs and will grow mosses in a future edition. The components of the model will be described in turn.

MAJOR COMPONENTS

Biomass Production

Each of the plant components (trees, shrubs, herbs, mosses) is grown according to the Chapman-Richards growth equation (Pienaar and Turnbull 1973) which has the form:

$$\text{volume (or biomass)} = B_1 * (1.0 - \exp(B_2 * \text{age}))^{B_3}$$

For lesser vegetation, this equation is fitted to empirical data on accumulated biomass at various ages in the absence of trees. For trees, the equation for commercial stem volume is used, volume being converted to biomass as follows:

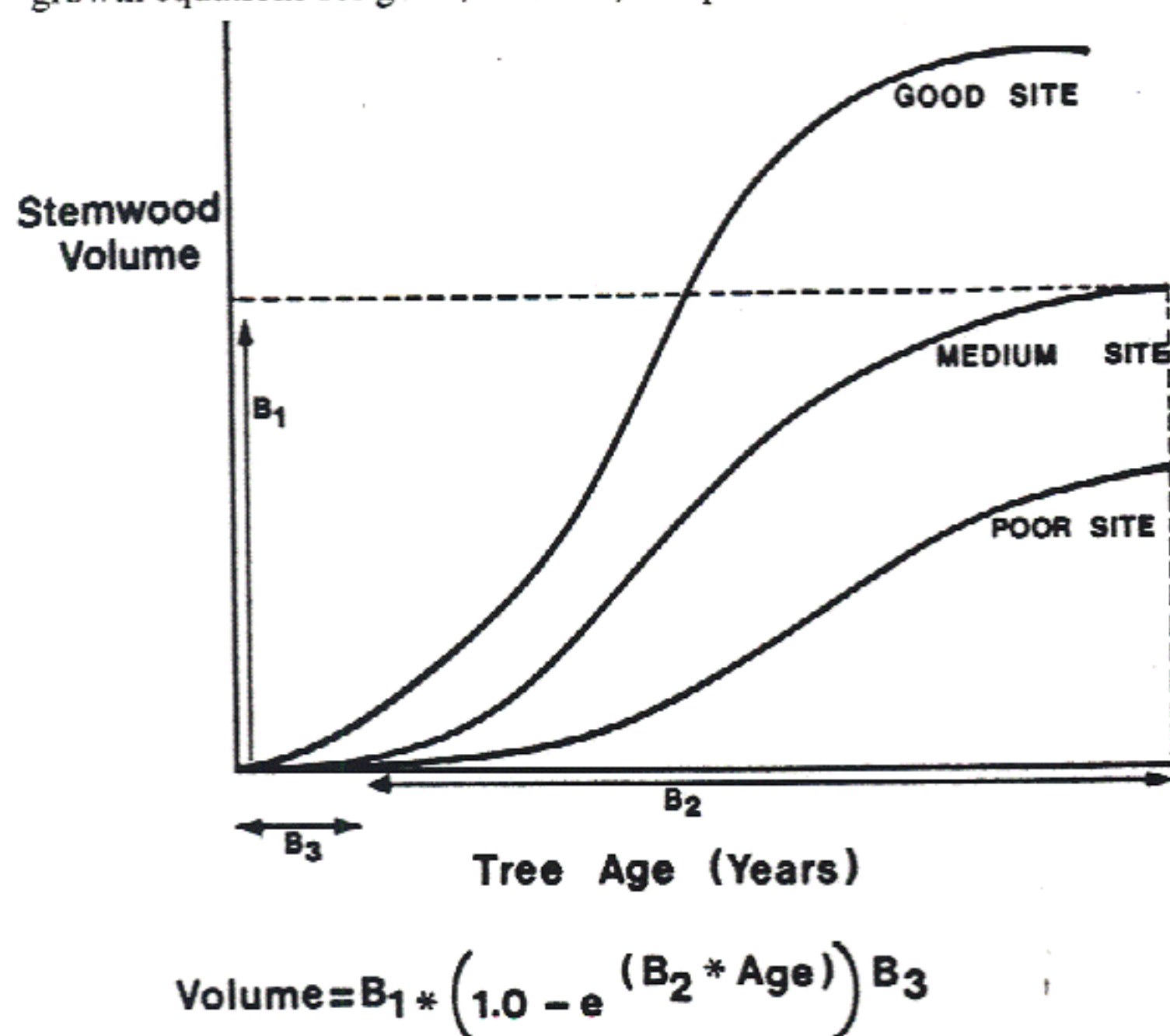
$$\text{stemwood biomass} = \frac{\text{predicted commercial volume} \times \text{specific gravity of stemwood}}{\% \text{ utilization}}$$

The main driving function of the model is a family of three volume/age curves for the tree species in question growing on good, medium and poor sites in the region of interest (Figure 2). The biomass of foliage, branches, stembark, and large, medium, and small roots as a function of age is obtained by applying age-specific ratios of biomass components to stemwood biomass: foliage/stemwood, branch/stemwood, bark/stemwood, and root/stemwood.

