

LAU-X-29E

# FOREST STAND DYNAMICS APPLIED TO BLACK SPRUCE IN QUEBEC (DYPEUFOR).

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## RESUME

Cette étude porte sur un modèle de simulation du développement d'une forêt dans le temps. Le but du modèle est de quantifier les effets dynamiques (sur le volume total et les dimensions des arbres) que l'on peut obtenir soit à partir d'interventions sylvicoles telles que l'éclaircie, la fertilisation, les travaux de drainage, soit à partir de phénomènes naturels stochastiques comme, par exemple, le châblis.

Les relations de causalité du système forestier sont présentées sous forme d'un modèle systémique à rétroactions multiples. Dans cette optique, l'accroissement de la forêt est perçu comme un état déterminé par un processus de cumul contrôlé par le volume total ( $\text{pi}^3/\text{acre}$ ) et la densité du peuplement (nombre d'arbres/acre).

A l'intérieur du modèle, le développement dans le temps d'une forêt non perturbée et les effets des différentes interventions sont déterminés par des équations différentielles.

L'approche dynamique des différentes interactions entre les éléments du modèle fournit deux principaux avantages incontestables:

- elle est propice à la représentation graphique, facilitant ainsi l'interprétation de différentes tendances du comportement de la forêt
- elle donne une vue globale du système forestier facile d'approche favorisant les communications entre les profanes et les experts forestiers.

## ABSTRACT

This paper describes a simulation model reproducing the development of a coniferous forest. The purpose of the model is to test the dynamic effects on total volume and tree dimensions of silvicultural activities like thinning, fertilizing or ditching, and to evaluate the consequences of natural phenomena such as wind throw, which is considered as a stochastic event.

Cause and effect relationships in the forest system are presented as a dynamic model: a multiloop feedback system. Forest growth is viewed as a state which is determined by an accumulation process controlled by total volume ( $\text{ft}^3/\text{acre}$ ) and stand density (number of trees/acre).

In addition, the development over time in an undisturbed forest or in stands impacted by external actions is determined by means of differential equations.

The structure of this model is so designed as to cause the complex interactions between elements of the model to act all at once and to show the real effect of any action taken on the forest ecosystem. This involves many advantages such:

- any behaviour or response of the forest can easily be visualized on graphics
- it provides the user with an overall view of the forest system as a whole in a way that is accessible to the uninitiated and so facilitates communications between laymen and experts.

## ACKNOWLEDGMENTS

This work could not have been completed without the assistance of a number of people. It was undertaken at the urging of Mr. Michel Boudoux, head of the Biometry Section of the Laurentian Forest Research Centre, who was always available to provide us with useful advice.

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## INTRODUCTION AND SYSTEMS APPROACH

The silvicultural management of coniferous species, such as black spruce, is being continually intensified in Quebec. It is therefore an opportune time to introduce a new tool which could help the forest manager to make better informed decisions.

DYPEUFOR, a model for simulating black spruce forests in Quebec is such a tool, resembling a laboratory, which offers the forest manager the possibility of perceiving the effects of various silvicultural treatments on the behaviour of a stand so that he can prescribe the best method.

The concept and design of DYPEUFOR were inspired by the model constructed by Kjell Kalgraf and Westye Egeberg to simulate spruce stands in Norway. The first version of that model was created within the framework of a comprehensive project of Gruppen for Ressursstudier (the group for resource studies) in Oslo, Norway to establish long-term strategies for forest resource utilization in Scandinavia. From this prototype we designed a model adapted to Quebec conifers.

Biological systems, like social and economic systems, are non-linear feedback systems, containing multiple loops. Even when we possess an excellent knowledge of the various parts of a given system, it is usually impossible for us to know how the system will behave over time, given its complexity.

To make up for the limitation of our judgment or intuition, we can resort to experimentation with the help of models. For this, we have available to us an approach called *industrial dynamics*, which is of very special value because it allows us to describe a system as a whole.

However, its immediate purpose is not to optimize a system, but rather to explain the trend of the system and consequently to identify the factors which are a key to improving the system in the most efficient way possible.

Three principles were followed in constructing the DYPEUFOR\* model:

- 1- The purpose of DYPEUFOR is to test the dynamic effects of silvicultural activities on the total volume and the size of the trees. All elements which influence these variables have been included in the model. In other words, the boundary which delimits DYPEUFOR lies where the elements excluded have no effect on the system's dynamic behaviour (Figure 1).
- 2- The second principle was to make the model as realistic as possible. To this end, the variables of DYPEUFOR correspond directly to those of the forest system studied and have the same units of measure as in the system. For example, the flow of volume of wood is measured in  $\text{ft}^3/\text{acre}$ , and not in equivalent dollars. This is intended to preserve the possibility of studying the relationships among the different loops of DYPEUFOR.

---

\* DYPEUFOR: Dynamique des peuplements forestiers (forest stand dynamics)

- 3- Finally, to preserve the model's flexibility, we neither assumed that the system is linear or stable nor presupposed that the model had to pass through any predefined point. This was to ensure that none of the most significant and useful characteristics of the system would be excluded from consideration.

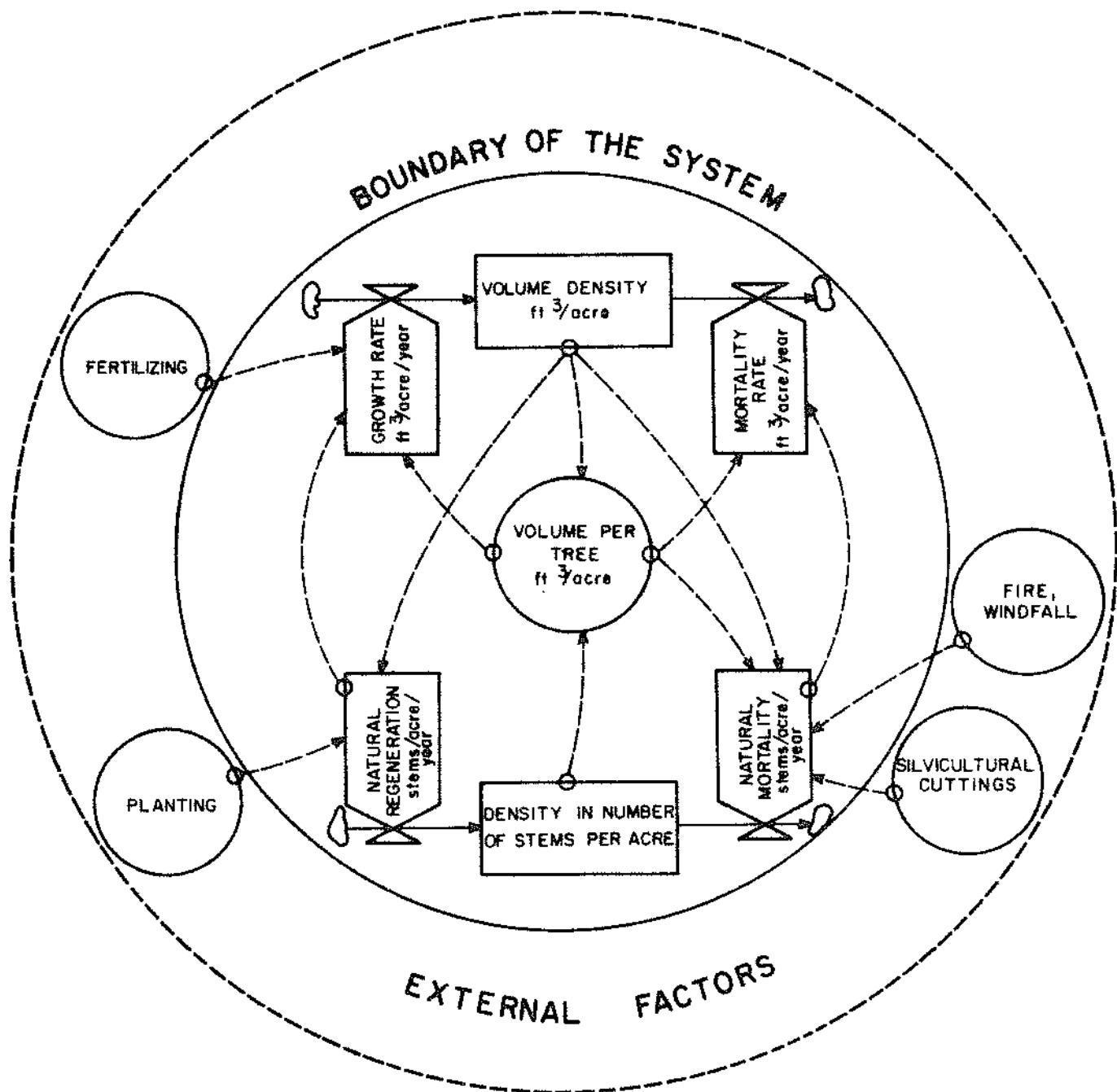


Figure 1: DYPERFOR networks with their main internal and external elements

## 1. CHARACTERISTICS OF INDUSTRIAL DYNAMICS AND OF DYNAMO

In order that the structure of DYPEUFOR and its constituent equations may be better understood, a brief outline of the main features of industrial dynamics and of DYNAMO is presented.

### 1.1- A basic DYPEUFOR network

Figure 2 shows a basic DYPEUFOR network, which included:

- a level
- flows transporting material at a rate from a source to the level represented by a rectangle, then from this level to a sink at a different rate
- rates (or decision functions) which act as values in controlling the flow
- information channels which link the decision functions (or rates) to the level

### 1.11- Feedback loop

The basic element of DYPEUFOR, and of any dynamic model, is the feedback loop (figure 2). DYPEUFOR has two information flows, each linking a rate to the level. These information flows transfer information concerning the level to the rates. In reaction to this information, each of the decision functions or rates adjusts the material flow accordingly.

### 1.12- Levels and rates

The networks contain two types of variables called levels and rates. Levels are variables produced by accumulation; they define the state of the system at a given moment. The rates are decision

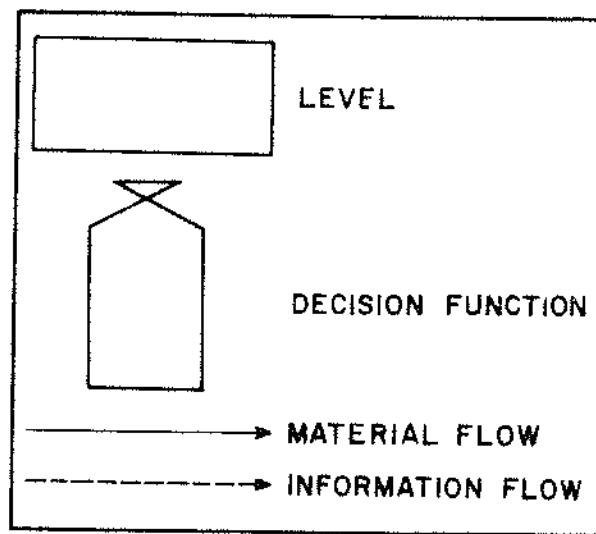
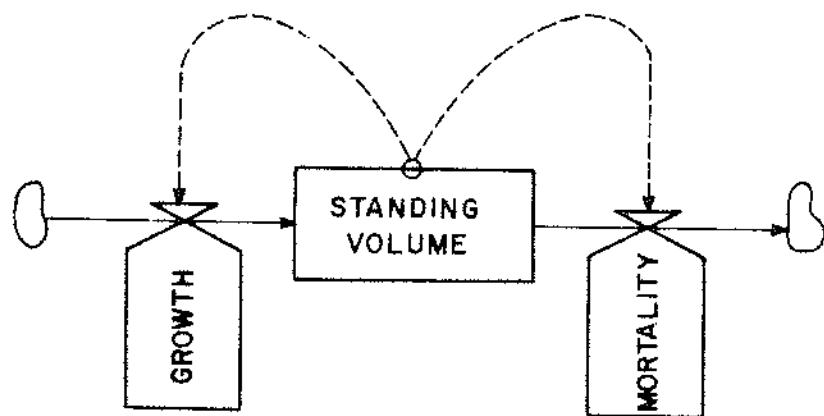


Figure 2: A basic DYPEUFOR network

variables which depend on the levels. They define the instantaneous flow between the levels of a system. A level is an accumulation (integration) within the system, whereas a rate determines the speed at which a level changes.

It should be noted that the unit in which a variable is measured does not always indicate whether the variable is a level or a rate. An empirical rule for distinguishing between levels and rates is to imagine that the system suddenly ceases to function. At that point, only the levels will continue to exist. The rates, being action variables, cease to exist as soon as action ceases. When a tree stops growing, its growth rate becomes zero, but the level of its accumulated height or volume will remain visible.

#### 1.13- DYNAMO (Dynamic Models)

Conceived by MIT's Industrial Dynamics Group, DYNAMO is a computer program which accommodates models constructed according to the principles and structure just described.

Its essential features are:

- it checks the logic of equations and prints any errors
- it reorganizes the model by rearranging level and rate equations and by ordering the interdependent auxiliary equations
- it does calculations step by step according to the interval between solutions and the simulated time period specified in control instructions
- it prepares and prints the results of the simulation in the form of tables and graphs

### 1.2- Order of calculations

We obviously need an adequate system of equations to describe the structure outlined above.

This system of equations must define the interactions of a set of variables over time. This implies that the equations must be solved periodically in order to describe the successive states of the system.

Let time K be the present time (see figure 3): interval JK has just ended and interval KL will follow. We therefore have access to the information accumulated during the time elapsed between the origin and time K. However, we have no information for time L and later (nor do we interval KL and following).

*At each step, the level equations are solved and the results are then used to solve the rate equations.*

The level equations enable us to find the levels at time K from the levels at time J and the rates during interval JK. The rate equations are then solved at the present time K after the level equations have been solved, and these rates will represent the actions to be taken during the following interval KL. In the diagram, the slopes of the lines are proportional to the rates. After the levels at time K and the rates during interval KL have been calculated, the positions J, K and L are each moved to the right by a distance equal to the time interval DT. The levels which have just been calculated are then called levels J and the present time K is moved forward by the interval DT.

The same order of calculations can be repeated to find a new state of the system at the end of time interval DT. Thus, step by step the model traces the behaviour of the system over time.

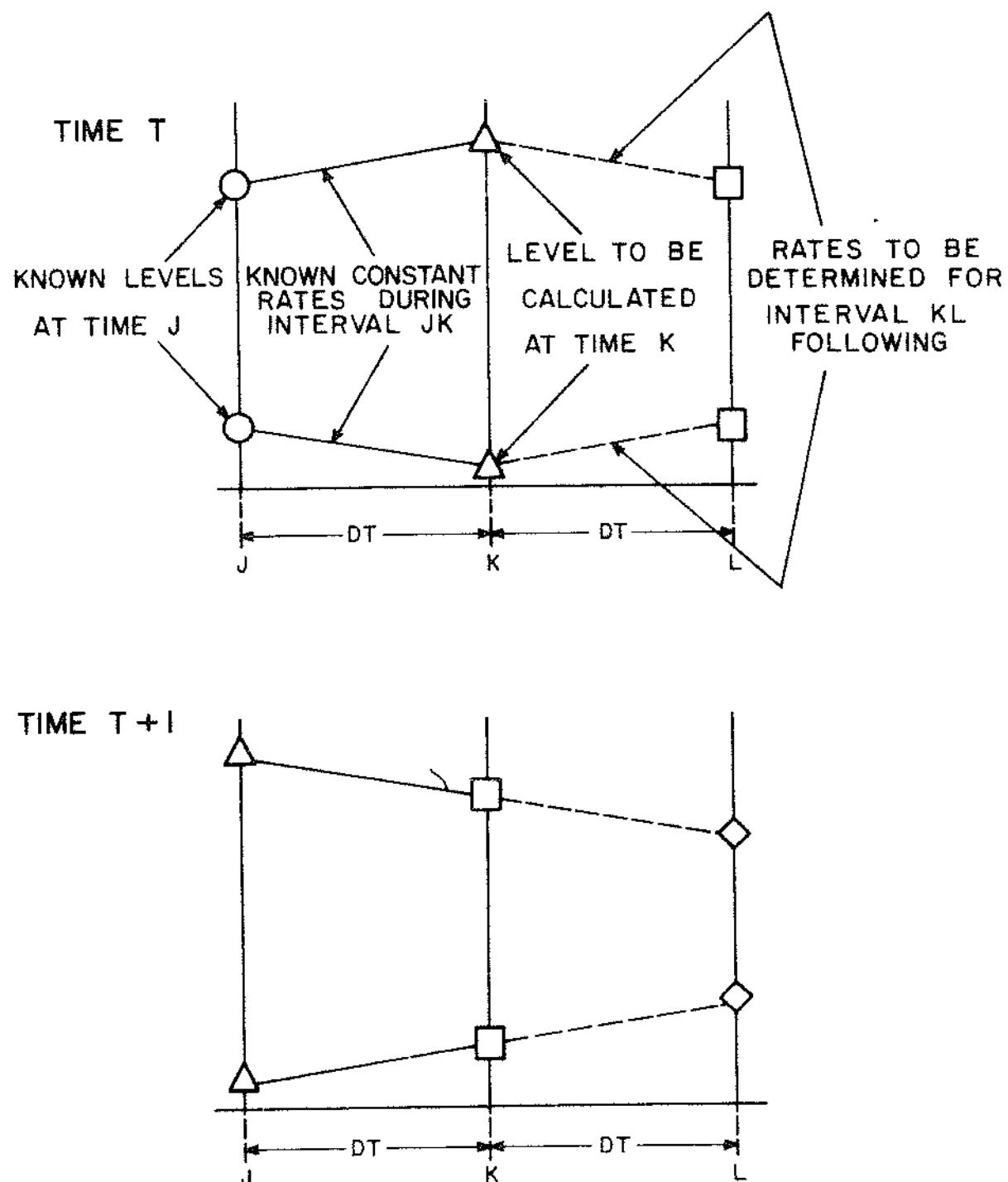


Figure 3: Order of calculations

### 1.3- Types of equations

#### 1.31- Level equation

The characteristic form of the level equation is:

$$L \cdot N.K = N.J + DT * (TE.JK - SO.JK)$$

where

L = letter identifying the level equation

N.K = new value of the level calculated at time K (units)

N.J = value of the level at the preceding time (units)

TE.JK = value of the inflow rate during interval JK (unit/unit of time) (TE = "taux d'entrée" = inflow rate)

SO.JK = outflow rate value during interval JK (unit/unit of time) (SO = "sortie" = outflow)

DT = length of interval between solutions, i.e between J and K (unit of time)

It should be noted that one or more rates can enter into the level calculations. The level equation is the only equation which contains the interval DT as a variable.

#### 1.32- Rate equation

Unlike the level equation, the rate equation can have several forms. One possible form is the following:

$$R.AB.KL = TI.K * A.K + 1E-5 * TPTI.JK + 1E-7 * TRTI.JK + 0.016 * MAR.JK$$

where

R = letter identifying the rate equation  
 AB.KL = rate of volume increase (unit/unit of time)  
 TI.K = number of stems at time K (level)  
 A.K = volume increase per stem per year  
 TPTI.JK = number of seedlings planted during interval JK  
 TRTI.JK = number of natural seedlings produced during  
           interval JK  
 MAR.JK = number of layers established during interval JK  
 1E-5, 1E-7 and 0.016 are the volume of a planted seedling, of a  
 natural seedling and of a layer respectively.

The rate equation has the following two characteristics:

- It never contains the variable DT.
- The left side of the equation contains the value of the rate defined for interval KL which comes immediately after time K at which the rate is evaluated.

### 1.33- Auxiliary equation

In principle, the auxiliaries are merely components of the rate equations, and theoretically do not have to exist. In practice, however, each auxiliary has its own proper signification, even if it does not directly affect the dynamics of the model, and its equation helps to refine the computer program.

The auxiliaries are evaluated after the levels on which they depend and before the rates of which they are components.

A sample auxiliary equation is:

$$A \ PM.K = PM50.K * KM.K$$

where

A = letter identifying the auxiliary equation

PM.K = percent mortality at time K

PM50.K = percent mortality at 50% of Vmax at time K

KM.K = correction factor at time K

The auxiliary equations have the same time identifier as the levels, but they differ from the latter in their form.