In applying these ratios, age is replaced by the ratio: stemwood biomass/maximum stemwood biomass. This was done in order to facilitate the use of heterogeneous data from the literature and to apply the ratios to sites of different quality. Allocation of root biomass between large, medium, and fine roots is done in the proportion: stemwood biomass/branch biomass/foliage biomass on the assumption that large roots are largely supportive and conducting, medium roots are largely conducting and connecting, while fine roots are mainly active in moisture and nutrient uptake.

Growth of any biomass component is made up of three major parts: replacement of litter losses of ephemeral parts (e.g., foliage, branches), replacement of losses due to natural tree mortality, and new growth to achieve the predicted

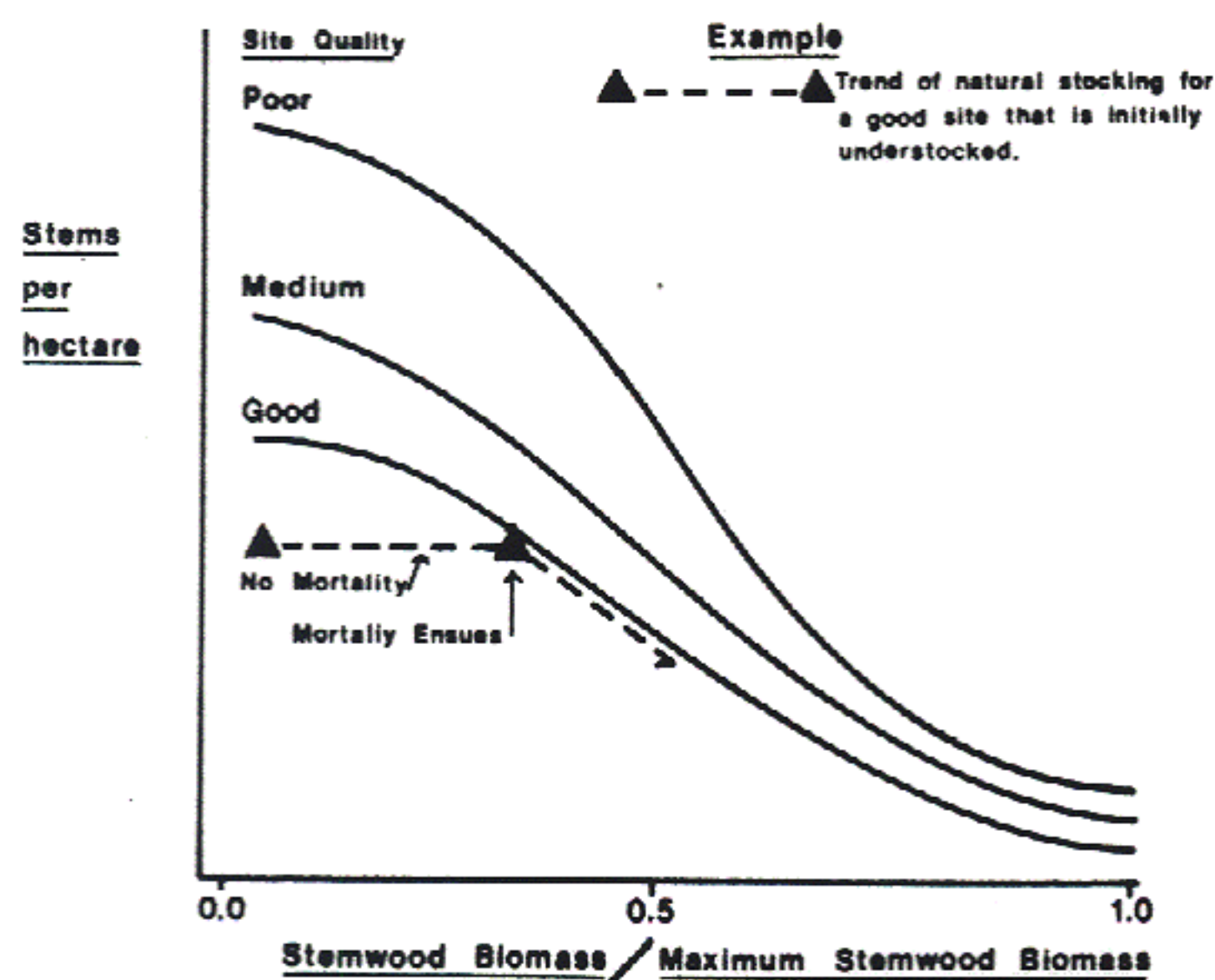
Figure 2. Major driving junction of FORCYTE: Chapman-Richards growth equations for good, medium, and poor sites.