#### 1.34- Source and sink

The forest stand is in a relationship with its environment. This relationship is manifested by:

- a) the unlimited capacity of the environment to absorb slash in the form of dead trees; thus mortality has a sink, as symbolized in figure 4
- b) the unlimited capacity of the system to absorb energy and raw material to replace the dead material by regeneration and growth; this unlimited capacity is represented by the source in figure 5

#### 1.35- Constant initial values and initialization

Finally,

- All levels have initial values before the start of a computation cycle

- Certain constants enter into rate, level and auxiliary calculations

#### 1.4- Standard symbols used in industrial dynamics

The letters and symbols shown in figure 6 were adopted for industrial dynamics to represent the various equations and graphs in the system.

It should be noted that in our diagrams there are two types of lines joining variables. These lines represent flows. The solid lines are flows of standing volume which enter and leave different levels (standing volume in  $\text{ft}^3/\text{acre}$  and number of stems per acre). The dotted lines represent the information flows which permit the auxiliaries and rates to be calculated (feedback).

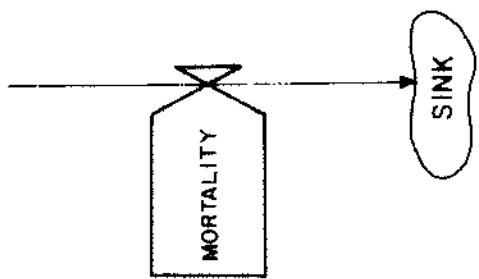


Figure 4: Sink

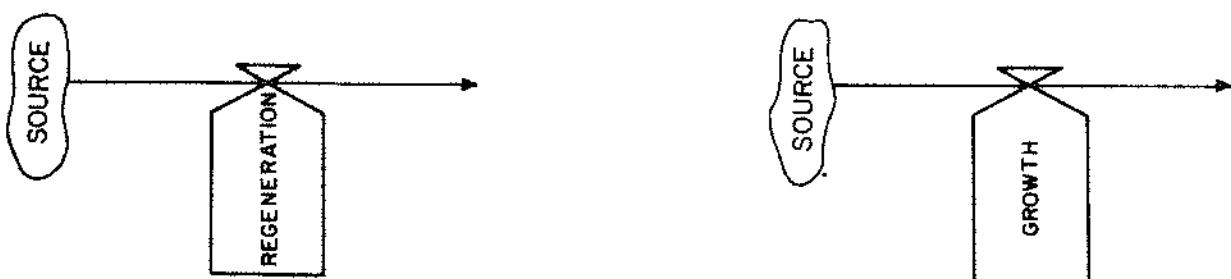


Figure 5: Source

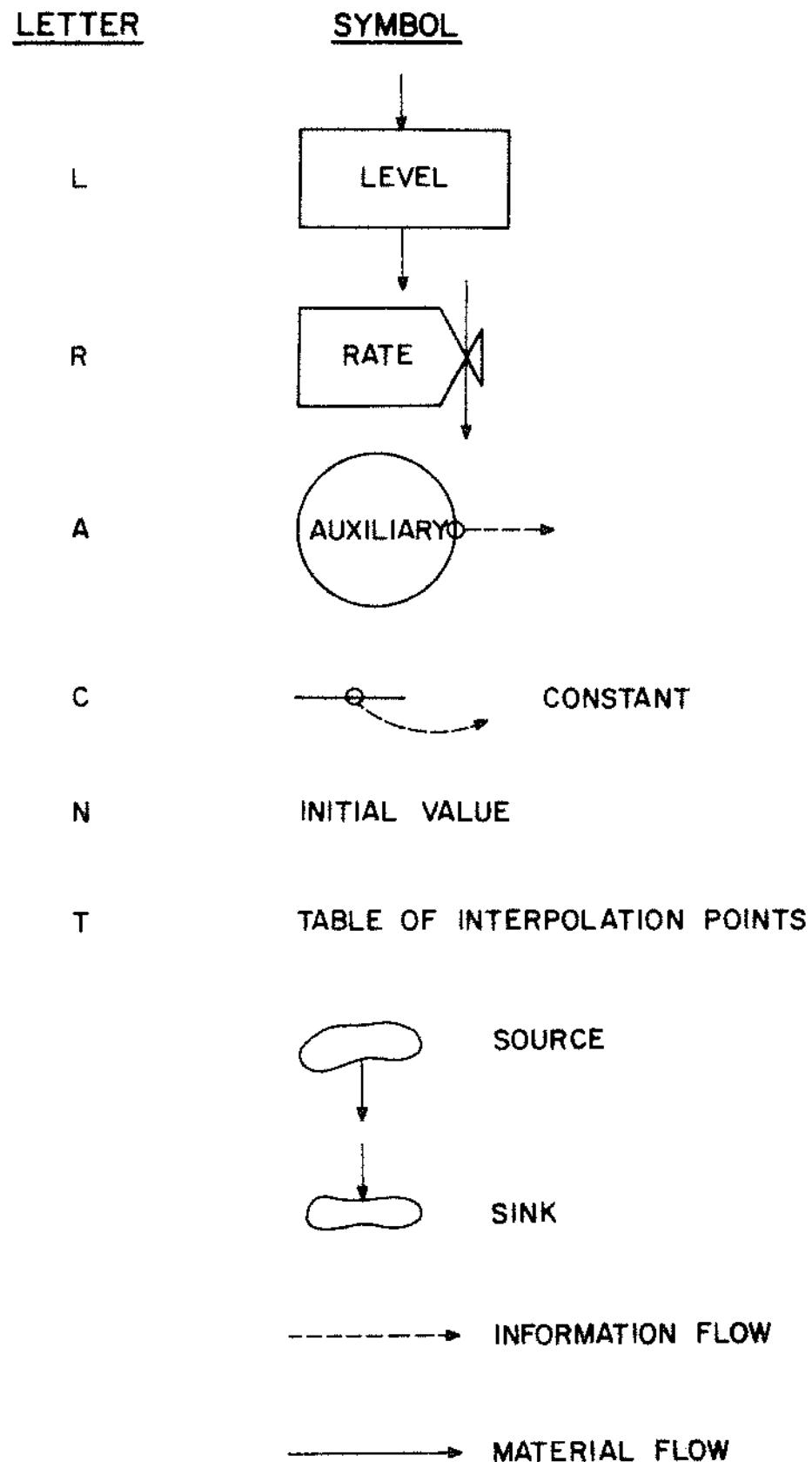


Figure 6: Letters and symbols used in industrial dynamics



## 2. COMPONENTS OF DYPEUFOR

The dynamic simulation model discussed herein comprises three main components: natural regeneration, growth and natural mortality. Figure 7 clearly illustrates the roles of these in conjunction with the impact of external factors such as planting and cutting.

### 2.1- Natural regeneration

It is generally accepted that a large number of black spruce (*Picea Mariana* [Mill] B.S.P.) stands growing in Quebec regenerated as a result of fires. An intense fire prepares favourable seedbeds and opens the semiserotinous cones without destroying the abundant seed they contain (Vézina 1975).

On the basis of earlier studies we posited as an initial hypothesis for the present model that the forest area was covered with 10,000 seedlings per acre following an intense fire. A final clear cutting is also a sufficiently intense treatment to give rise to a good restocking (Weetman *et al* 1973), especially if it is done by patches so as to maintain permanent seed sources (Vézina 1975); so it could also be the source of the stand under study. Of course, such disturbances do not always lead to a total restocking of the stand, and we therefore had to introduce a regenerative process which enables new seedlings to become established when the stocking becomes too thin.

#### 2.1.1- Number of seeds germinated

The regenerative process should allow for new seedlings to fill the gaps left by the disappearance of standing trees, whether fortuitous or caused by human intervention. This process is described by the number of seeds produced per acre annually and by the actual germination rate as follows:

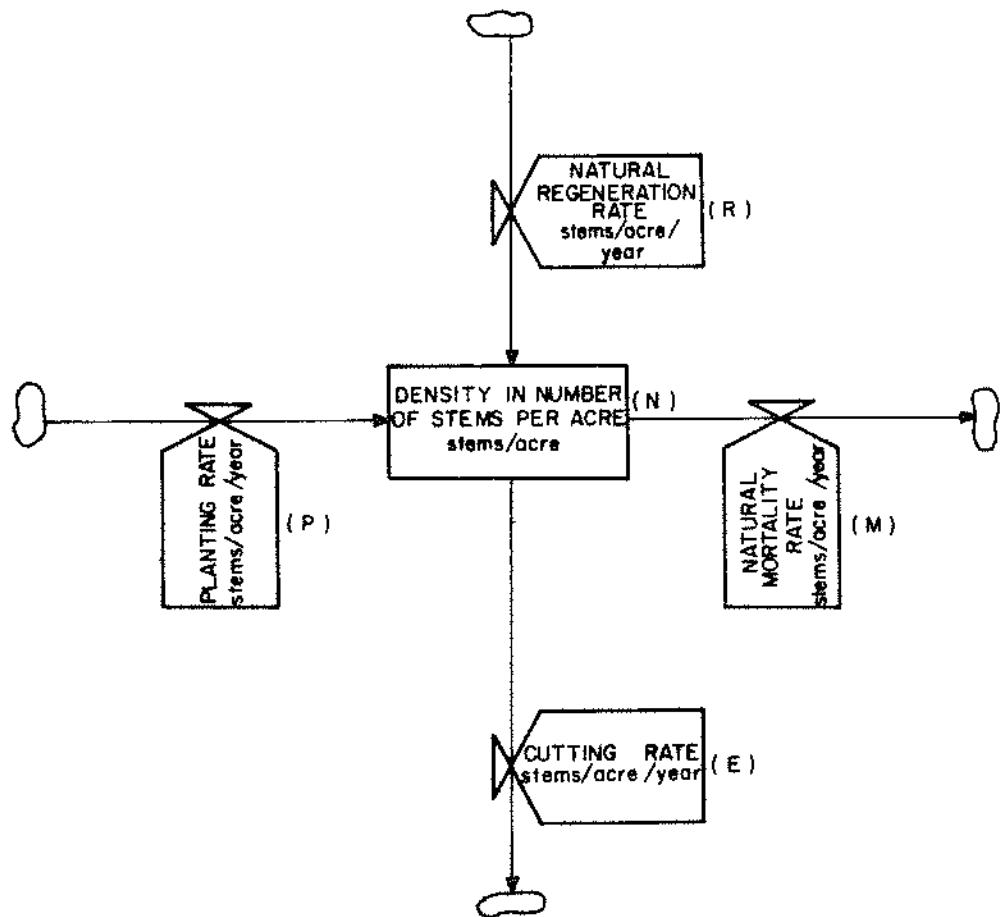


Figure 7: Principal rates determining the density expressed as the number of stems per acre

$$\text{TRTI} = \text{NSEM} \times \text{TG}$$

where

TRTI = regeneration rate in number of stems/acre/year

NSEM = number of seeds produced/acre/year

TG = actual germination rate

### DYNAMO

$$R \cdot \text{TRTI.KL} = \text{NSEM.K} * \text{TG.K}$$

#### a) Seed production

We know that trees do not produce seed at all levels of stocking, but rather need to reach a certain degree of maturity before becoming seedbearers. According to G. Frisque (personal communication), black spruce produces seed over a period of eighty years, from age forty to one hundred and twenty. To these ages correspond values for mean volume per tree, which we used to graph figure 8. At its optimum, the stand produces up to a million viable seeds per acre per year.

Seed production was simulated in DYNAMO with the help of the following table of values:

### DYNAMO

$$A \cdot \text{NSEM.K} = \text{NMS} * \text{PSEM.K}$$

$$C \cdot \text{NMS} = 1E6$$

$$A \cdot \text{PSEM.K} = \text{TABHL}(\text{PSEMT}, \text{VA.K}, 0, 1.8, 0.2)$$

$$T \cdot \text{PSEMT} = 0/0/0/.34/.66/1/1/1/1/0$$

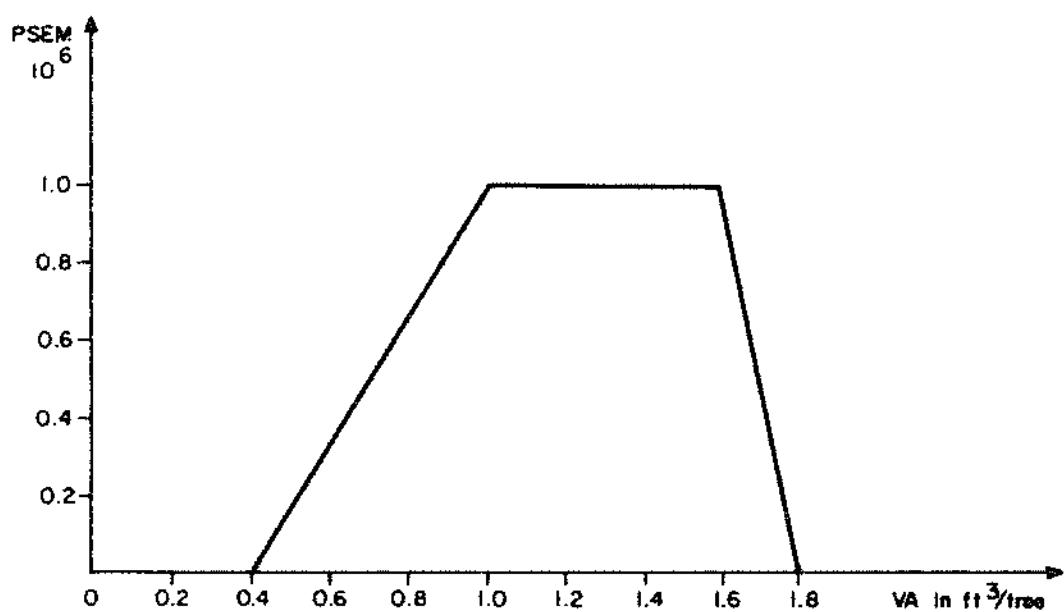


Figure 8: Number of seeds produced per acre per year as a function of the mean volume per tree

b) Germination rate (survival)

The germination rate is observed to change as cover closes in black spruce stands. The ratio V/Vmax being a measure of stand's closure, determines the germination rate of seeds.

We shall let TGT designate the ratio of actual germination rate (TG) to maximum potential germination rate (CGT)

$$TGT = \frac{TG}{CGT}$$

Now if we plot TGT values as a function of closure (Figure 9) one realizes that germination rate decreases very sharply as V/Vmax increases.

Knowing the relative germination rate TGT, we can deduce the actual germination rate TG.

$$TG = CTG \times TGT$$

where

$$CTG = 0.01$$

DYNAMO

```
A TG.K = CTG*TABHL(TGT,V.K/VM.K,0.,0.25,0.0125)
T TGT = 1/.6/.3/.1/.05/.01/.005/.001/.0005/.0001/.00005/
      1E^-5/5E^-6/1E^-6/5E^-7/1E^-7/5E^-8/1E^-8/5E^-9/1E^-9/0
C CTG = 0.01
```

Thus we see how a regeneration is established naturally in a more or less open area as a function of the maximum number of available seeds and of their germination rate. The seed volume is generally considered to be negligible. However, to conform to the

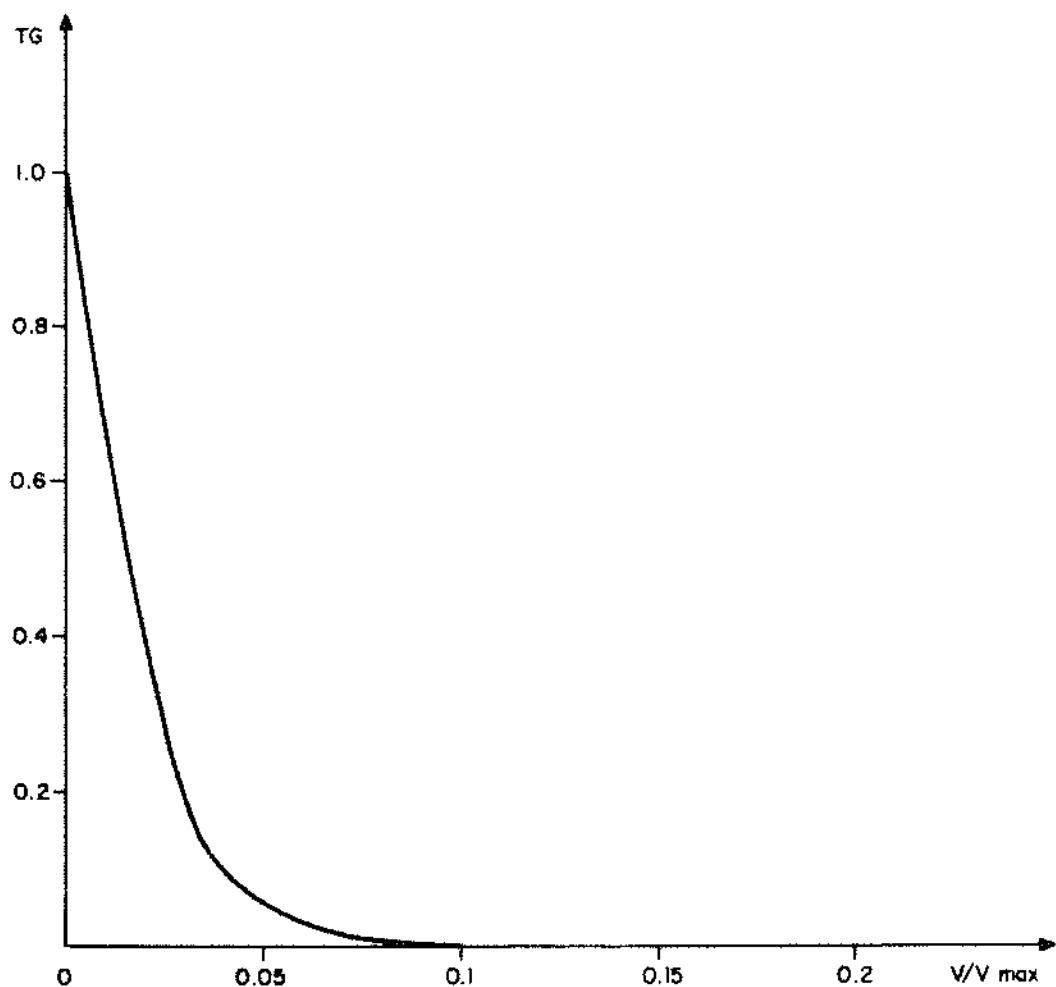


Figure 9: Relative germination rate as a function of the ratio  $V/V_{\text{max}}$

structure of the model, we have assumed this volume to be one ten millionth of a cubic foot ( $10^{-7} \text{ ft}^3$ ).

#### 2.12- Layering

In general, black spruce does not reproduce well sexually, but does reproduce well vegetatively, by means of layers. In a natural stand, layers begin to appear at about 100 years, when the stand is beginning to become open, that is, when the mean volume per tree begins to decrease as the largest and oldest trees fall. Their growth is subject to apical dominance; the layers formed from the lower branches of a mother tree remain more or less inert as long as they are under its dominance. When the mother tree falls or is harvested, one of the layers, generally the one that is most developed, takes over and comes to dominate the others, behaving as a normal stem.

At the time it becomes independent, the layer is assumed to have a mean volume of half that of a one-inch stem (the smallest size class in use), or  $0.016 \text{ ft}^3$  for a class III site (Vézina and Linteau 1968).

In our model we therefore replaced each dead or fallen stem by a layer at the end of 100 years.

#### DYNAMO

```
R MAR.KL = STEP((TETI.JK+TMTI.JK),100)
R AB.KL = TI.K*A.K+VP*TPTI.JK+VSEM*TRTI.JK+0.016*MAR.JK
```

Figure 10 summarizes the regeneration processes as developed in DYPEUFOR.