biomass (stemwood) or predicted biogass ratios (other components).

FORCYTE requires information on the "normal," natural stocking density of the species on the three different site types. Curves of normal stocking as a function of the ratio stemwood biomass/maximum stemwood biomass dictate natural mortality, which removes entire trees from the stand and converts them to mortality-related litterfall. This occurs only in the absence of thinnings that harvest this mortality. If the stand is understocked, mortality does not occur until the natural mortality curve is reached (Figure 3). Future modification to the

Figure 3. Natural stand mortality curves.



model will account for stagnation that occurs in some species when chronically overstocked.

Shrubs and herbs are grown in much the same manner as trees, except there is no natural mortality of individual plants. Herb growth is modified by the growth of shrubs and trees. Shrub growth is affected by the growth of trees. Moss growth, when included, will be affected by the growth and litterfall of all other plants.

Litterfall

Litterfall is calculated for foliage, branches, and bark by keeping track of new growth each year and converting this litterfall at the end of some defined period: foliage retention time for foliage, number of live branch whorls for branches, and so on. Each year, the contents of each "age class box" is transferred into the next oldest box, the contents of the oldest box becoming litterfall and new growth being placed in the youngest box. Figure 4 summarizes this method of simulating litterfall. Live branches are converted to dead branches, which remain on the tree for some defined period before being transferred to the forest floor. Stemwood and large-rootwood annual increments are also monitored and after a defined period of time are converted from sapwood into heartwood, but without litterfall. Bark is similarly converted from live bark to dead bark after a defined period.

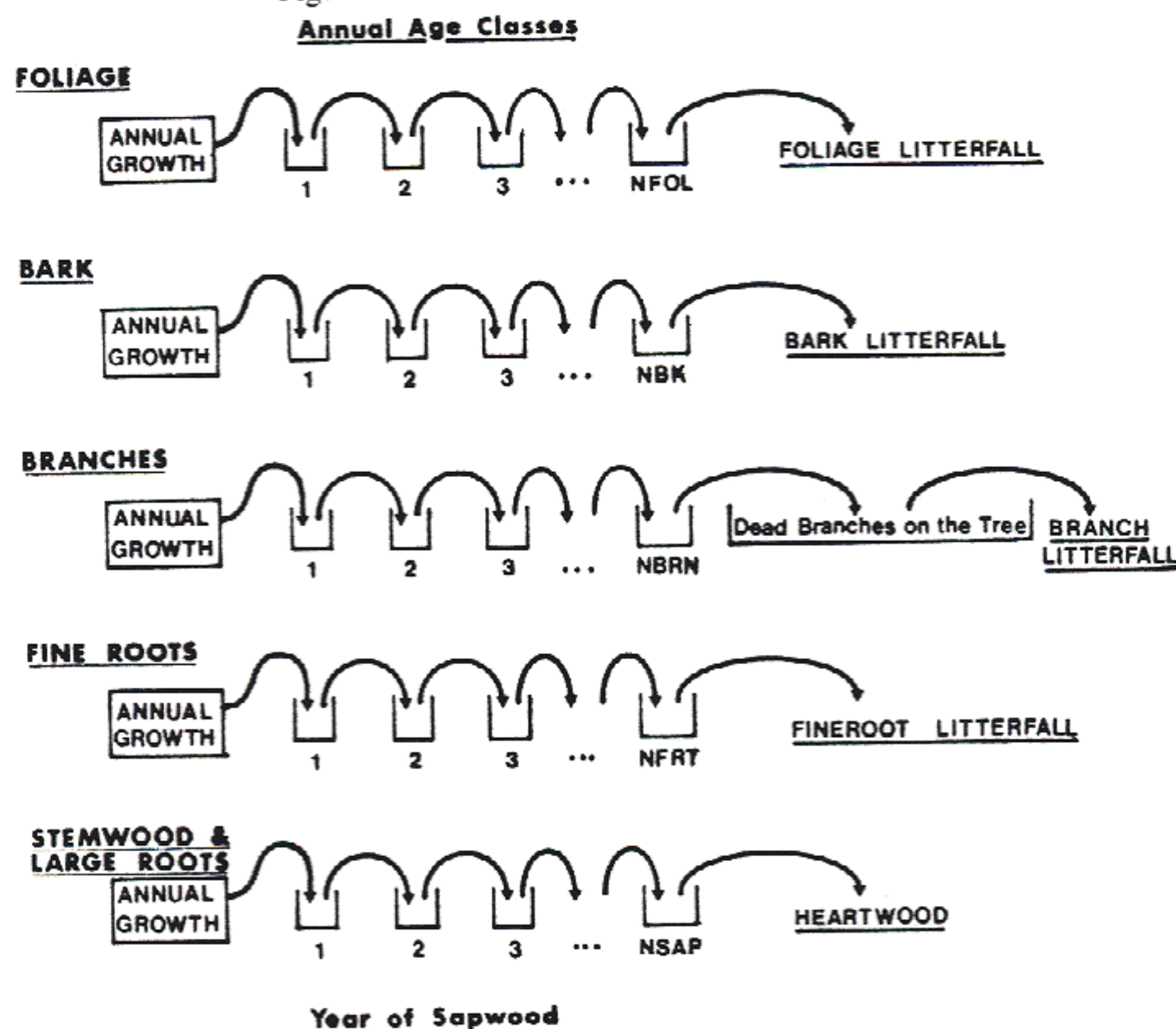
Nutrient Content of Biomass and Nutrient Cycling