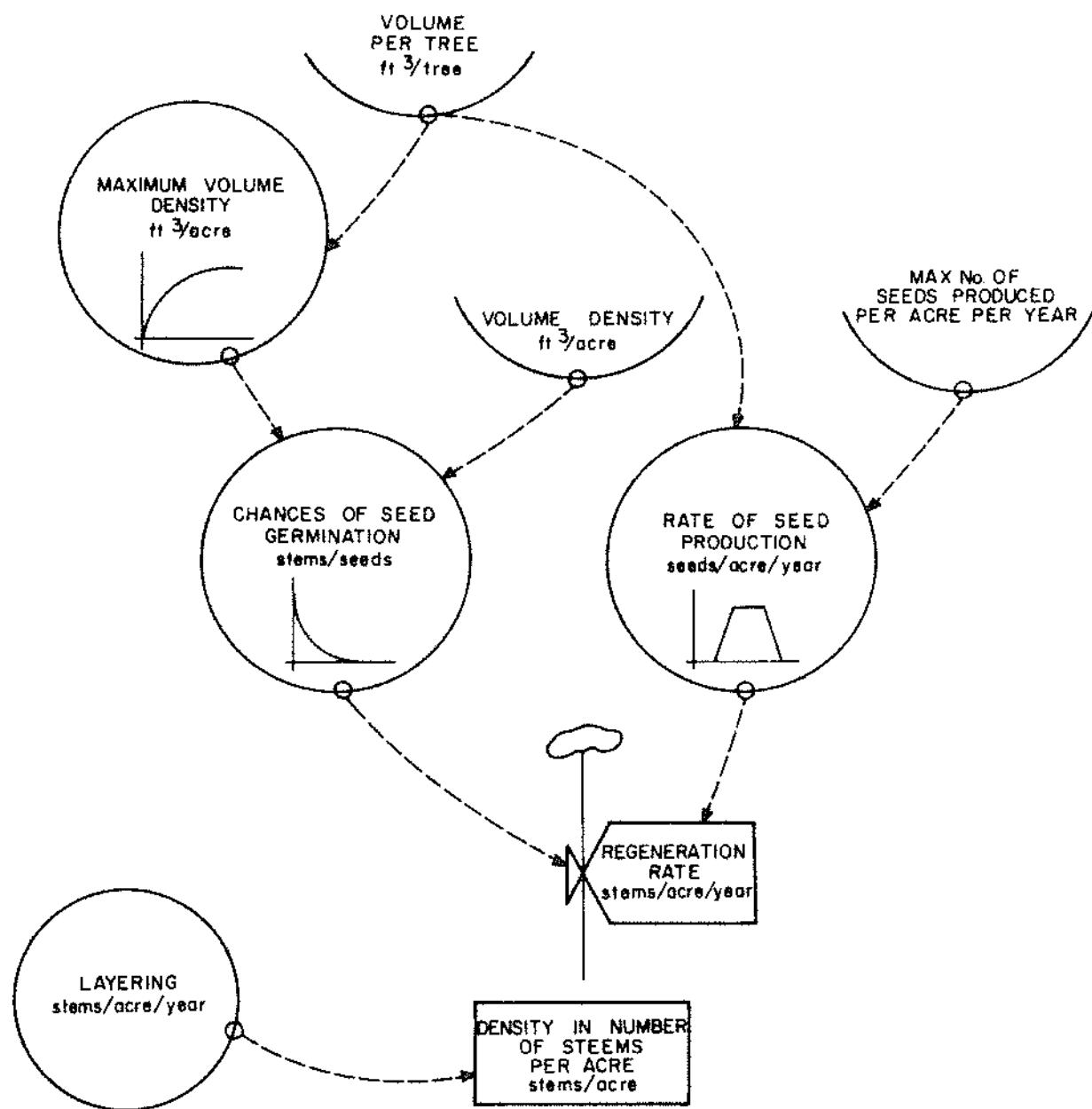


Figure 10: Regeneration diagram

## 2.2- Growth increments

Black spruce growing in a natural stand have a characteristic height, diameter and volume, which were described by Boudoux in a series of empirical yield tables (Boudoux 1977). We used these tables to make the calculations for our model.

### 2.21- Determination of tree volume at 1 to 3 inches dbh

Users of yield tables are generally interested in the merchantable volume; the tables therefore contain no information on the volume of stems with a diameter less than four inches. Our model, on the other hand, must have information on all diameter classes in order to give a faithful representation of the forest. In order to obtain the mean volume per tree for the 1-, 2- and 3-inch classes, we used the normal yield tables prepared by Linteau and Vézina (1968), which apply to a 50 year-old stand on a class III site.

This tables gave us the following values:

dbh (inches)	volume per tree ( $\text{ft}^3$ )
1	0.030
2	0.209
3	0.598

It was then necessary to know their frequency distribution as we were looking for mean volume for each of these diameter classes.

In Bolghari's (1973) doctoral thesis we found a graph giving the distribution of observed frequencies for stems in a 46 year-old black spruce stand.

dbh (inches)	number of stems per acre	percentage
1	690	50
2	450	32.6
3	240	17.4
Total	1380	100

From this table we retained but the percentage, in order to assign a suitable distribution to the total number of stems with a diameter less than four inches, obtained from Boudoux's tables (1977).

Thus, for a 50 year-old stand on a class III site, there are 1199 stems per acre, distributed as follows:

dbh (inches)	percentage	number of stems per acre
1	50	600
2	32.6	391
3	17.4	208
Total	100	1199

Knowing the volume per tree and the number of stems per acre for each diameter class, we can now calculate the volume per acre for each class,

dbh (in)	vol/tree	number of trees/acre	volume/acre (ft <sup>3</sup> )
1	0.030	600	18.0
2	0.209	391	81.7
3	0.598	208	124.1
Total		1199	224.1

and hence obtain the mean volume per tree.

$$\begin{aligned}
 \text{Mean volume per tree} &= \text{Volume per acre}/\text{Number of trees per acre} \\
 &= 224.1/1199 \\
 &= 0.19 \text{ ft}^3
 \end{aligned}$$

Thus, by combining the data provided by Vézina and Linteau, Bolghari and Boudoux, we were able to extract the one figure we lacked in order to find the total volume per acre, namely the mean volume per tree.

#### 2.22- Determination of the total volume per acre

It is now possible to complete the table given by Boudoux, by adding it the volume for trees one to three inches in diameter, which is the product of their average volume ( $0.19 \text{ ft}^3$ ), times the number of stems in this class. These new data complete the information set on the stand and provide a table better suited to our purpose.

#### 2.23- Determination of the maximum volume, $V_{max}$

Assuming that there is a relation between the maximum volume which a unit area of forest land can support and the area of the crown cover of this maximum forest volume, we can write:

$$V_{max} = \frac{43,560}{KCA^2 \cdot d^2} \cdot VA$$

AGE	NUMBER OF STEMS PER ACRE			Merchantable volume ft <sup>3</sup> /acre	VOLUME (ft <sup>3</sup> /acre)		Mean volume per tree ft <sup>3</sup>
	1" to 3"	4" +	Total		1" to 3"	Total	
40	1566	278	1844	464	298	762	0.41
45	1373	329	1702	660	261	921	0.54
50	1199	375	1574	873	228	1071	0.68
55	1045	416	1461	1011	199	1210	0.83
60	907	455	1362	1061	173	1334	0.98
65	797	481	1279	1295	152	1447	1.13
70	704	505	1209	1410	134	1544	1.28
75	631	523	1154	1508	120	1628	1.41
80	577	537	1114	1587	110	1697	1.52
85	544	544	1088	1647	103	1750	1.61
90	520	547	1067	1688	101	1789	1.68
95	538	543	1081	1711	102	1813	1.68
100	564	535	1099	1714	107	1821	1.66
105	610	521	1131	1698	116	1814	1.60
110	677	501	1178	1663	129	1792	1.52
115	764	476	1240	1608	145	1753	1.41
120	871	445	1316	1534	165	1699	1.29

Table 1: Determination of the total volume per acre

where

$43,560 \text{ ft}^2$  = area of one acre

$KCA \cdot d^2$  = crown cover of the mean tree

d = dbh of the mean tree in feet

KCA = factor by which the dbh is multiplied to obtain the crown diameter

VA = mean volume per tree

#### a) Determination of factor KCA

As one sees in figure 11, KCA is a factor which is used in conjunction with dbh to determine the area covered by the crown of each tree (Kalgraf and Egeberg 1975).

For intolerant species factor KCA is constant because these trees cannot live under cover and therefore will not tolerate crowding of their canopy. Black spruce is a species which is able to live even under a closed canopy, and factor KCA should therefore vary with the dbh in order best to represent this aspect.

This was carried out simply by observing the behaviour of this species in a natural stand. Owing to competition, the black spruce does in fact receive a reduced amount of light. Hence Spruce trees with identical crown covers but varying diameter can be seen fairly often (G. Frisque, personal communication). In such a situation, it is possible for temporarily suppressed stems to break through the crown, since the dominants are no longer striving to widen their canopy and suppress them.

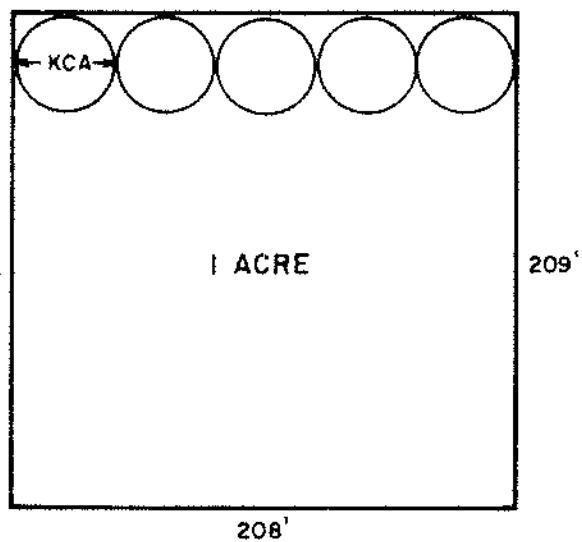


Figure 11: Area of crown cover

Here then is how we arrived at values for KCA:

Factor KCA was determined from the normal yield tables of Vézina and Linteau. These tables were prepared for high stand densities, and we therefore thought it safe to assume that they would provide the best basis for calculating KCA. We took from the tables, for site class III, the vectors for dbh and number of stems in order to obtain a KCA value for each pair, as follows.

In the relation

$$V_{max} = \frac{43,560}{KCA^2 \cdot d^2} \quad VA$$

the term  $43,560/KCA^2 \cdot d^2$  represents the maximum number of stems ( $nt_{max}$ ) of volume VA which an acre of forest land can support.

$$nt_{max} = \frac{43,560}{KCA^2 \cdot d^2}$$

Hence,

$$KCA = \sqrt{\frac{43,560}{nt_{max} \cdot d^2}}$$

Table 2 gives the KCA values obtained for each pair dbh-number of stems, together with the corresponding volume per tree.

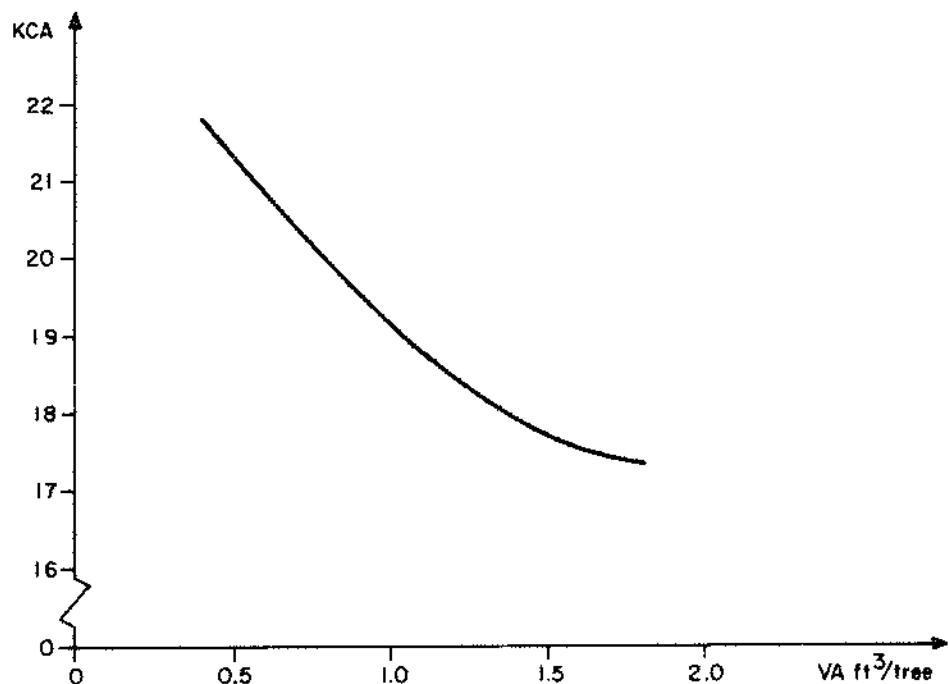


Figure 12: Factor KCA as a function of the mean volume per tree

dbh in feet	number of stems per acre	KCA	VA
0.217	2070	21.172	0.52
0.242	1790	20.413	0.69
0.267	1600	19.567	0.87
0.292	1460	18.728	1.04
0.308	1350	18.423	1.22
0.325	1260	18.092	1.40
0.342	1190	17.708	1.57
0.358	1140	17.251	1.73
0.367	1090	17.241	1.89
0.375	1045	17.217	2.05
0.392	1010	16.767	2.19
0.400	980	16.668	2.33
0.408	955	16.540	2.46
0.417	930	16.425	2.60
0.425	910	16.279	2.74
0.433	890	16.145	2.88
0.433	875	16.282	2.99

Table 2: Values of factor KCA corresponding to various dbh and numbers of stems

b) Relation between height and dbh

It should be recalled that the concept of maximum volume applies to a normal stand. It is therefore logical to determine the relation linking height and diameter (dbh) from the normal yield table prepared by Vézina and Linteau (site class III).

In order to be able to carry out the mathematical transformations necessary for determining the maximum volume, we shall express the height-dbh relation in allometric form:

$$h = \beta_0 d^{\beta_1} \dots \dots \dots \dots \dots \dots \quad (1)$$

In logarithmic form, (1) becomes

$$\ln h = \ln \beta_0 + \beta_1 \ln d \dots \dots \dots \dots \dots \dots \quad (2)$$

This expression can be written

$$y = a + bx$$

where

$$y = \ln h$$

$$x = \ln d$$

$$a = \ln \hat{\beta}_0$$

$$b = \hat{\beta}_1$$

The parameters of the regression equation of  $\ln h$  on  $\ln d$  are:

$$a = 4.5638$$

$$b = 0.8766$$

$$\hat{\beta}_0 = e^a = 95.948$$

$$\hat{\beta}_1 = b = 0.877$$

(1) can thus be written

$$\hat{h} = 95.948 d^{0.877} \dots \dots \dots \quad (3)$$

For comparison, we present table 3, which shows the observed values opposite the values obtained using model (1).

c) Maximum volume,  $V_{max}$

Assuming the stem form of the black spruce to be a paraboloid, the mean volume per tree,  $VA$ , can be written

$$VA = \frac{1}{2} \cdot \frac{\pi d^2}{4} \cdot h \dots \dots \dots \quad (4)$$

where

$\frac{1}{2}$  = form factor for a paraboloid (Pardé 1961)

$d$  = dbh in feet

$h$  = height in feet

From equation (3) we also know that

$$\hat{h} = 95.948 d^{0.877} \dots \dots \dots \quad (3)$$

from which we extract

$$d = \left( \frac{h}{95.948} \right)^{1.140} \dots \dots \dots \quad (5)$$

or

$$d^2 = \left( \frac{h}{95.948} \right)^{2.280} \dots \dots \dots \quad (6)$$

Age (years)	dbh (feet)	Height (feet)	$h = \beta_0 d^{\beta_1}$
20	0.075	9.9	9.9
25	0.117	14.4	14.6
30	0.150	18.4	18.2
35	0.183	21.9	21.7
40	0.217	25.1	25.1
45	0.242	27.8	27.6
50	0.267	30.2	30.1
55	0.292	32.3	32.6
60	0.308	34.1	34.2
65	0.325	35.8	35.8
70	0.342	37.3	37.4
75	0.358	38.6	39.0
80	0.367	39.9	39.8
85	0.375	41.0	40.6
90	0.392	42.0	42.2
95	0.400	42.9	43.0
100	0.408	43.7	43.7
105	0.417	44.5	44.5
110	0.425	45.2	45.3
115	0.433	45.9	46.1
120	0.433	46.5	46.1
125	0.442	47.1	46.9
130	0.450	47.7	47.6
Mean		35.31	35.29
Variance		122.70	122.72
 <sup>*</sup> Residual standard error = 0.0442 feet			
 $R^2 = .99$			
 $F = 61137.04$			

Table 3: Regression of  $h$  on  $d$  according to the model  
 $h = \beta_0 d^{\beta_1}$

\* Residual standard error,  $R^2$  and  $F$  are of course calculated from  $h = \beta_0 d^{\beta_1}$  and not from its logarithm  $\ln h$ .



Mean volume per tree (ft <sup>3</sup> /tree)	KCA	Maximum volume (ft <sup>3</sup> /acre)
.41	21.8	872
.54	21.1	1010
.68	20.5	1148
.83	19.8	1307
.98	19.2	1463
1.13	18.7	1611
1.28	18.2	1765
1.41	17.8	1902
1.52	17.6	1992
1.61	17.5	2048
1.66	17.4	2092
1.68	17.4	2098

Table 4: Vmax for different values of VA and KCA

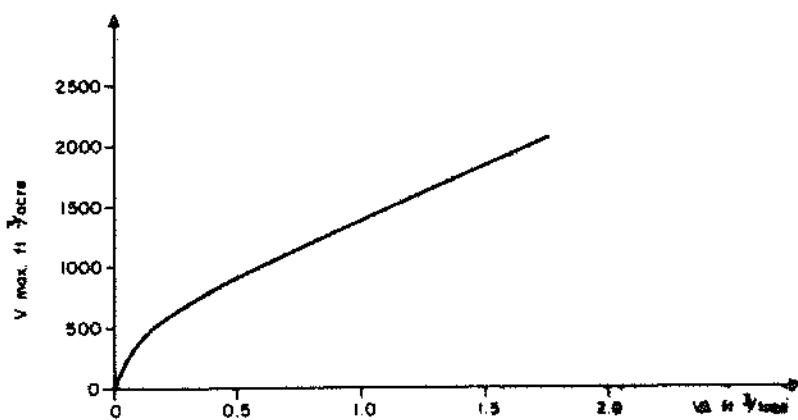


Figure 13:  $V_{\text{max}}$  as a function of the mean volume per tree (VA)

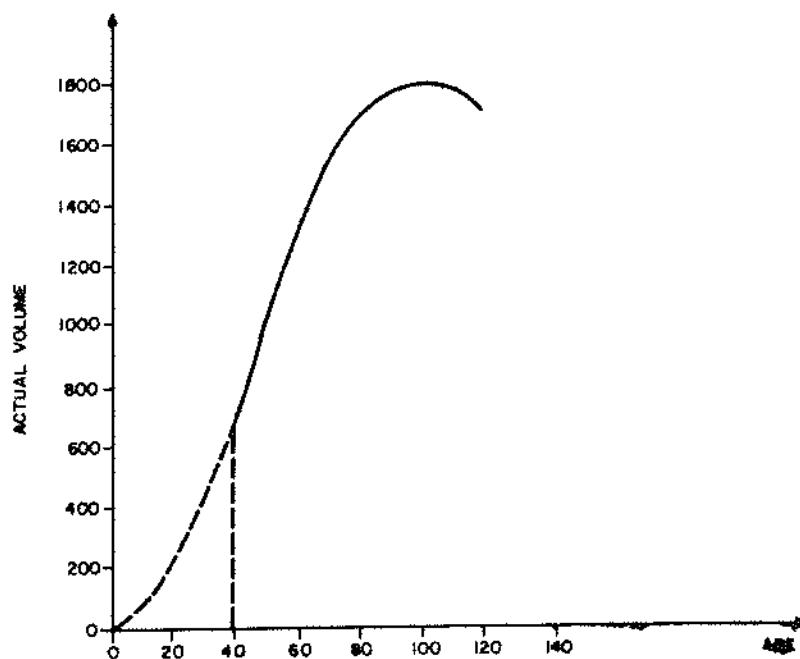


Figure 14: Variation over time of the total volume of a black spruce stand of site class III

Figure 13 shows  $V_{max}$  as a function of the mean volume per tree.

#### 2.24- Doubling time

Knowing the value of the maximum volume from the calculations in the preceding section, we can now calculate the doubling time at fifty per cent of the maximum volume (regarding this latter parameter,  $\frac{V_{max}}{2}$  see section 2.26).

Figure 14 represents the change over time in the total volume of a black spruce stand of site class III. The volume values are those taken from Boudoux's (1977) tables, to which was added the volume of nonmerchantable stems with a dbh less than four inches.

From figure 13 we can see that the volume does not increase at a uniform rate; rather, the rate varies with time. Thus, for example, a stand of a given age may grow at a rate of six per cent per year. At this growth rate, its volume will double in a certain number of years, and this doubling time will change as the growth rate increases or decreases. This, in short, is what we mean by doubling time. In order to calculate it, we must first examine the volume graph to find the ages at which the maximum volume and half the maximum are reached. For example if  $VA_{40} = 0.41 \text{ ft}^3/\text{tree}$  at the age of 40 years, the maximum volume  $V_{max}$  corresponding to this mean volume is  $872 \text{ ft}^3/\text{acre}$ .

The volume curve gives us

$$\begin{aligned} V_{max} &= 872 \text{ ft}^3/\text{acre} \text{ at } 43 \text{ years} \\ \text{and } \frac{V_{max}}{2} &= 436 \text{ ft}^3/\text{acre} \text{ at } 29 \text{ years} \end{aligned}$$

The difference between these ages gives us the doubling time at fifty per cent of the maximum volume for

$$VA_{40} = 0.41 \text{ ft}^3/\text{tree}$$

$$D50 = 43 - 29 = 14 \text{ years}$$

Table 5 gives the values obtained for doubling time at 50% of Vmax (D50) at different mean volumes per tree (VA), and figure 15 graphs D50 as a function of VA.

#### 2.25- Percent growth at 50% of Vmax

If we now let PA50 designate the percent growth at fifty per cent of the maximum volume, knowing D50 we can write:

$$e^{PA50 \times D50} = 2$$

$$PA50 \times D50 = \ln 2$$

It might help to recall at this point that to a given age there corresponds a mean volume per tree VA and a doubling time D50.

Knowing the doubling time of the volume as a function of the mean volume per tree VA, we can find PA50:

$$PA50 = \frac{\ln 2}{D50}$$

DYNAMO

A PA50.K = LOGN(2)/D50.K

Age in years	VA*	V *	Vmax			Age at Vmax	Age at $\frac{Vmax}{2}$	D50
	Mean volume per tree ft <sup>3</sup> /tree	Actual volume ft <sup>3</sup> /acre	Maximum volume ft <sup>3</sup> /acre	$\frac{Vmax}{2}$				
40	0.41	762	872	436	43	29	14	
45	0.54	921	1010	505	48	31	17	
50	0.68	1071	1148	574	53	34	19	
55	0.83	1210	1307	653	59	37	22	
60	0.98	1334	1463	731	66	39	27	
65	1.13	1447	1611	805	74	41	33	
70	1.28	1544	1765	882	87	44	43	

Table 5: Calculation of doubling time

\* VA and V were calculated from the figures in Boudoux's (1977) empirical yield tables.

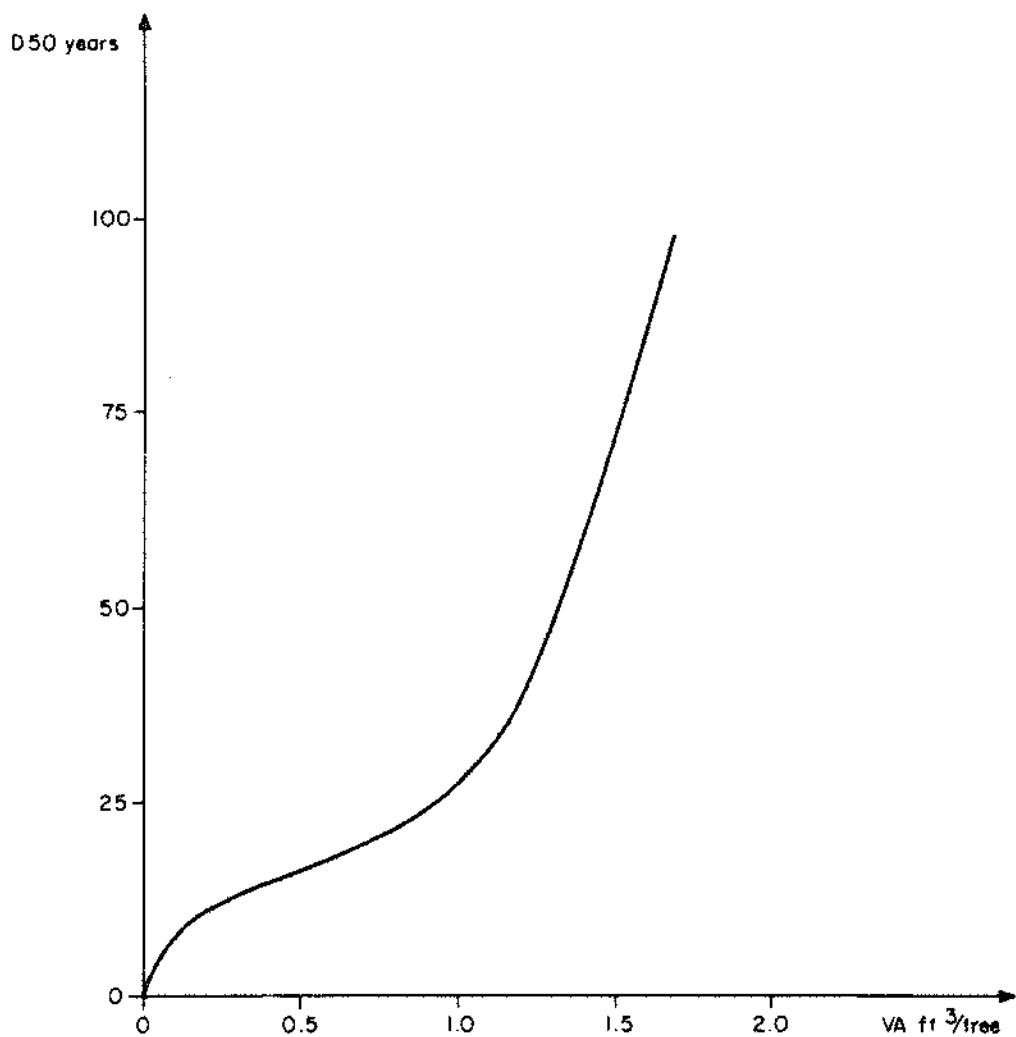


Figure 15:  $D_{50}$  as a function of  $VA$

## 2.26- Percent growth at V/Vmax or percent actual growth

The volume growth depends among other things on the closure of the canopy. In an open stand of low density, where the volume  $V$  per acre is less than  $\frac{V_{max}}{2}$ , crowns receive more sunlight over a greater portion of their length, and their photosynthetic efficiency is therefore increased in comparison with that of a stand with a standing volume equal to  $\frac{V_{max}}{2}$ . If in a denser stand, however, the volume  $V$  exceeds  $\frac{V_{max}}{2}$ , the photosynthetic efficiency is reduced and everything else being equal, the volume growth is less than that of the stand where volume equals  $\frac{V_{max}}{2}$ .

We have just seen that  $\frac{V_{max}}{2}$  serves as a reference value and that the ratio  $V/V_{max}$  may be considered to be the relative closure of the canopy.

If we let  $KA$  designate the correction factor for  $PA50$  (percent growth at 50% of  $V_{max}$ ), the percent actual growth (or percent growth at  $V/V_{max}$ ) can be expressed as

$$PA = KA \times PA50$$

**DYNAMO**

$$A PA.K = KA * PA50.K$$

Figure 16 represents factor  $KA$  as a function of the ratio  $V/V_{max}$ .

## 2.27- Growth per tree per year

Knowing the percent annual growth  $PA$ , we can calculate the growth per tree per year:

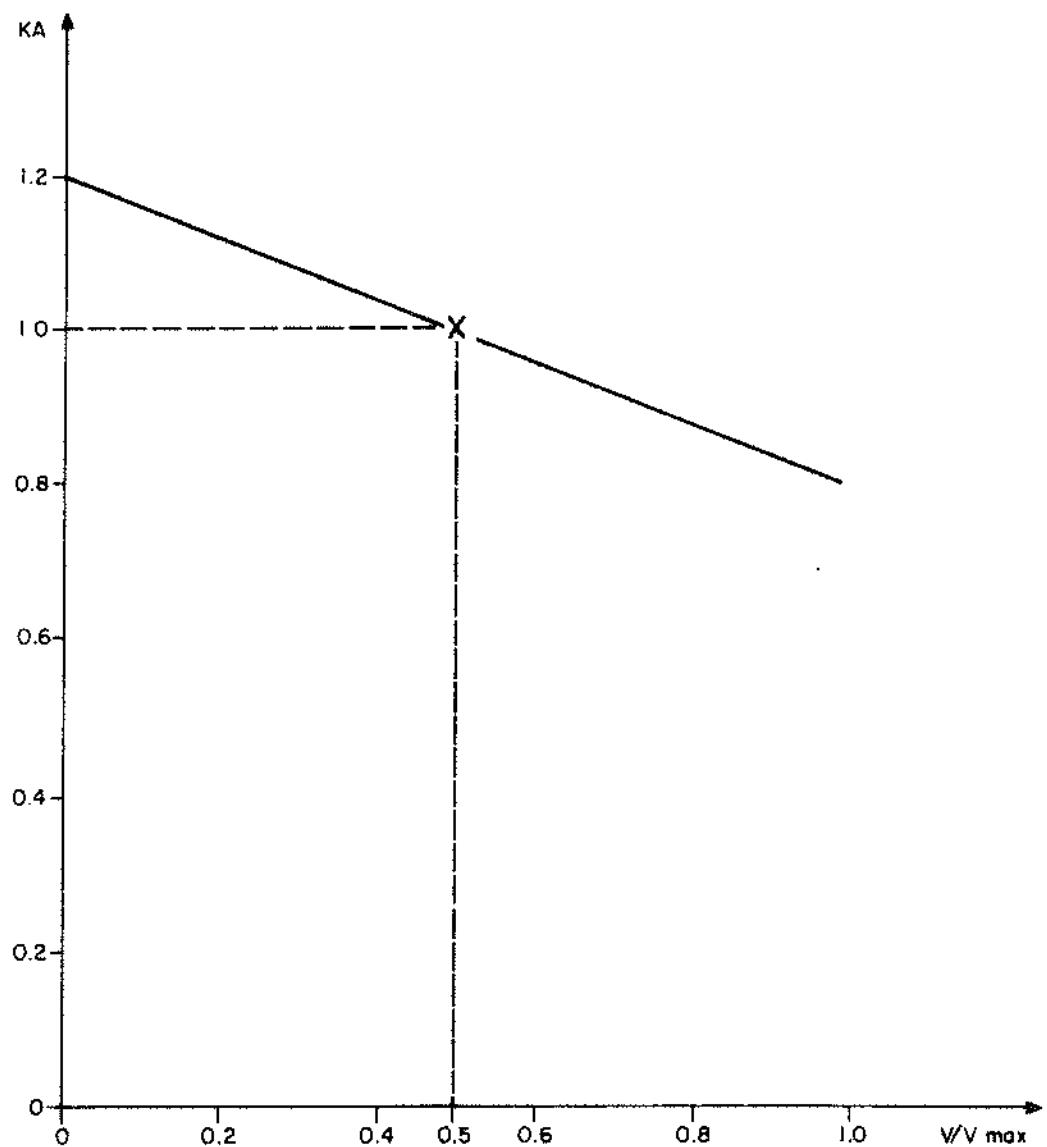


Figure 16: KA as a function of the ratio V/V<sub>max</sub>

$$A = PA \times VA \text{ (ft}^3/\text{tree/year)}$$

VA being the mean volume per tree ( $\text{ft}^3/\text{tree}$ ).

### ~~DYNAMO~~

$$AA.K = PA.K * VA.K$$

2.28- Total growth per year

TI being the number of stems per acre, the growth per acre can be written

$$AB = TI \times A \text{ (ft}^3/\text{acre/year})$$

To this must be added the volume produced annually by planting and by sexual and vegetative reproduction.

### ~~DYNAMO~~

$$R AB.KL = TI.K * A.K + \underbrace{1E-5 * TPTI.JK}_{\text{Planting}} + \underbrace{1E-7 * TRTI.JK}_{\text{Sexual reproduction}} + \underbrace{0.016 * MAR.JK}_{\text{Layering}}$$

Figure 17 gives a summarized growth diagram.

2.3- Mortality

Along with growth we must consider mortality, the entropy indicator in our system. Mortality increases during the life of the stand and may reach a final rate which is in equilibrium with the growth rate.

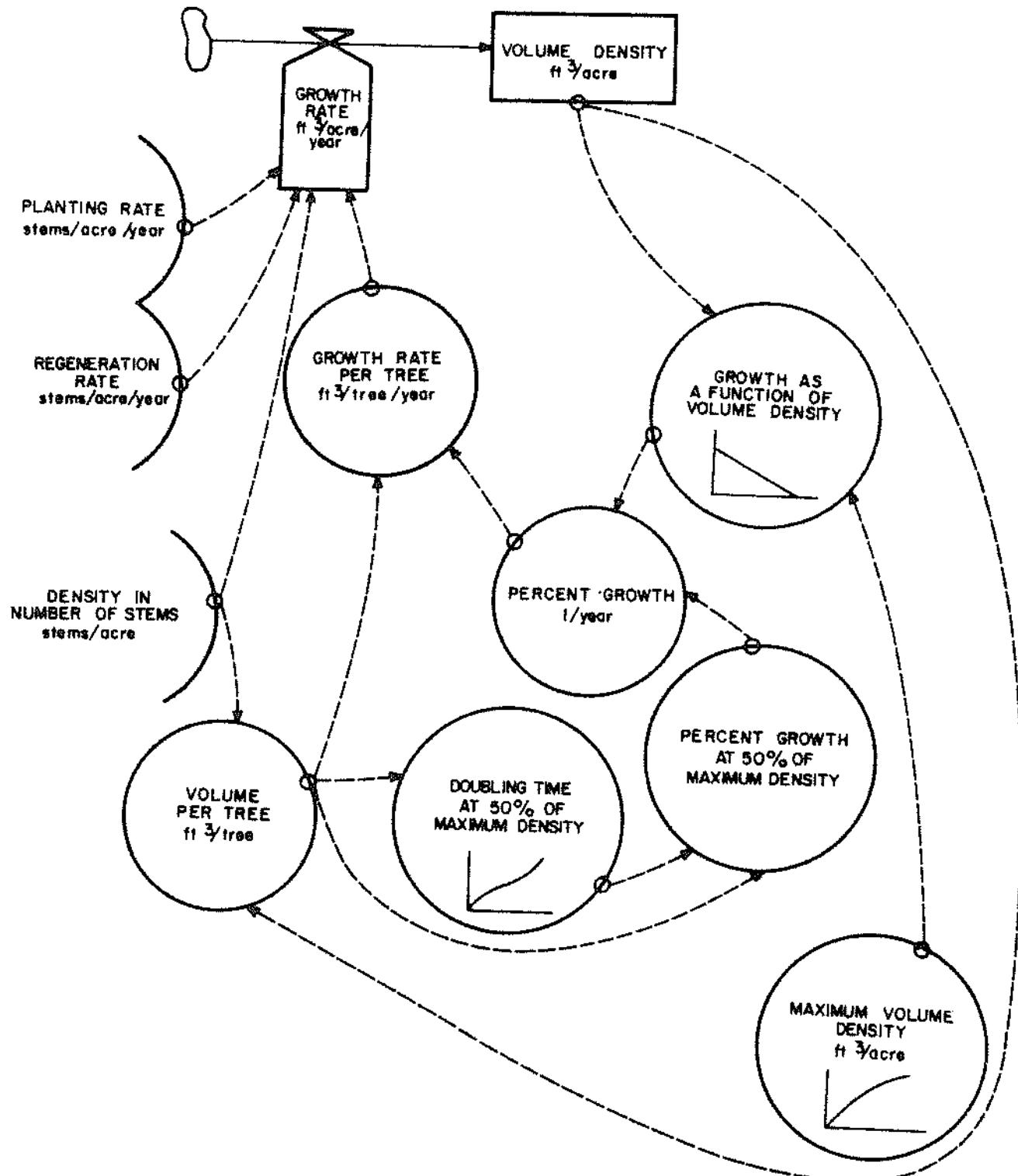


Figure 17: Growth diagram

Here all similarity with the growth situation ceases. In the case of growth, we were able to establish a curve for the doubling time using existing data, but in the case of the stand's half-life, such an approach proved impossible because of the lack of relevant mortality data.

It appears in fact that no detailed study has yet been made of the volume lost annually by a forest due to mortality, or of the relative size of Nature's annual toll.

The importance of mortality cannot be overemphasized in forest management, in general, either in simulating various management hypotheses (including harvesting) in order to derive the greatest profit from forest lands. A knowledge of loss volumes, as well as of annual growth, would yield a better understanding of the dynamics of wood production and of the mechanics involved in the circulation of matter and energy from the environment to the forest system and back to the environment.

This gap in knowledge had to be circumvented in order to provide the model with the information it needed to function. We therefore proceeded with a series of tests, trying out various curve patterns based on the Kalgraf and Egeberg (1975) model for Norwegian spruce (*Picea abies* [L.] Karst) and seeking to fit the results to the empirical data obtained by Boudoux (1977).

#### 2.31- Percent mortality at 50% of Vmax

Let PM50 designate the percent annual mortality of a stand with a volume equal to  $\frac{V_{max}}{2}$ . The time it takes the stand to lose half its volume at this rate PM50 is called the half-life, DV50, and is expressed by

$$e^{PM50 \times DV50} = 2$$

$$PM50 \times DV50 = \ln 2$$

Knowing the half-life, PM50 can be calculated:

$$PM50 = \frac{\ln 2}{DV50}$$

DYNAMO

$$\Delta PM50.K = LOGN(2)/DV50.K$$

Figure 18 shows the best half-life curve which we were able to obtain under the given constraints.

### 2.32- Percent mortality at V/Vmax

The situation for stand mortality is opposite to that which we found for growth. The denser the stand becomes, or the closer the volume comes to the maximum volume, the greater the competition and the greater the mortality.