The input data file defines the average nutrient concentrations in each of the age classes of each of the identified biomass components. These concentrations vary according to site quality. The model deals with only one nutrient at a time in its present formulation but it is hoped to combine two or three nutrients in future editions of the model.

Nutrient removals from plants in litterfall are defined as biomass times nutrient concentration for each litterfall component. The quantity of the nutrient removed from each component of the vegetation by foliar leaching is defined in the input file. Internal redistribution of the nutrient within the tree is calculated by keeping track of the nutrient content of each annual biomass increment as it ages and becomes litterfall. Where this content declines with age, the loss is assumed to be due to either leaching losses or internal recycling.

Nutrient uptake by the vegetation is calculated by adding the quantity of the nutrient required to produce the predicted new growth (biomass nutrient demand) to the quantity needed for replacement of losses from the plant by leaching and litterfall, less the amount of this demand that can be satisfied by internal redistribution within the plant. If internal redistribution plus the amount of the nutrient available in the soil are insufficient to satisfy the demand, growth is reduced. More will be said on this later.

Figure 4. Method of calculating litterfall.



Decomposition

The biomass and nutrient concentration of each litterfall component is known when the material enters the forest floor. The number of years required to decompose each component to humus is defined in the data input file, together with the rate at which decomposition occurs during this period. It is assumed that this rate varies with time, and different decay rates are given for different stages of decomposition (this is a weak part of the model since reliable data on long-term decay rates are scarce).