Taking the percent mortality at 50% of Vmax as our reference, percent actual mortality can be expressed by

$$PM = PM50 \times KM$$

where

$$KM = \text{correction factor for PM50}$$

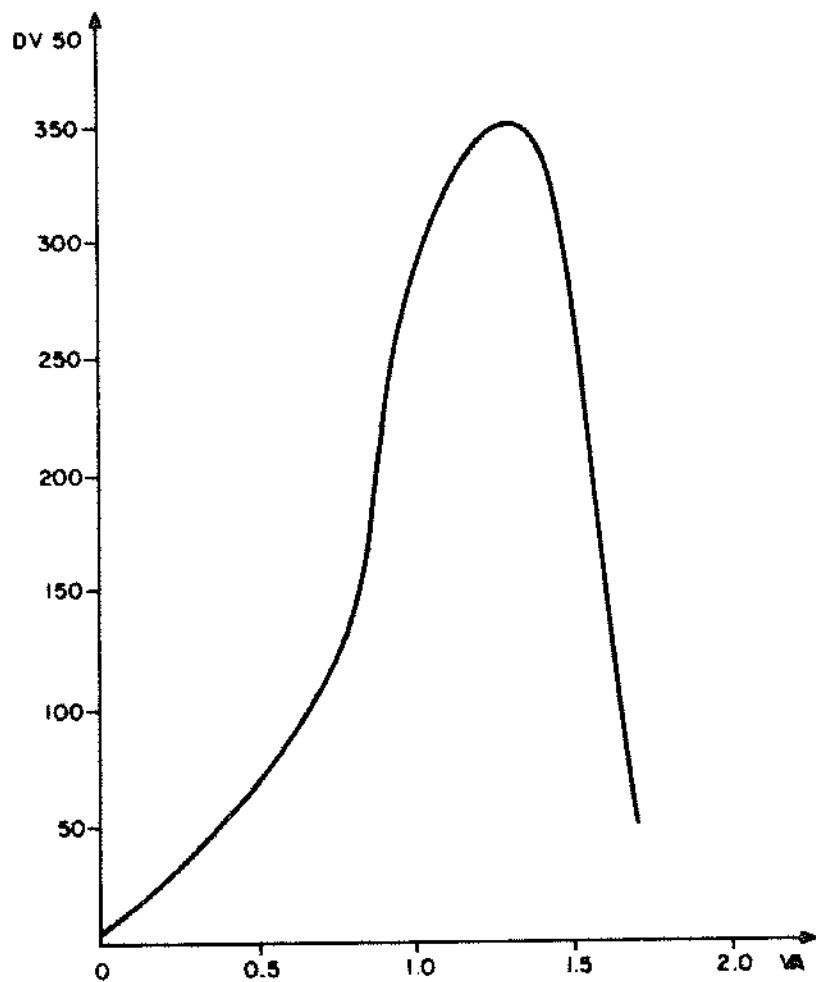


Figure 18: Half-life as a function of the mean volume per tree

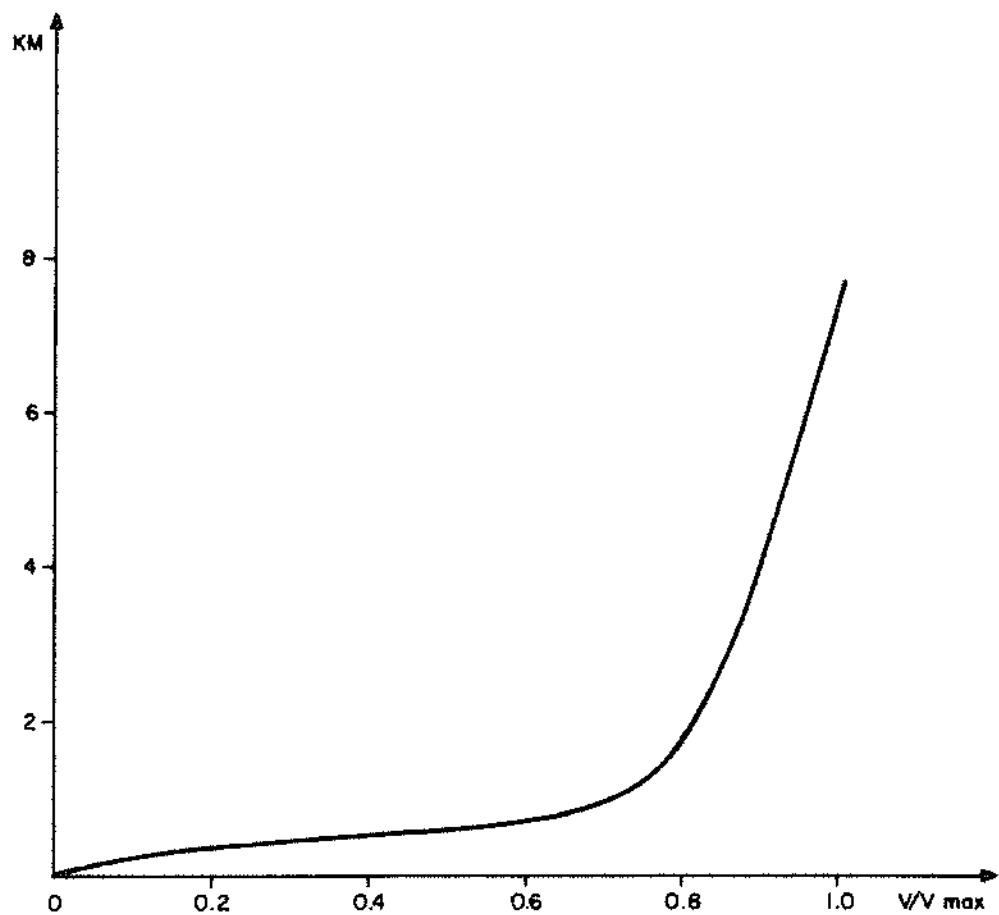


Figure 19: Factor KM as a function of the ratio V/V<sub>max</sub>

**DYNAMO**

$$A \cdot PM \cdot K = PM50 \cdot K \cdot KM \cdot K$$

Figure 19 shows factor KM as a function of the ratio  $V/V_{max}$ .

#### 2.33- Number of dead trees per year

Mortality is here calculated in terms of number of dead stems in the stand, and corresponds to a reduction in the number of trees standing. The number of dead trees per year is therefore written

$$TMTI = TI \times PM$$

where

TI = number of stems/acre

TMTI = number of dead stems/acre/year

**DYNAMO**

$$R \cdot TMTI \cdot KL = TI \cdot K \cdot PM \cdot K$$

#### 2.34- Volume of dead trees per year

Knowing VA, the mean volume per tree and TMTI, the number of dead trees per year, the annual loss volume per acre can be calculated:

$$TM = TMTI \times VA \times GRAM \quad (\text{ft}^3/\text{acre/year})$$

where

GRAM = relative size of the dead trees

DYNAMO

R.TM.KL = TMTL.JK\*VA.K\*GRAM.K

#### 2.35- Relative size of dead trees

Another difficulty to overcome was determining the relative size of dead trees. No one could say whether these were trees of average size or larger than average. We had to derive a linear relation between the relative size of dead trees and volume per tree, which would enable us to better interpret data in the empirical tables. Such a relation is shown in figure 20. Figure 21 is a diagram representing the determination of natural mortality rate.

#### 2.4- Stand conditions at time t

It now remains to relate the phenomena of natural regeneration, growth and natural mortality in order to learn how the stand behaves at any given moment in response to these three determinants.

#### 2.41- Density in number of stems per acre

Stand density (trees/acre) is a level ( $N$  = "niveau") determined by regeneration and planting on the one hand, which provide new growth, and by silvicultural cutting and mortality on the other, which eliminate a certain number of stems.

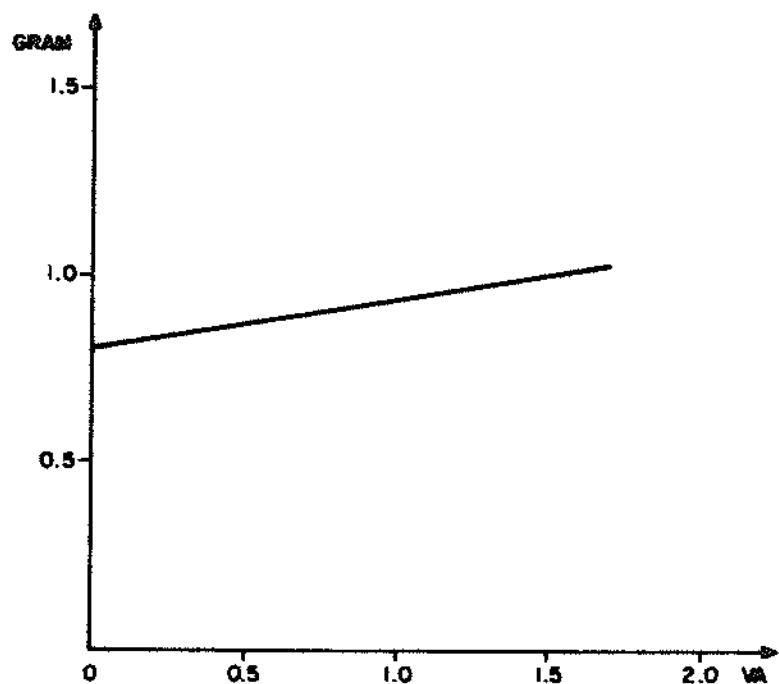


Figure 20: Relative dead tree size as a function of the mean volume per tree

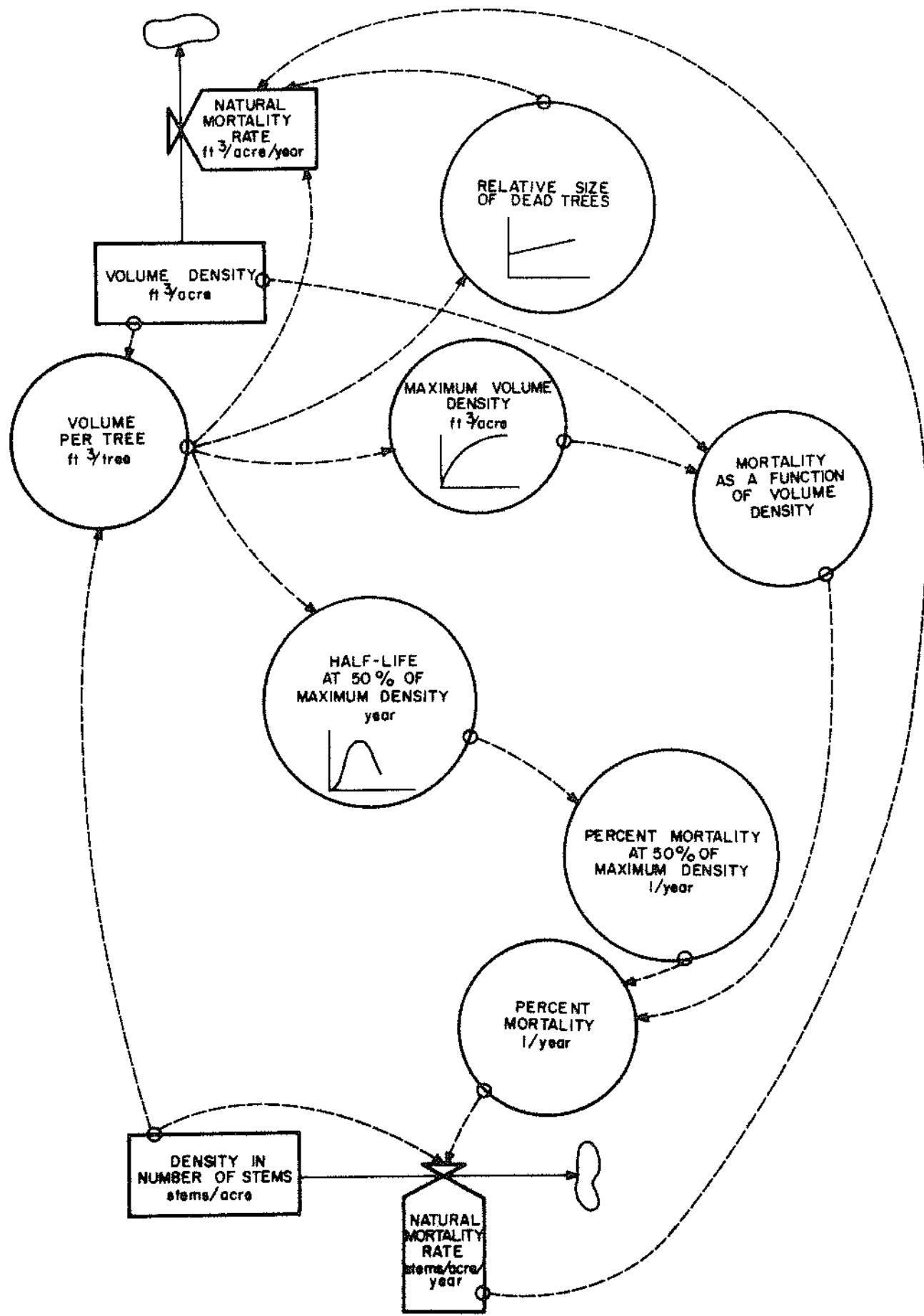


Figure 21: Diagram of natural mortality

The situation can be summarized by the equation

$$TI_t = TI_{t-1} + dt(TPTI + TRTI + MAR - TETI - TMTI)$$

where

TPTI = annual planting rate

RTTI = annual rate of sexual reproduction

MAR = annual rate of layering

TETI = annual cutting rate

TMTI = annual mortality rate

### DYNAMO

$$L TI.K = TI.J + DT * (TPTI.JK + TRTI.JK + MAR.JK - TETI.JK - TMTI.JK)$$

2.42- Volume density (cu ft/acre)

The volume per acre varies over time in response to growth, mortality and various silvicultural treatments:

$$V_t = V_{t-1} + dt \times (AB - TE - TM) \dots \dots \dots \dots \dots \dots \dots \quad (13)$$

where

AB = Growth volume

TE = Cutting volume

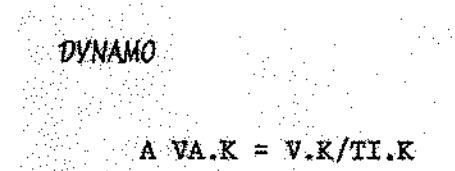
TM = Mortality volume

### DYNAMO

$$L V.K = V.J + DT * (AB.JK - TE.JK - TM.JK)$$

## 2.43- Mean volume per tree

$$VA = \frac{V}{TI} \text{ ft}^3/\text{stem}$$



## 2.5- Summary of relations

Figure 22 gives an overview of interactions of various "internal" variables in the DYPEUFOR simulation model described in this chapter. This general diagram brings together the three fundamental development processes in a forest stand: regeneration, growth and mortality.

Essentially, the diagram is composed of two networks, that of the volume density ( $\text{ft}^3/\text{acre}$ ) and that of the density in number of stems (number of stems/acre), the two being linked by the model's basic variable, the mean volume per tree.

Here is a brief explanation of the diagram:

- a) Regeneration: the mean volume per tree is used in calculating seed production rate and germination rate; the latter two variables in turn are used to determine natural regeneration rate.
- b) Growth: the mean volume per tree is used to determine the growth rate per tree, by doubling time at 50% of the maximum volume and the percent growth at 50% of the maximum density.

- c) Mortality: the mean volume per tree is used in calculating the half-life at 50% of the maximum density; the latter is then used to calculate the percent mortality, which together with the density in number of stems determines the natural mortality rate.

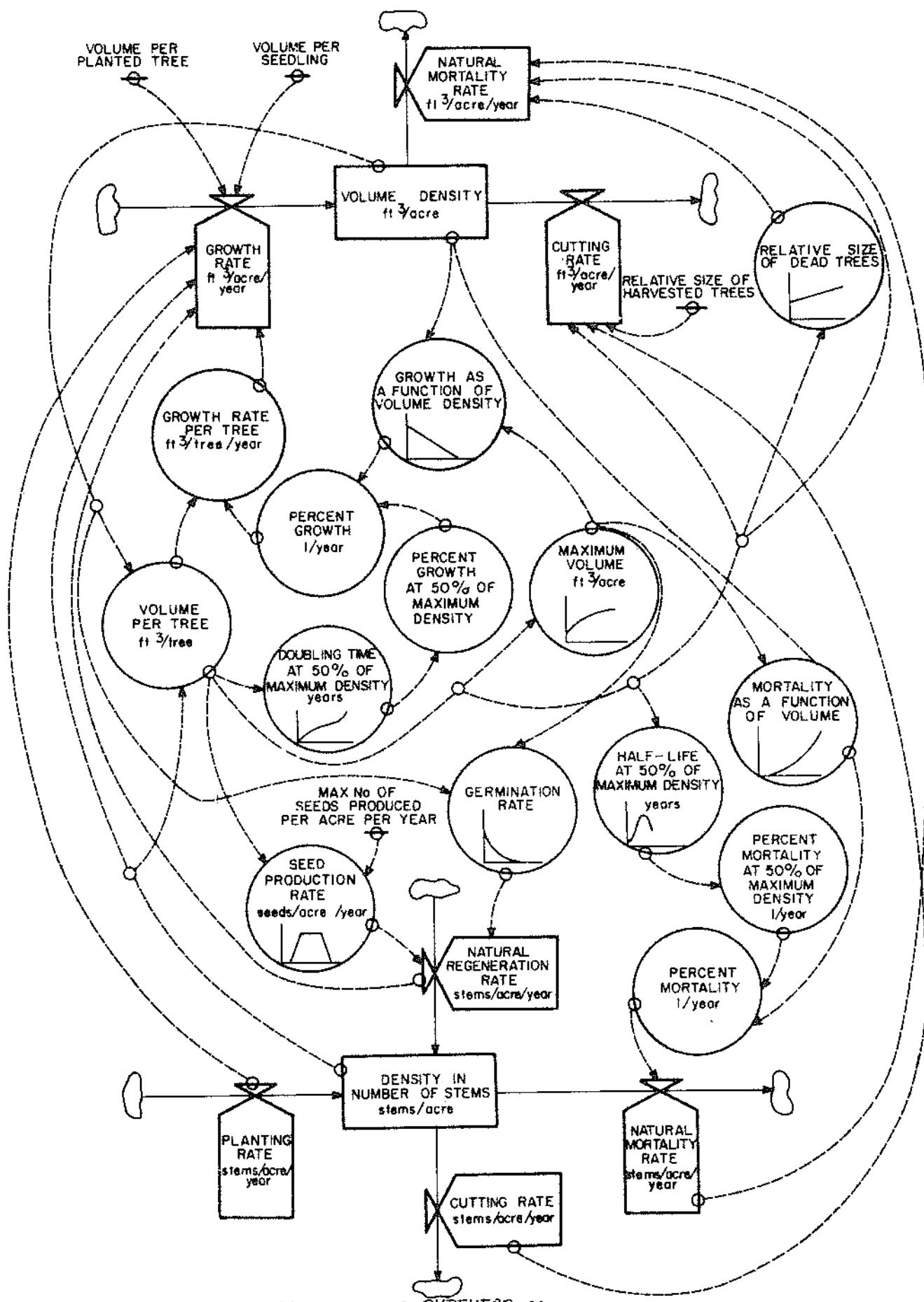


Figure 22: General DYPERFOR diagram



### 3. RESULTS

#### 3.1- Application of DYPEUFOR without external action

In this first part we shall study the results obtained from the simulation by considering only the internal system variables, i.e. the development of the forest stand in the absence of external influences. The practical applications of DYPEUFOR, in which external variables are introduced, will be discussed in the second part of the chapter.

The version of the program used in this simulation is shown in appendix 2. The values obtained are given in figure 23 and table 6.

Studying this simulation, we can see that in the regeneration phase the stand has a strictly positive material balance, characterized by seed input and an increase in wood volume. The immature phase is likewise characterized by a positive balance, with a resultant increase in the biomass.

In its prime phase, the stand acquires its maximum wood volume. The stand then goes through a relatively brief plateau period before entering in its senescent phase.

During the senescent period entropy increases, first balancing and later exceeding the material flow (input), so that a negative balance results with a loss of volume. This trend continues until the balance is once again zero. At this point the stand reaches equilibrium, which will not be disturbed unless there is outside interference.

Thus an undisturbed black spruce stand of site class III appears to be a system in dynamic equilibrium, whose characteristic behaviour over time can be represented by the graph in figure 24.