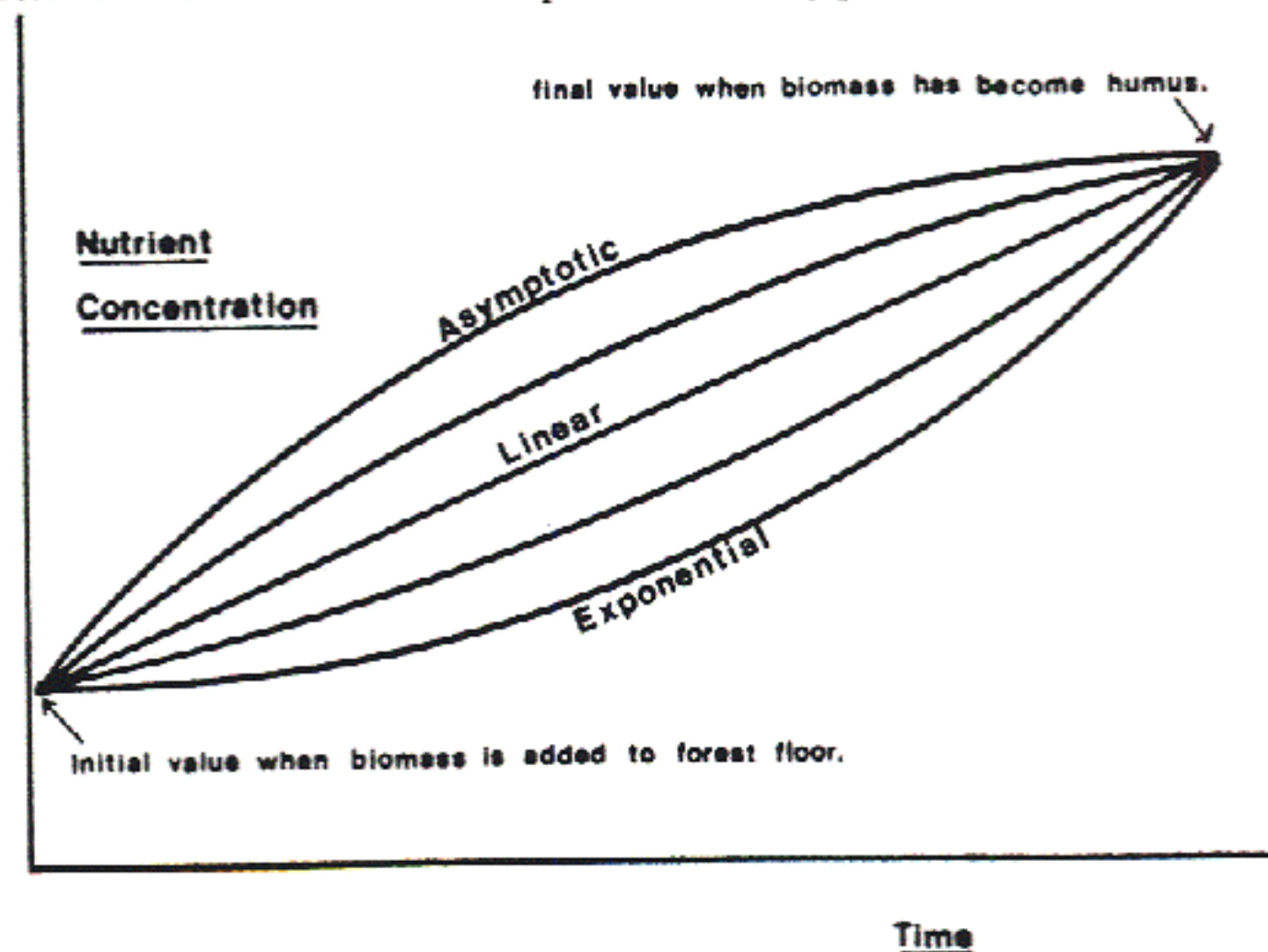
The decomposition rates define the shape of the weight-loss/time curve. The concentration of the nutrient in the decomposing material changes during the decomposition period from its initial value in fresh litterfall to the final value of humus. The shape of the nutrient-concentration/time curve, which varies in the different types of litter materials, is defined in the input data file: some curves are asymptotically increasing, some are exponentially increasing, and some are linear (Figure 5). Very little information is available to define the shape of these curves. Hypothetical values are used in the absence of such data.

The combination of weight change and nutrient concentration change defines the nutrient content of decomposing, which in turn determines net immobilization or net release of the nutrient to or from the decomposing litter each year. The balance between immobilization and release, together with inputs of the nutrient from seepage, soil weathering, through-

fall, precipitation and biological fixation, determines the amount of the nutrient in the available soil pool. Where this pool is less than the net nutrient demand for growth by the plants, growth is reduced in proportion to the deficiency. Where such growth reduction occurs for three successive years, site quality is reduced by a small increment, changing a wide variety of parameters in the model by a small amount.

Conversely, where there is an excess of available soil nutrients (e.g., following fertilization) growth increases to a degree that is defined in the model. Where the excess persists

Figure 5. Various possible patterns of change in nutrient concentrations of various biomass components during period of decomposition.



for 3 yr, site quality is increased by a small increment, again changing several other parameters in the model. Competition for nutrients occurs between herbs and shrubs and between minor vegetation and trees. The outcome of this competition is determined by the relative development of the root systems of the different vegetation layers.