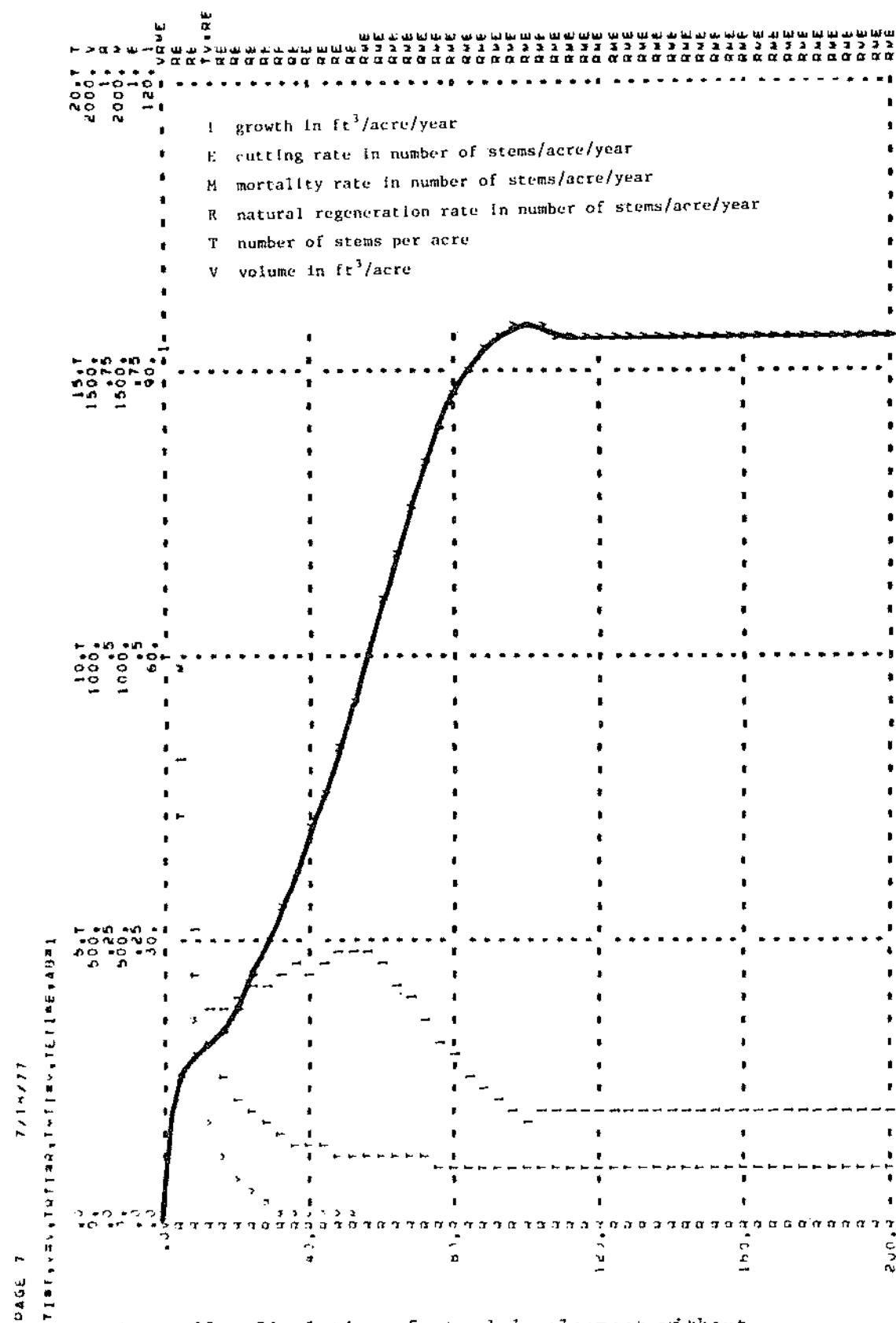


Figure 23: Simulation of stand development without external action

Table 6: Simulation of stand development without external action

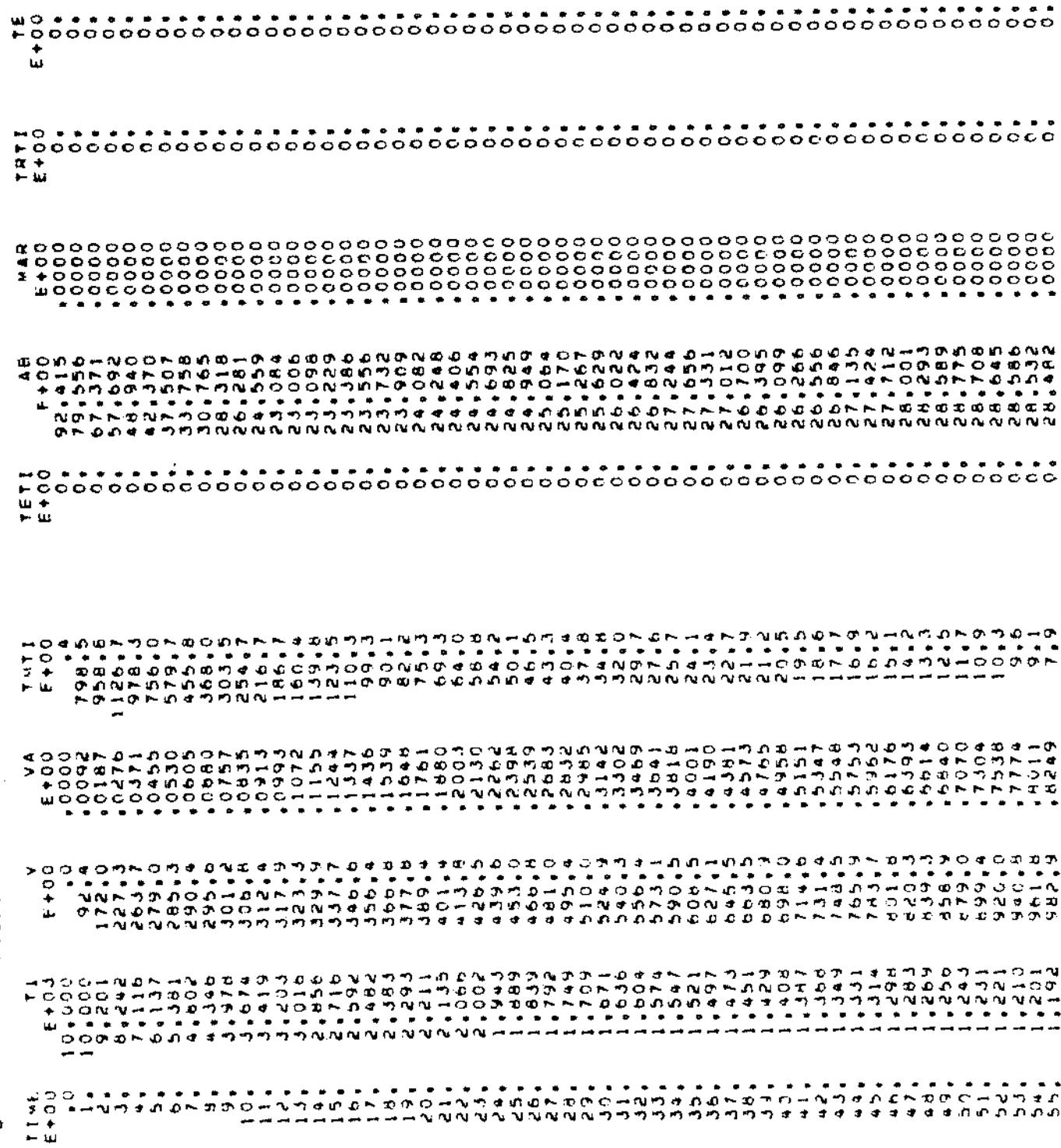




Table 6 continued

E	.....
F	.....
G	.....
H	.....
I	.....
J	.....
K	.....
L	.....
M	.....
N	.....
O	.....
P	.....
Q	.....
R	.....
S	.....
T	.....
U	.....
V	.....
W	.....
X	.....
Y	.....
Z	.....



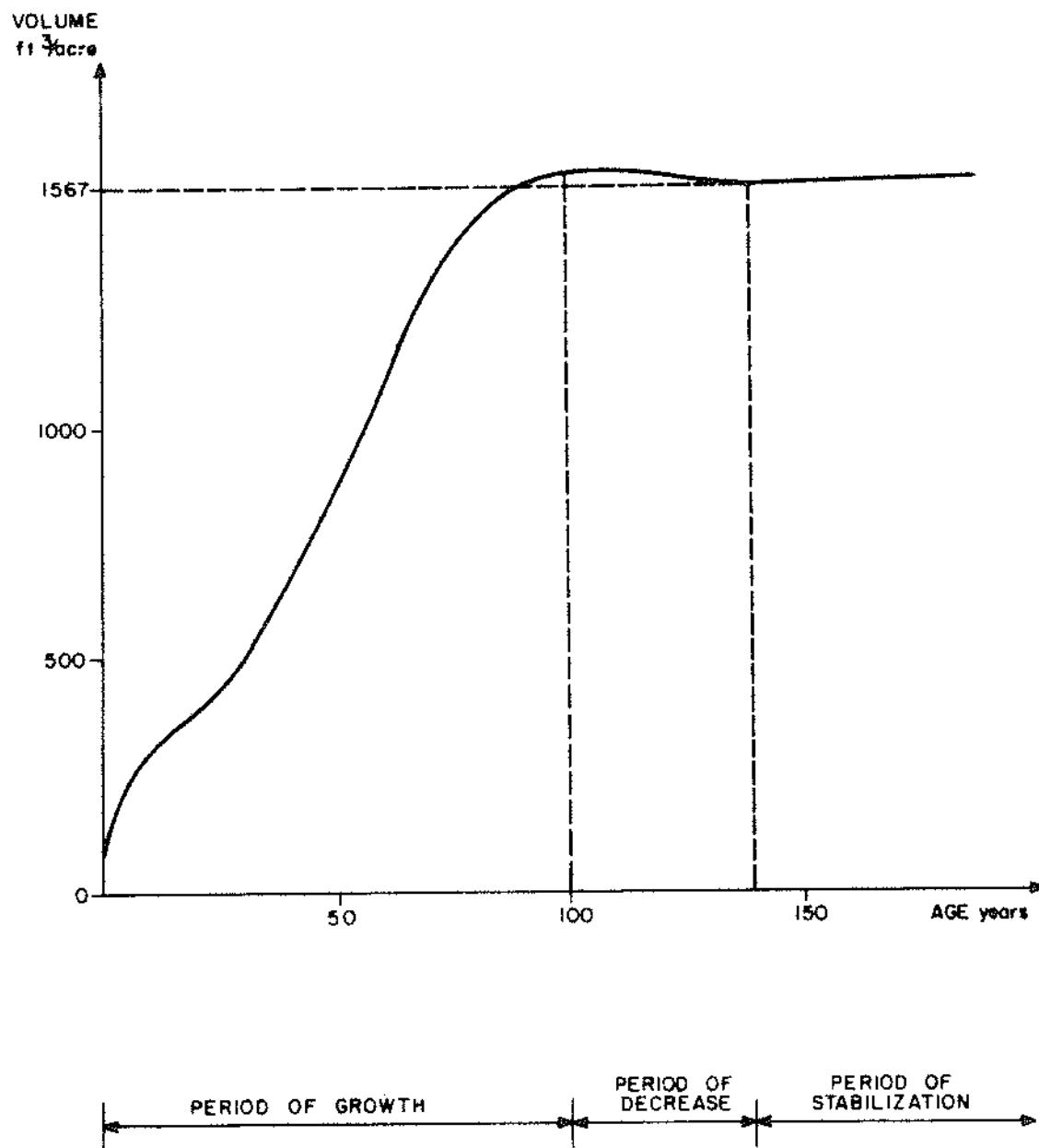


Figure 24: Development over time of the volume per acre  
of a black spruce stand of site class III  
without external action

This behaviour is a result of the simultaneous existence of a positive feedback loop responsible for growth and a negative feedback loop which brings the system back to a state of dynamic equilibrium in which the positive and negative forces balance each other, (figure 25).

### 3.2- Applications of DYPEUFOR with external actions

A study of the forest in its natural state would be of little interest if it did not take into account the user's potential influence on its development.

Therefore a second model must be designed which will accommodate silvicultural treatments. Such treatments could be of two types: those which reduce the standing volume and those which produce or promote an increase in the volume.

#### 3.21- Treatments reducing the standing volume

Final cuttings and thinnings bring about an immediate reduction in the standing volume, while contributing to sound, optimum site utilization.

##### 3.211- Utilization rate

The utilization rate is expressed as both number of stems and volume removed annually.

Each year, a certain number of stems may be removed by thinning (ETI.K) or by final cutting (CF.K).

In order to be able to simulate various types of thinnings, the concept of relative size of harvested trees is introduced into the calculation of the volume removed by thinnings.

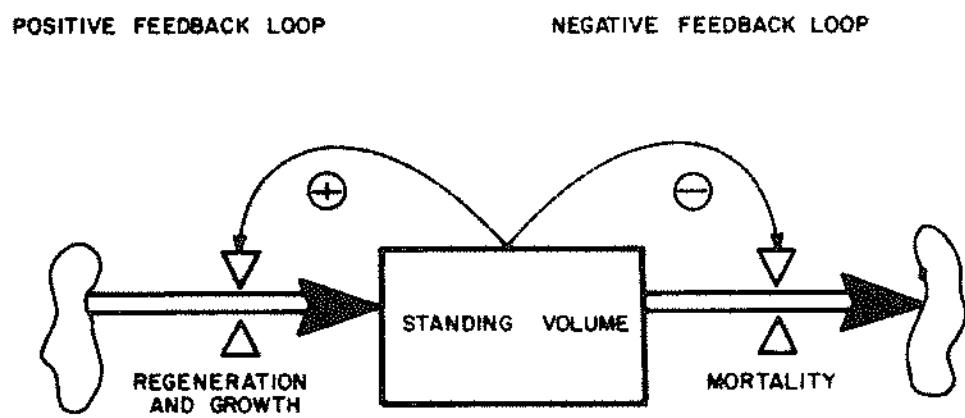


Figure 25: Feedback loops

## DYNAMO

$$R_{TE,KL} = CF.K * VA.K + ETI.K * VA.K * GRAE$$

TE.KL = volume of wood removed during interval KL ( $\text{ft}^3/\text{acre}/\text{year}$ )

CF.K = number of stems removed in the final cut at time K  
(stems/acre/year)

VA.K = mean volume per tree at time K ( $\text{ft}^3$ )

ETI.K = number of stems removed in thinnings at time K (stems/  
acre/year)

GRAE = relative size of harvested trees

GRAE is either the ratio of the mean volume of the harvested stems to the mean volume of the standing stems before thinning, or the ratio of their respective mean diameters.

Depending on the type of thinning, the value of GRAE will be:

GRAE = 1, mixed thinning

GRAE < 1, thinning from below

GRAE > 1, thinning from above

### 3.212- Thinning and final cutting

#### a) The PULSE function

The thinnings and final cutting are introduced into DYPEUFOR in the form of pulses produced at the desired moments. The intensity of the pulse corresponds to the number of stems removed.

The function used for this purpose is called PULSE, and has three arguments:

PULSE(HAUT, PREM, INT)

HAUT = magnitude of the pulse (HAUT = "hauteur" = "height")

PREM = date of the first pulse (PREM = "première" = first)

INT = interval between two successive pulses

The pulse is produced during the time interval DT. The first pulse takes place at time PREM and subsequent pulses at times PREM+INT, PREM+2×INT, PREM+3×INT and so on.

b) Illustration

Appendix 3 gives a version of DYPEUFOR which simulates two thinnings, the first from below at 50 years with an intensity of 500 stems per acre, and the second from above at 65 years with an intensity of 300 stems per acre.

Figure 26 and table 7 show the results of this simulation.

Various types of thinnings were simulated, the results being assembled in table 8.

In general, the volume which can be harvested is low. Bearing in mind that stand mortality is not accurately known, a close study of the results shows that:

- mixed thinnings are preferable to two successive thinnings of different types;

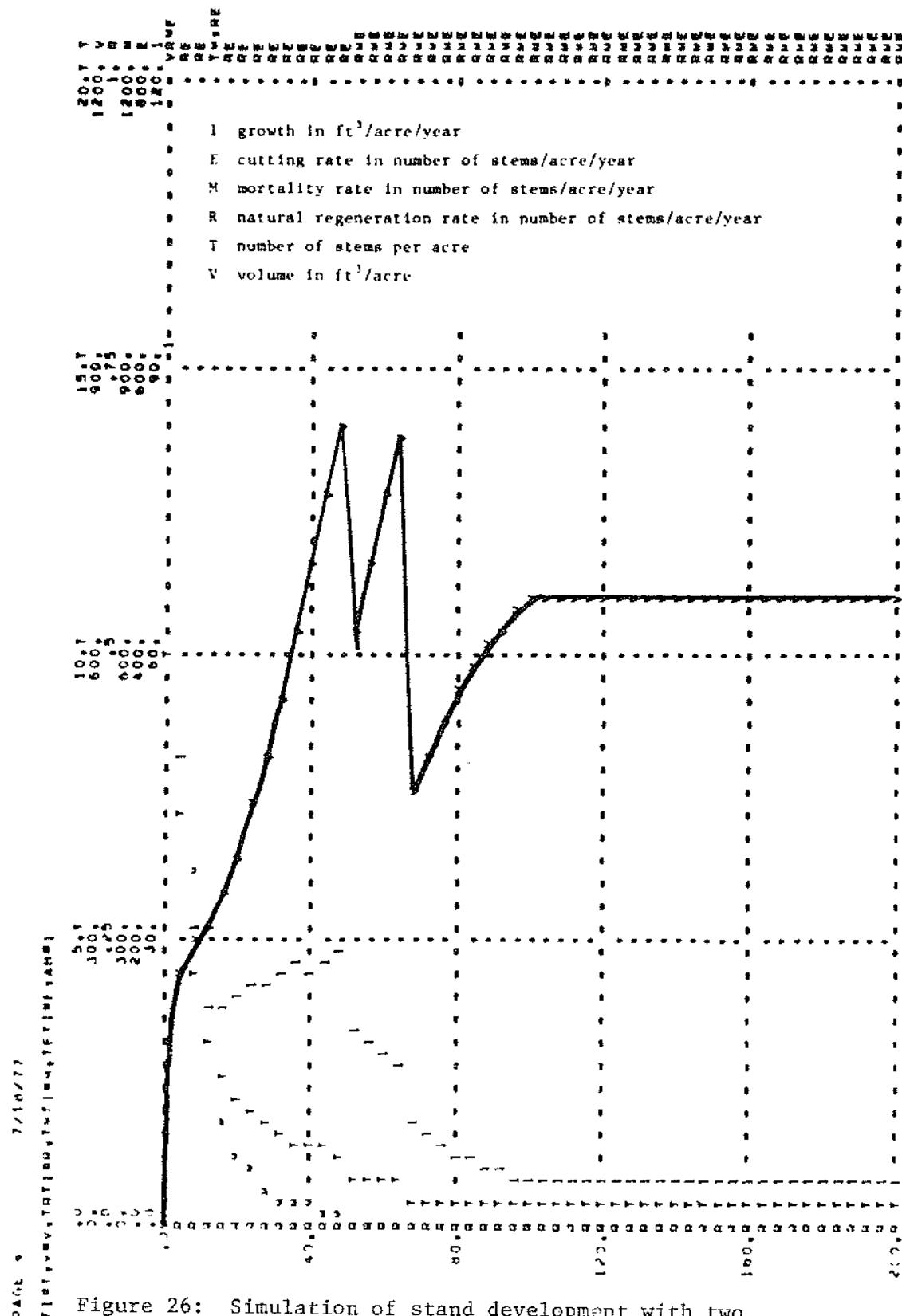


Figure 26: Simulation of stand development with two thinnings



Description of treatment	Volume removed per acre ft <sup>3</sup> /acre	Volume removed per tree ft <sup>3</sup>	Age at which maximum volume is reached after thinnings	Maximum volume after thinnings ft <sup>3</sup> /acre (a)	Volume per tree relative to (a) ft <sup>3</sup>	Volume at 200 years ft <sup>3</sup> /acre	Volume per tree ft <sup>3</sup>	Total volume removed by thinnings ft <sup>3</sup> /acre
Mixed thinnings GRAE = 1								
50 years, 500 stems	354	0.71	98	854	1.72	642	1.71	686
65 years, 300 stems	332	1.11						
Thinning from below 300 stems GRAE = 0.8								
50 years, 500 stems	354	0.71	105	659	1.70	658	1.70	711
Thinning from above GRAE = 1.2								
65 years, 300 stems	357	1.19						
Mixed thinnings GRAE = 1								
50 years, 200 stems	141	0.71	101	1191	1.67	1188	1.67	356
65 years, 200 stems	215	1.08						
Mixed thinnings GRAE = 1								
50 years, 200 stems	141	0.71	119	1280	1.66	1280	1.66	299
95 years, 100 stems	158	1.58						
No treatment	-	-	100	1575	1.61	1567	1.61	

Table 8. Simulation of various thinning programs

- disturbances in the form of thinnings in stands of site class III do not lead to increased yields;
- the advantage which can be foreseen from thinnings consists in being able to harvest wood earlier, if the thinnings are economically justifiable.

### 3.22- Treatments which produce or promote growth

These typical silvicultural treatments basically involve planting new trees or promoting growth by fertilizing.

#### 3.221- Planting

If a number of seedlings are to be planted according to a fixed timetable, the effects of this treatment can be predicted with the help of the model. All that is needed is to prepare a table of the number of seedlings to be planted per year.