Feedback Between Nutrient Availability and Biomass Production

The most critical part of FORCYTE is the section that provides feedback between nutrient availability and biomass production. Figure 6 provides a simplified flowchart that summarizes the major components of this feedback. It has two parts. If in any one year the nutrient demanded by the predicted new biomass growth cannot be met from the soil or by internal cycling, growth in that year is reduced in proportion to the deficiency. If the deficiency continues for more than 3 yr, the quality of the site is reduced by a small amount. This modifies a large number of processes in the model, such as biomass growth, decomposition, and biomass chemical composition. Similarly, if supply exceeds demand, growth is increased in that year, and if the excess persists for 3 yr, the site quality is improved by a small amount. These feedbacks are potentially unstable, but with appropriate damping mechanisms they appear to work in a realistic manner.

OUTPUT

Because of the complexity of the model, it is provided with a variety of output formats. Most of these are merely to provide the user with a detailed understanding of annual changes in various parameters and processes. This is important to give the user confidence in the biological reality of the model. For example, values of up to 140 parameters can be printed out annually in a series of 14 graphs for runs of up to 500 yr. Currently, the model prints out the following eight graphs:

1. Annual biomass values for herb shoots and roots; shrub leaves, twigs, and roots; tree foliage, branches, stembark, stemwood, and roots. The graph utilizes a relative scale so that herbs and trees can be plotted on the same graph.
2. Annual increments of each of the above ten biomass categories.
3. Nutrient content of these ten biomass categories.
4. Annual biomass values for the forest floor, broken into the above ten biomass categories.
5. The amount of nutrient cycled annually in stemwood, stembark, branches, and roots; total tree internal cycling; total tree uptake from soil; shrub internal cycling and uptake from soil; and herb uptake from soil.
6. Ten parameters of the forest floor: available nutrient pool, annual soil leaching losses, humus biomass and nutrient content, annual biomass and nutrient increment of humus, site quality, total forest floor biomass and nutrient content, and decomposing logs as a percentage of the forest floor.
7. Annual litterfall for above ten biomass categories.

Figure 6. Simplified flowchart of feedback relating nutrient availability to biomass production. This is an expansion of part of Figure 1.