##### a) The TABHL function

Figure 27 shows a graph with a horizontal asymptote.

By dividing the X axis into equal segments and finding the corresponding values for Y, we obtain table 9.

Notice that:

- the left column is an arithmetic progression, and can therefore be represented by the first and last terms and the size of the increment;

X	Y
0	0
1	70
2	210
3	410
4	510
5	550
6	500
7	350
8	200
9	120
10	100
11	100
12	100
13	100
14	100

Table 9: X and Y co-ordinates of various points on the curve shown in figure 27.

- the values in the right column are equal to 100 after  $X = 10$ ; this column can therefore be cut off at  $X = 10$  and a value of  $Y = 100$  assigned for all  $X$  greater than 10.

This is accomplished in the TABHL function, which has the following five arguments:

TABHL(TAB, X, XINFER, XSUPER, RAI)

TAB = name of the table

X = independent variable

XINFER = lower limit of X

XSUPER = upper limit of X

RAI = size of the increment of the progression (RAI = "raison")

For example, if Y is an auxiliary, we can write

A Y.K = TABHL(YT, X.K, 0, 10, 1)

T YT = 0/70/210/410/510/550/350/200/120/100

TABHL is a linear interpolation function which yields the values between the points in the table, if DT is less than the size of the increment.

#### b) Illustration

Consider the planting timetable shown in figure 28 which serves as a basis for the next simulation.

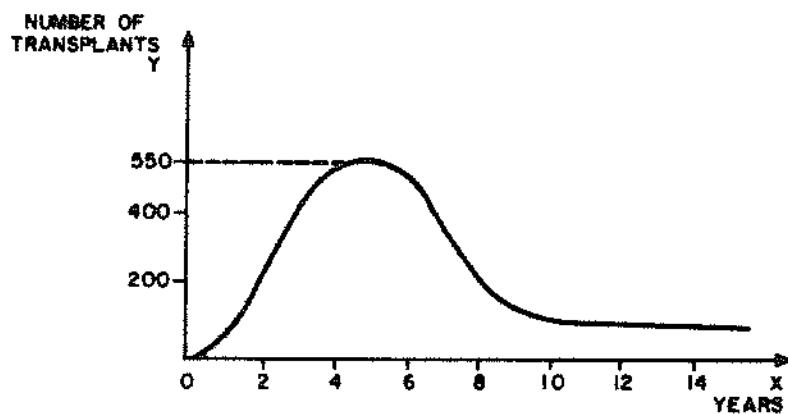


Figure 27: Graph of values which could be interpolated in the TABHL table

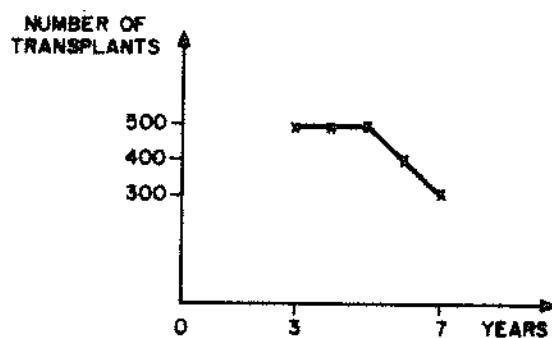


Figure 28: A planting timetable

Appendix 4 gives a version of DYPEUFOR which simulates the effect of this planting program.

The results of the simulation shown in figure 29 and table 10, show that the planting program is completely useless. It is made superfluous by the existence of a good natural regeneration in the first year. Nevertheless, it would be of great value and interest to determine an optimal planting program for a site on which seedlings are not easily established naturally. The DYPEUFOR user could then determine the starting date for his planting schedule, its length and the number of seedlings needed each year during the program.

### 3.222- Fertilizing

The equation for calculating percent growth could be made to take fertilizing into account by modifying the value of the growth factor FA according to curve patterns such as those shown in figure 30.

#### a) The RAMP and STEP functions

The TABHL function described above could easily be used for simulating various fertilization curve patterns. But another way of simulating them which is both elegant and convenient (because it eliminates the need for introduction interpolation points in the tables) consists in combining the RAMP and STEP functions. These functions each have two arguments, and behave as follows:

$$\text{RAMP} = 0 \quad , \text{ for } \text{TIME} \leq \text{DEB}$$

$$\text{RAMP} = \sum_{\text{DEB}}^{\text{TIME}} \text{PEN} \times \text{DT}, \text{ for } \text{TIME} > \text{DEB}$$

PAGE 4 7/18/77  
TIME-VOLUME-STEMS/ACRE-TABLE

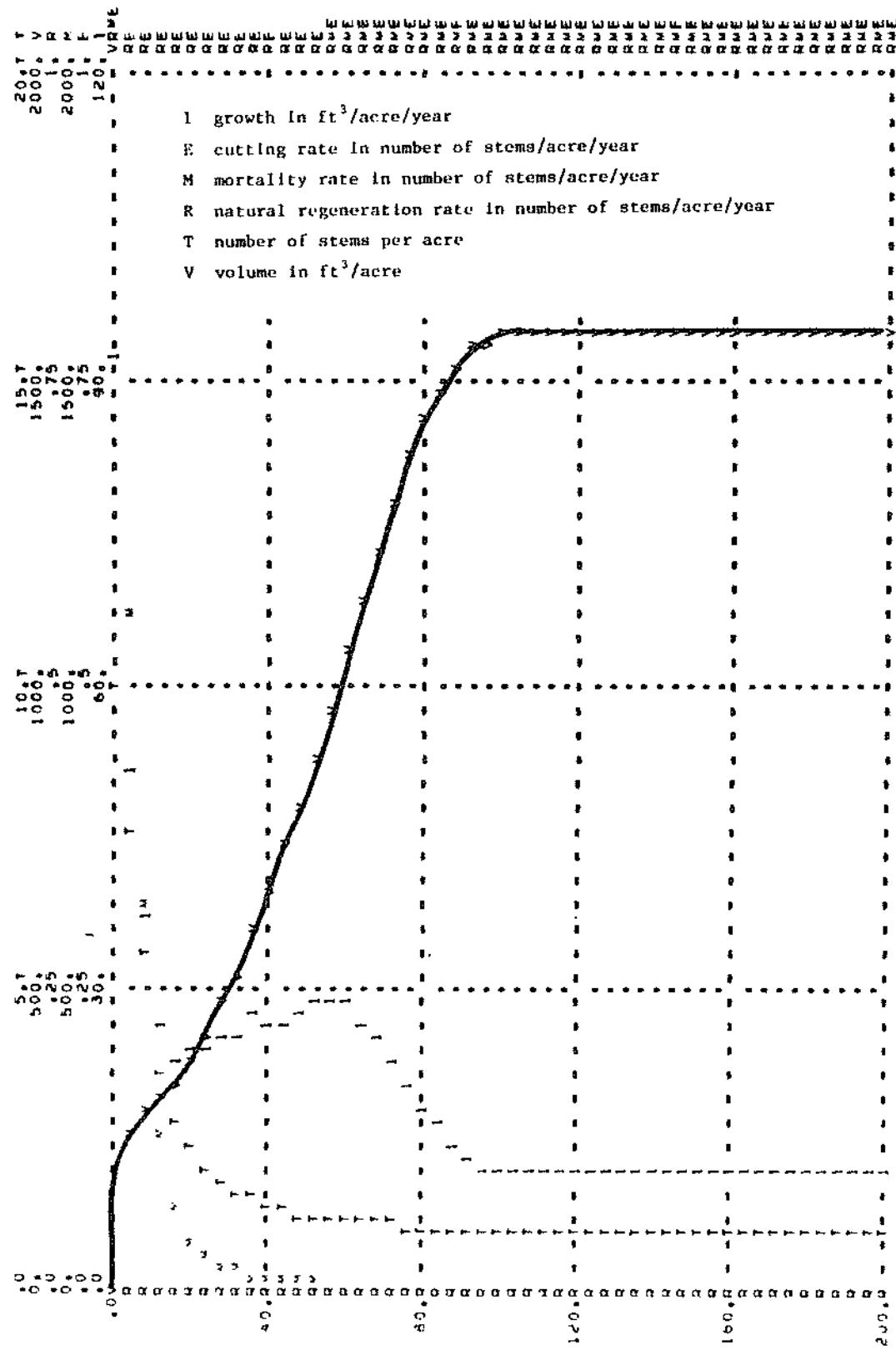


Figure 29: Simulation of stand development with a planting program



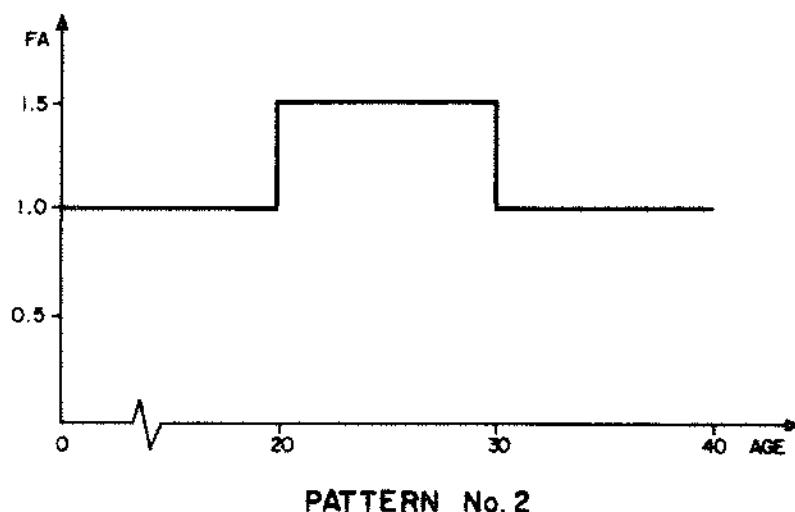
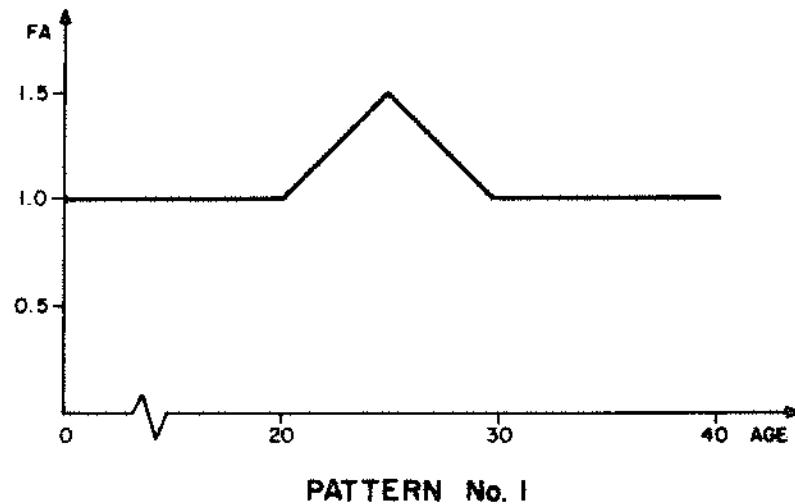


Figure 30: Curve patterns illustrating the effect of fertilizing on growth between 20 and 30 years

where

```

PEN = slope ("pente")
DEB = start ("début")

STEP(HAUT,DEB)

STEP = 0      , for TIME < DEB
STEP = HAUT   , for TIME ≥ DEB

```

where

```

HAUT = height ("hauteur")
DEB = start

TIME being the iteration counter (intrinsic variable of DYNAMO).

```

#### b. Illustration

Patterns 1 and 2, for a fertilization which has an effect between 20 and 30 years, were obtained with the help of the following combinations of functions:

Pattern N° 1

A FA.K = STEP(1,1) + RAMP(.1,FER)-RAMP(.2,FER + 5) + RAMP(.1,FER + 10)

C FER = 20

Pattern N<sup>o</sup> 2

A FA.K = STEP(1,1)+STEP(.5,FER)-STEP(.5,FER+10)

C FER = 20

As an illustration, appendix 5 gives the version of DYPEUFOR which simulates pattern N<sup>o</sup> 1. The results appear in figure 31 and table 11.

The results of simulations of various treatments are shown in table 12.

It seems that fertilizing would be of doubtful value in a class III stand. In fact, such a treatment occurring between years 20 to 30 of stands life and having curve pattern 1 would produce only a year earlier a maximum volume of 1588.9 ft<sup>3</sup>/acre; that is, an improvement of 4.1 ft<sup>3</sup>/acre in comparison with a non treatment policy. Further analysis of table 12 shows that pattern 2 seems to be better than pattern 1 and that in the case of a treatment consisting of fertilizing alone, the later the application, the greater the volume. However, other simulations (the results of which are not shown in the table) indicate that the maximum volume ceases to increase when fertilizer is applied later than 35 years.

A policy of combined fertilizing and thinning is disadvantageous in comparison with a no-treatment policy, because it increases the age at which the maximum volume is produced without producing an appreciable increase in volume in all cases.

Appendix 6 gives a version of DYPEUFOR which simulates stand development with pattern 2 fertilization applied at 10 years, combined with mixed thinnings of 200 stems at 50 and 65 years. Figure 32 and table 13 give the results.

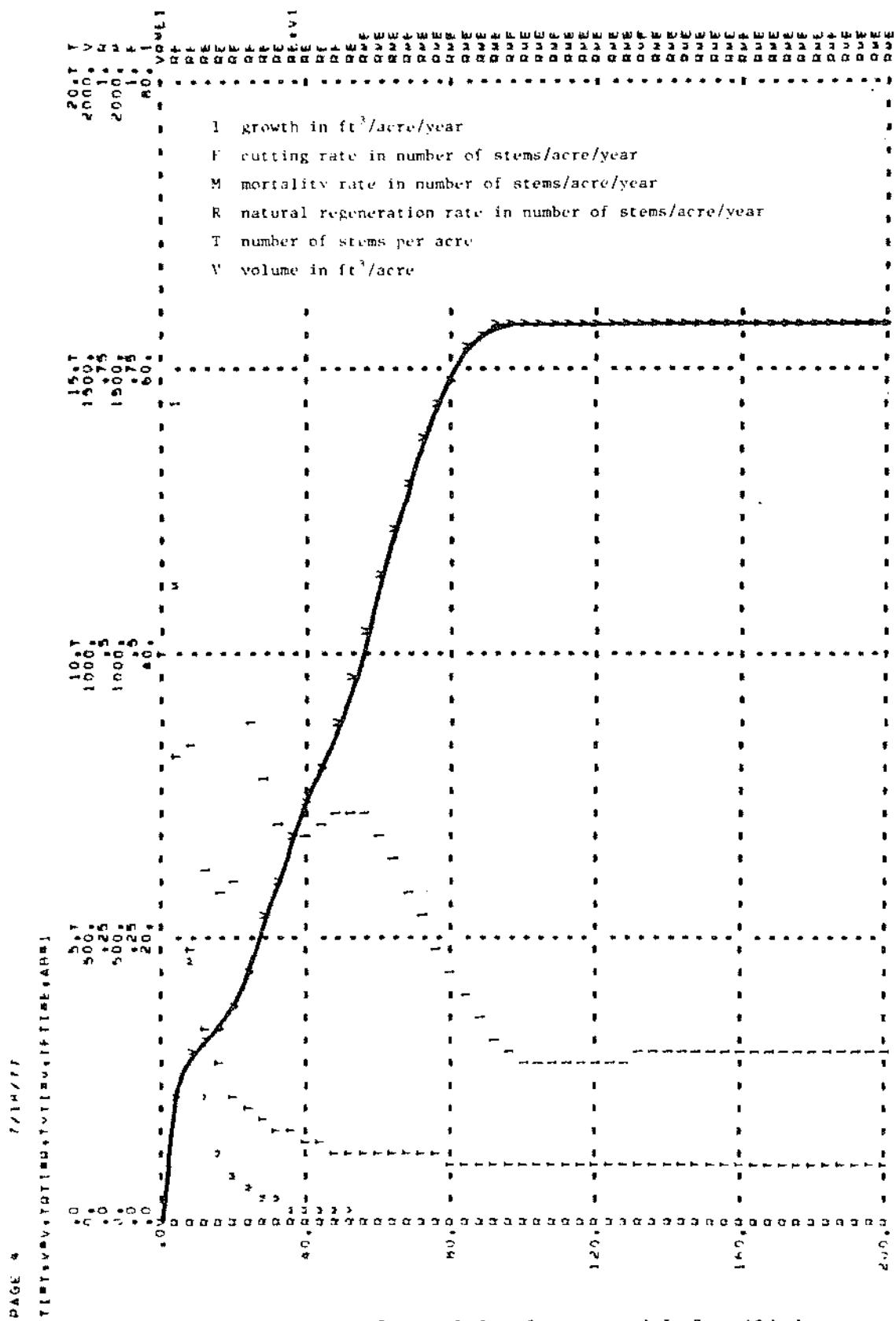


Figure 31: Simulation of stand development with fertilizing



Description of treatment and pattern number		Age at which the maximum volume is reached	Maximum volume (ft <sup>3</sup> ) per acre	Volume at 200 years (ft <sup>3</sup> ) per tree	Volume at 200 years (ft <sup>3</sup> ) per acre	Total volume removed by thinnings (ft <sup>3</sup> )
11-19	#1	99	1584.7	1.61	1568.2	1.61
11-19	#2	97	1591.1	1.61	1556.9	1.61
21-29	#1	99	1588.9	1.61	1572.5	1.60
21-29	#2	97	1593.8	1.61	1559.6	1.61
26-34	#1	99	1589.5	1.61	1572.5	1.60
26-34	#2	97	1594.3	1.61	1558.9	1.61
11-19	#1	121	1206.3	1.67	1206.3	1.67
Thinnings 50 years 200 stems-146 ft <sup>3</sup> 65 years 200 stems-213 ft <sup>3</sup>						359
11-19	#2	118	1207	1.67	1207	1.67
Thinnings 50 years 200 stems-156 ft <sup>3</sup> 65 years 200 stems-221 ft <sup>3</sup>						377
21-29	#1	122	1217	1.67	1217	1.67
Thinnings 50 years 200 stems-147 ft <sup>3</sup> 65 years 200 stems-214 ft <sup>3</sup>						361
21-29	#2	121	1226	1.67	1226	1.67
Thinnings 50 years 200 stems-156 ft <sup>3</sup> 65 years 200 stems-222 ft <sup>3</sup>						378