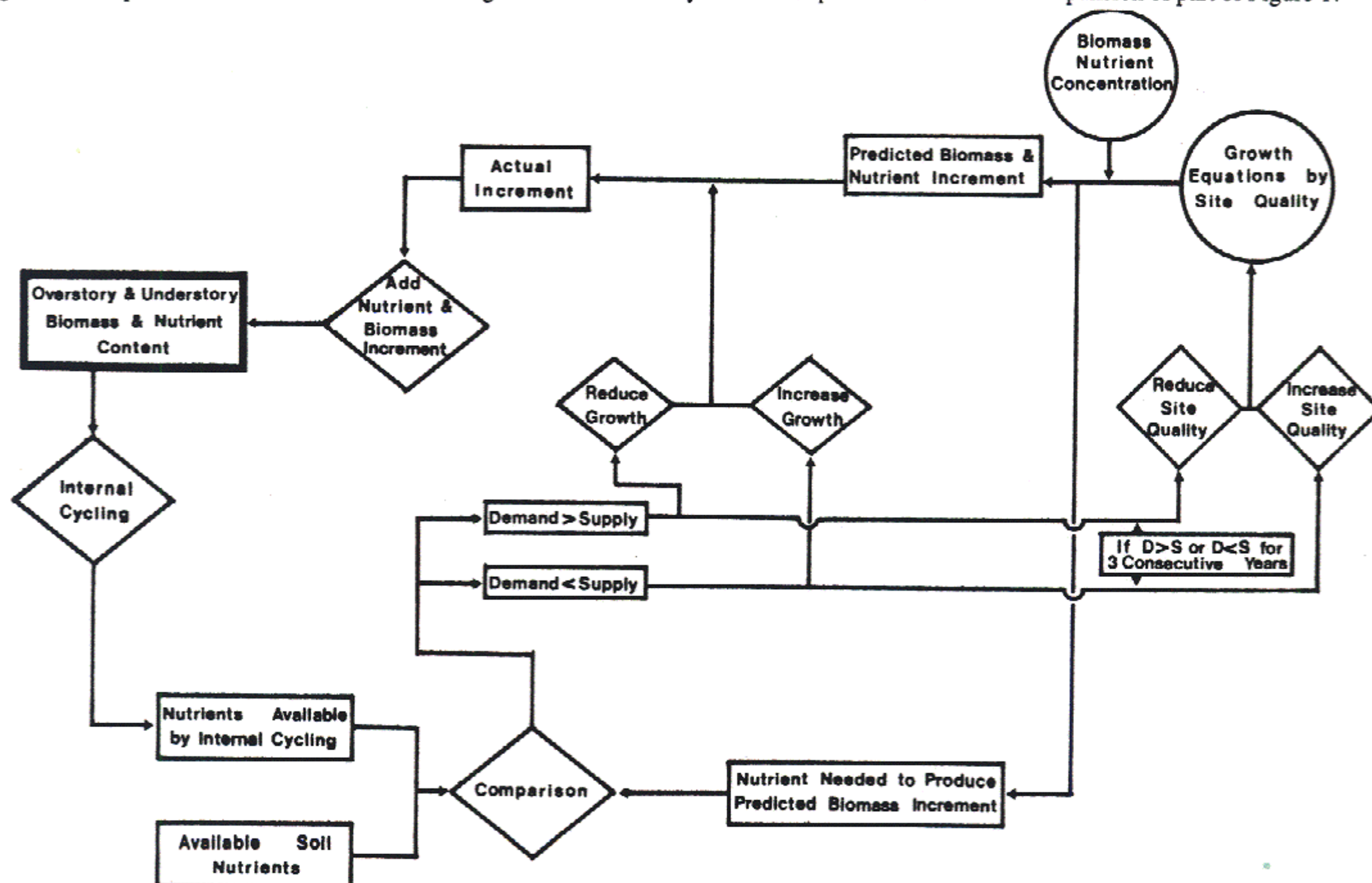


Table 2. Summary of some predictions of FORCYTE based on input data for a medium Douglas-fir site in southwestern British Columbia.^a

Rotation	Treatment	Stand age	Parameter	Wood	Bark	Branches	Foliage	Roots	Total
A. Biomass and nutrient content in harvested trees and slash (kg/ha)									
1	Thinning 1 40 yr		Biomass removal	10 333	3 922	11 025	9 021	0	34 301
			Slash biomass	211	436	1 225	1 002	16 216	19 090
			N removed	6	12	26	97	0	142
			N in slash	<1	1	3	11	82	97
	Harvest 1 80 yr		Biomass removed	54 598	17 161	14 822	23 012	0	109 654
			Slash biomass	1 114	1 907	1 654	2 557	42 348	49 580
			N removed	28	48	30	233	0	340
			N in slash	767	5	3	26	169	205
				At start		At end			
			Total site N	945		972			
			Total site biomass	124 176		133 116			
			Trees	Shrubs		Herbs			
Parameter			Rotation Annual	Rotation Annual	Rotation Annual	Rotation Annual	Rotation Annual	Rotation Annual	Rotation Annual
B. Biomass and nitrogen in ecosystem processes (kg/ha)									
Biomass									
Total production			657 273	8 216	19 835	248	18 268	228	
Total litterfall			439 967	5 500	19 831	248	18 271	228	
Litter as % of production			67		100		100		
Nitrogen									
Total uptake			2 910	36	138	1.7	1.21	1.5	
Total litterfall			2 127	27	138	1.7	121.	1.5	
Total internal cycling			2 424	30	96	1.2	136.	1.7	
Biomass production/ N uptake			276		144		151.		
N inputs and losses									
Precipitation input			400	5					
Soil weathering			0	0					
Biological fixation			160	2					
Fertilization			0	0					
Soil leaching			50	0.6					

^aThe 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 presented merely to illustrate the potential capabilities of the model. The run assumed a commercial thinning at 40 yr and a whole-tree harvest at 80 yr. The forest behaved in an N-deficient manner, which was alleviated in a subsequent run by N fertilization.

8. Biomass each year of seven components of the "average tree," tree density (stems per hectare), tree density change, and percentage tree density change. The other four graphs are available for the addition of an additional 40 variables.

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 details 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 budget 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.

CONCLUSIONS

FORCYTE is not yet at the stage of its development at which it can be considered to be a useful management tool. We believe, however, that it already has greater potential as a management planning tool than other existing models. Its future development will make it more site specific and biologically realistic, and will include an energy and economics package that will enable to be used for energy budget and economic predictions. A more complete description of the model will be published in 1980 by the Canadian Forestry Service, who commissioned and funded the work on the model.

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