Table 12: Simulation of various fertilizing programs

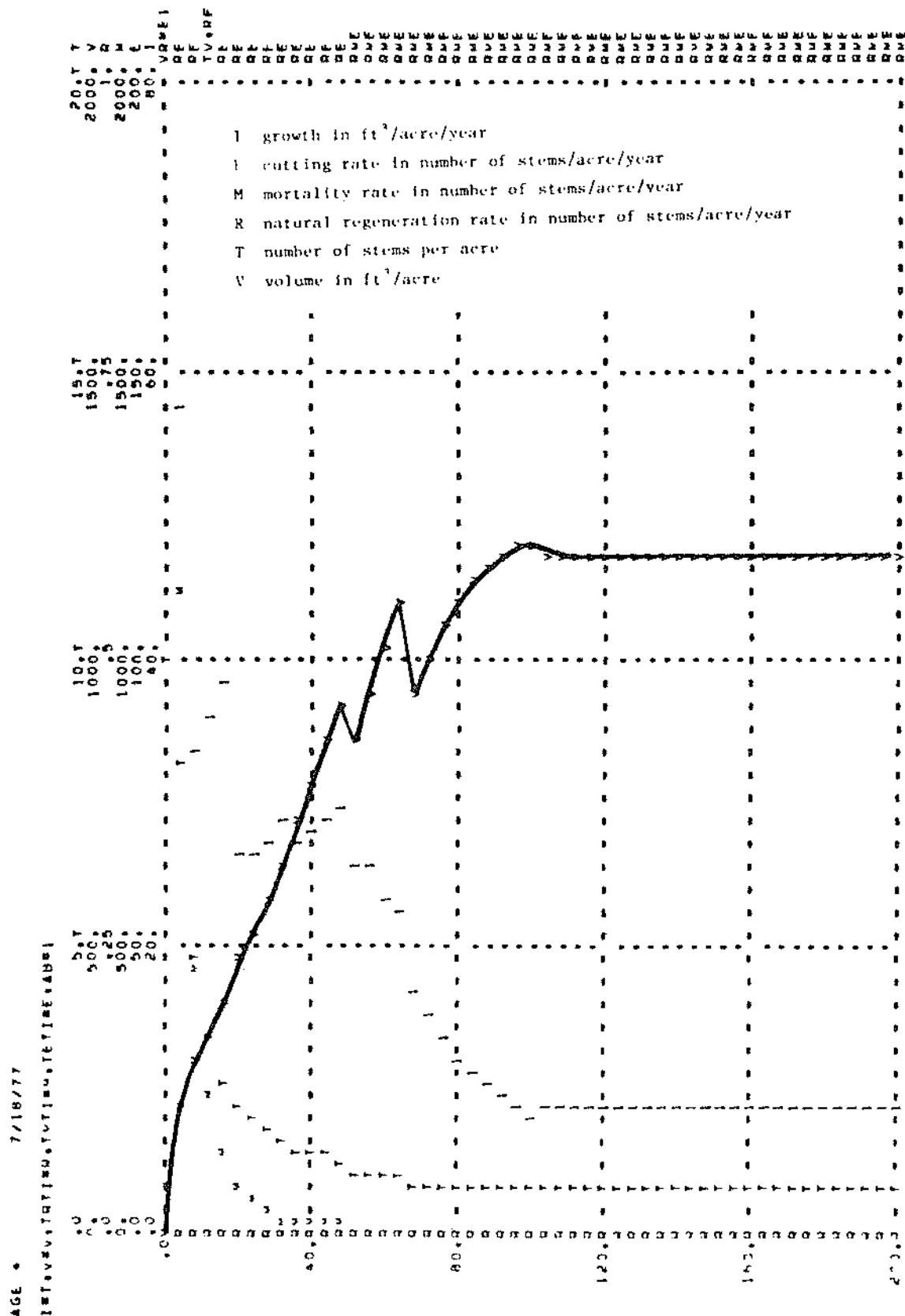


Figure 32: Simulation of stand development with a combined fertilizing and thinning program

PAGE 3	7/16/77	V1	V4	TWT1	MAR	FA
		E+00	E+00	E+00	E+00	E+00
5*	10*	0.016	0.016	0.0374	0.000	0.000
10*	17*978	301.2	338.6	1.371	4.677	4.677
20*	22*870	487.7	542.1	2.197	3.551	3.551
30*	30*661	613.1	542.1	2.889	2.650	2.650
35*	35*516	699.6	516.1	1.371	1.481	1.481
40*	40*600	780.9	635.5	1.371	1.635	1.635
45*	45*311	869.8	663.5	1.371	1.481	1.481
50*	50*246	969.8	778.3	1.371	1.635	1.635
55*	55*001	917.9	902.4	1.371	1.371	1.371
60*	60*986	1025.8	1.397	1.397	1.397	1.397
65*	65*704	1124.7	1.674	1.674	1.674	1.674
70*	70*778	1197.4	1.778	1.778	1.778	1.778
75*	75*72	1041.8	1.098	1.098	1.098	1.098
80*	80*757	1142.7	1.142	1.142	1.142	1.142
85*	85*746	1176.6	1.176	1.176	1.176	1.176
90*	90*703	1204.8	1.187	1.187	1.187	1.187
95*	95*739	1171.1	1.171	1.171	1.171	1.171
100*	100*711	1187.0	1.187	1.187	1.187	1.187
105*	105*711	1187.0	1.187	1.187	1.187	1.187
110*	110*711	1187.0	1.187	1.187	1.187	1.187
115*	115*711	1187.0	1.187	1.187	1.187	1.187
120*	120*711	1187.0	1.187	1.187	1.187	1.187
125*	125*711	1187.0	1.187	1.187	1.187	1.187
130*	130*711	1187.0	1.187	1.187	1.187	1.187
135*	135*711	1187.0	1.187	1.187	1.187	1.187
140*	140*711	1187.0	1.187	1.187	1.187	1.187
145*	145*711	1187.0	1.187	1.187	1.187	1.187
150*	150*711	1187.0	1.187	1.187	1.187	1.187
155*	155*711	1187.0	1.187	1.187	1.187	1.187
160*	160*711	1187.0	1.187	1.187	1.187	1.187
165*	165*711	1187.0	1.187	1.187	1.187	1.187
170*	170*711	1187.0	1.187	1.187	1.187	1.187
180*	180*711	1187.0	1.187	1.187	1.187	1.187
185*	185*711	1187.0	1.187	1.187	1.187	1.187
190*	190*711	1187.0	1.187	1.187	1.187	1.187
195*	195*711	1187.0	1.187	1.187	1.187	1.187
200*	200*711	1187.0	1.187	1.187	1.187	1.187

Table 13: Simulation of stand development with a combined fertilizing and thinning program

### 3.23- Windfall: a natural stochastic phenomenon

As an example of a natural stochastic event, the effect of windfall on the behaviour of the stand was tested.

Probabilities were assigned to various relative wind speeds. To these wind speeds correspond degrees of damage expressed as the proportion of trees overturned (table 14).

For this test two DYNAMO functions were used:

NOISE

CLIP

#### 3.231- The NOISE and CLIP functions

- a) The NOISE function generates random numbers, uniformly distributed between - 0.5 and 0.5.

In order to obtain random numbers NO between 0 and 1 we use

DYNAMO

A NO.K = 0.5+NOISE( )

- b) The CLIP function is the equivalent of a conditional branch. It has four arguments, and behaves as follows:

CLIP(P, Q, R, S)

CLIP = P , for R ≥ S

CLIP = Q , for R < S

Cumulative probability	Windfall damage expressed as the proportion of trees overturned
* 0-0.90	0
0.90-0.94	0.001
0.94-0.97	0.005
0.97-0.99	0.01
0.99-1	0.10

Table 14: Cumulative probabilities of various degrees of windfall damage

\* Lower limit included

To determine the proportion of windfallen trees (CHA) corresponding to a given probability, the following combination is used:

#### DYNAMO

```
A CHA.K = CLIP(CLIP(CLIP(CLIP(.1,.01,NO.K,.99).005,  
NO.K,.97),.001,NO.K,.94),0,NO.K,.90)
```

#### 3.232- Illustration

Appendix 7 gives the version of DYPEUFOR which simulates the effect of windfall.

The results of the simulation are given in table 15 and figure 33.

As might be expected, the effect of windfall is neither greater nor less than that of thinning.

The principal aim of this test was to show that stochastic phenomena can be incorporated into DYPEUFOR if it is desired to quantify the effect such phenomena could have on silvicultural policies being studied.

#### 3.24- Analysis of parameter sensitivity

Two parameters were tested:

- the reference germination rate (CTG)
- the initial number of stems (ITI)

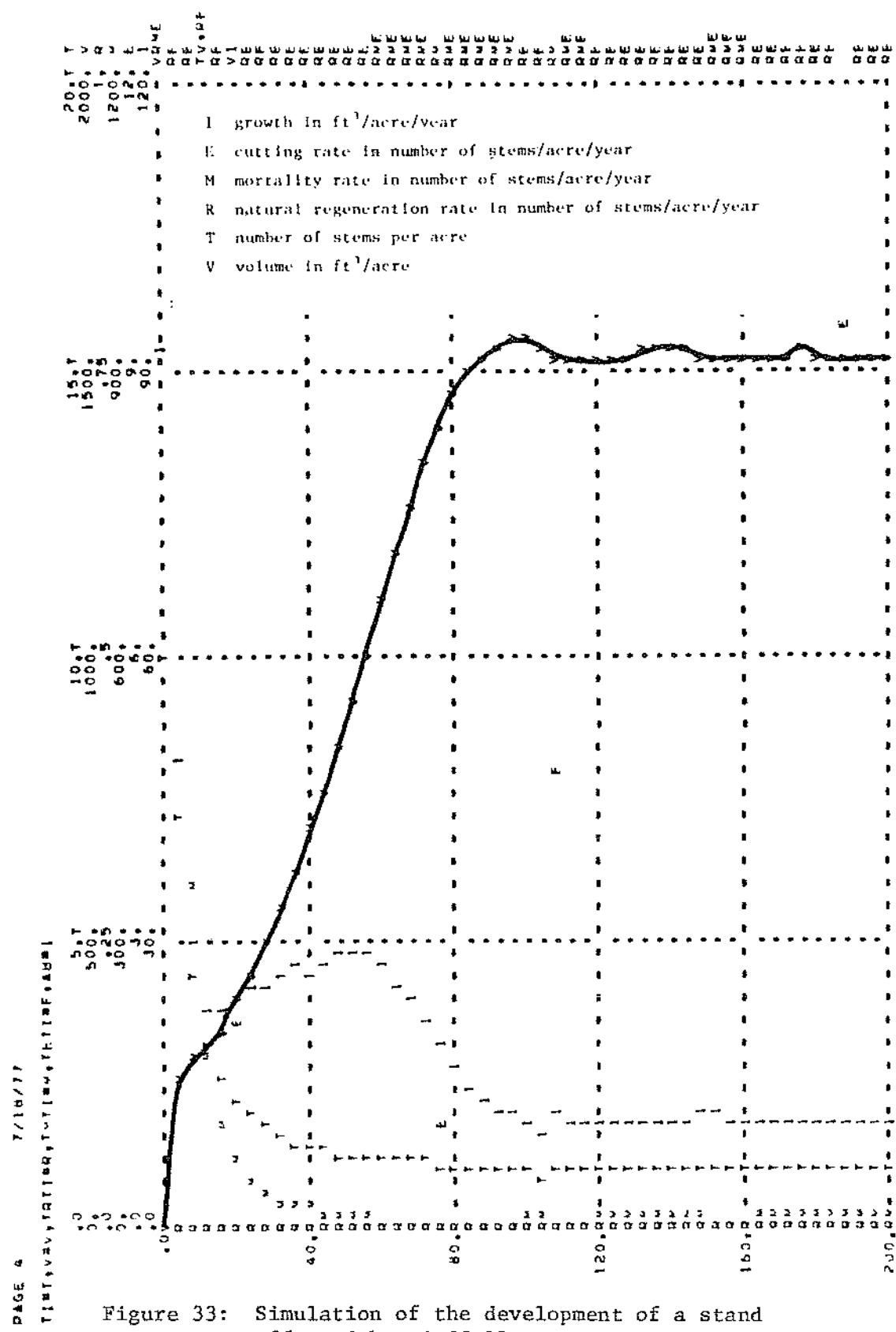


Figure 33: Simulation of the development of a stand affected by windfall



### 3.241~ Reference germination rate

We should here recall our assumption that the stand being studied originated after a fire, from seed buried in the soil before the fire.

However, the results of the simulation of natural stand development (undisturbed) have shown us that once established, a stand reproduces solely by layering. Sexual reproduction does not take place, then, unless a fairly intensive crown thinning is undertaken at a time when the stand is ready to produce viable seed.

The reference germination rate (CTG) was tested by a thinning of 1200 stems at 50 years. The results of the tests are shown in table 16.

This table shows that the reference germination rate is a very sensitive parameter, which means that accurate information on this parameter is absolutely essential for studying a black spruce stand.

### 3.242~ Initial number of stems

The initial number of stems represents the number of seedlings established after a fire. Varying it between 8,000 and 12,000 (seedlings per acre), we find from the results of the simulations that this is not a very sensitive parameter.

CTG	Volume		Age at which the maximum volume is reached	Volume	
	Maximum volume after thinning ft <sup>3</sup> /acre	per tree ft <sup>3</sup>		at 200 years ft <sup>3</sup> /acre	per tree ft <sup>3</sup>
0.0001	289.2	2.5	200	289.2	2.5
0.001	498.9	1.9	200	498.9	1.9
0.01	1611.6	1.5	182	1611.6	1.5

Table 16: Sensitivity analysis of the reference germination rate.

ITI	Volume		Age at which the maximum volume is reached	Volume	
	maximum pi <sup>3</sup> /acre	per tree pi <sup>3</sup>		at 200 years pi <sup>3</sup> /acre	per tree pi <sup>3</sup>
8,000	1574	1.62	100	1564	1.61
10,000	1575	1.61	100	1567	1.61
12,000	1574	1.61	100	1568	1.61

Table 17: Sensitivity analysis of the initial number of stems.



#### 4. CONCLUSIONS

The increasing remoteness of timber sources has brought about a renewed interest in intensive silvicultural management of coniferous species. Forest resources cannot be managed blindly, however, without risking considerable losses. *DYPEUFOR*, in its present form, is intended as a decision-making tool which will enable the forest manager to foresee at a glance the results of a given management program.

It must be remembered, however, that this model was adapted to existing conditions in Quebec using the information available. We have pointed out the complete lack of knowledge and data regarding the standing volume lost each year from natural causes. This factor, hitherto ignored in formulating management policies, is of decisive importance in determining the balance of regeneration, growth and mortality in an area of a forest at a given moment.

The importance of filling this gap, which is brought into sharp focus by the *DYPEUFOR* total systems approach, cannot be overemphasized, nor can the tremendous volume of research which remains to be done in order to throw some light on this factor.

Nevertheless, we were able to get around this problem, and tested a number of possibilities in order to explore the model's potential. For the time being, of course, the results are dependent on values which had in part to be invented, and which are only partially reflective of reality. It nevertheless remains true that *DYPEUFOR* is a valuable tool which will provide highly useful information for sound forest management as soon as complete, accurate information can be supplied. Among the potential practical applications which appear to us to be the most promising are the determination, by iteration, of optimum combinations of

duration, intensity and type of silvicultural treatments. We have already obtained a number of preliminary conclusions regarding fertilizing and thinning, among others, during the course of this study.

In addition, the interplay of the various biological variables, clearly brought out by the system analysis used in the model, make it an excellent pedagogical tool. Among other possibilities, it enables the student to get an overall grasp of the effects on a forest system of any disturbance to the stand dynamics, whether a natural stochastic phenomenon or an artificial intervention.

In short, this model, designed to permit a large degree of flexibility, has enabled us to gain a better understanding of the current state of forestry knowledge.

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## APPENDIX 1

## Glossary of variables used in DYPEUFOR

A	growth ("accroissement") in ft <sup>3</sup> /tree/year
AB	growth in ft <sup>3</sup> /acre/year
CF	number of stems removed in the final cut ("coupe finale") per acre per year
CHA	percentage of trees overturned by windfall ("chablis") an indirect representation of wind speed
CTG	coefficient of germination rate ("coefficient du taux de germination")
CVM	coefficient of maximum volume ("coefficient du volume maximum")
D50	doubling time at 50% of the maximum volume
D50T	table of interpolation points of D50
DV50	half-life ("demi-vie") at 50% of the maximum volume
DV50T	table of interpolation points of DV50
E1	number of stems removed at the 1st thinning ("éclaircie") per acre per year

E1A	year ("année") in which the 1st thinning is done
E1TI	number of stems ("tiges") removed at 1st thinning per acre
E2	number of stems removed at 2nd thinning per acre per year
E2A	year ("année") in which 2nd thinning is done
E2TI	number of stems removed at 2nd thinning
E3	number of stems removed at 3rd thinning per acre per year
E3A	year in which 3rd thinning is done
E3TI	number of stems removed at the 3rd thinning per acre
ETI	number of stems removed by thinning per acre per year
FA	growth factor ("facteur d'accroissement")
FER	time at which fertilizing starts to have an effect
GRAE	relative size of trees harvested (grandeur relative des arbres exploités)
GRAM	relative size of dead trees (grandeur relative des arbres morts)
GRAMT	table of interpolation points of GRAM
INT	interval of time separating two cuttings

ITI	initial number of stems per acre ("nombre initial de tiges")
KA	correction factor for percent growth ("accroissement") at 50% of maximum volume
KAT	table of interpolation points of KA
KCA	factor by which dbh is multiplied to obtain the crown diameter
KCAT	table of interpolation points of KCA
KM	correction factor for percent mortality at 50% of maximum volume
KMT	table of interpolation points of KM
MAR	layers ("marcottes") produced per acre per year
NMS	maximum number of seeds ("nombre maximum de semences") produced per acre per year
NO	random number distributed uniformly between 0 and 1, generated by the DYNAMO language
NSEM	number of seeds ("nombre de semences") produced per acre per year
NSEMT	table of interpolation points of NSEM
PA	percent growth ("pourcentage d'accroissement")

PA50	percent growth at 50% of maximum volume
PM	percent mortality
PM50	percent mortality at 50% of maximum volume
PSEM	percentage of seeds ("pourcentage de semences") produced per acre per year
REV	rotation ("révolution") length
TE	cutting rate ("taux d'exploitation") in ft <sup>3</sup> /acre/year
TETI	cutting rate in number of stems ("tiges") per acre per year
TG	germination rate ("taux de germination")
TGT	table of interpolation points of TG
TI	number of stems ("tiges") per acre
TM	mortality rate ("taux de mortalité") in volume, ft <sup>3</sup> /acre/year
TMTI	mortality rate in number of stems/acre/year
TPTI	planting rate ("taux de plantation") in number of stems/acre/year
TPTIT	table of interpolation points of TPTI

TRTI	natural regeneration rate ("taux de régénération") in number of stems per acre per year
V	volume in ft <sup>3</sup> /acre
VA	mean volume per tree ("arbre")
VM	maximum volume in ft <sup>3</sup> /acre
VSEM	volume of seedlings ("semis")



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```

L V,K=V,J+DT*(AB,JK=TE,JK=TM,JK)
N V=VI
C VI=10E-4
R AB,KL=TI,K*A,K+VP*TPTI,JK+VSEM*TRTI,JK+(0.016*MAR,JK)
C VDS=1E-5
C VSEM=1E-7
R MAR,KL=STEP((TETI,JK+TMTI,JK),100)
A A,K*PA,K*VA,K
A PA,K*PA50,K*KA,K*FA
C FA=1
A PA50,K=LOGN(2)/D50,K
A D50,K=TABHL(D50T,VA,K,0,1,7,,1)
T D50T=0/9/11/13/14/17/18/19/21/23/27/31/37/45/56/70/84/98
A VA,K=V,K/TI,K
A KA,K=TABHL(KAT,V,K/VM,K,0,1,7,,2)
T KAT=1,2/1,12/1,04,.96/.88/.8
A VM,K=54260*EXP(.305*LOGN(VA,K))/EXP(2*LOGN(KCA,K))
A KCA,K=TABHL(KCAT,VA,K,0,1,7,,1)
T KCAT=24,3/23,6/23/22,4/21,8/21,3/20,8/20,3/19,9/19,5/
X 19,1/18,8/18,4/18,1/17,8/17,8/17,5/17,3
R TE,KL=CF,K*VA,K+ETI,K*VA,K*GRAE
C GRAE=1
R TM,KL=TMTI,JK*VA,K*GRAM,K
A GRAM,K=TABHL(GRAMT,VA,K,0,1,7,,1)
T GRAMT=.8/.82/.84/.86/.88/.9/.92/.94/.96/.98/1/1,02/
X 1,04/1,06/1,08/1,1/1,12/1,14
L TI,K=TI,J+DT*(TPTI,JK+TRTI,JK+MAR,JK=TETI,JK=TMTI,JK)
N TIBITI
C ITI=10000
R TRTI,KL=NSEM,K*TG,K
A NSEM,K=NMS*DSEM,K
C NMS=1E6
A PSEM,K=TABHL(PSEMT,VA,K,0,1,8,,2)
T PSEMT=0/0/0/.34/.66/1/1/1/1/0
A TG,K=CTG*TABHL(TGT,V,K/VM,K,0,.25,.0125)
T TGT=1/.6/.3/.1/.05/.01/.005/.001/.0005/.0001/.00005/1E-5/
X 5E-6/1E-6/5E-7/1E-7/5E-8/1E-8/5E-9/1E-9/0
C CTG=.01
R TMTI,KL=TI,K*PM,K
A PM,K=PM50,K*KM,K
A PM50,K=LOGN(2)/DV50,K
A DV50,K=TABHL(DV50T,VA,K,0,1,7,,1)
T DV50T=5/14/26/40/60/70/85/10/144/235/280/320/344/350/344/
X 240/180/53
A KM,K=TABHL(KMT,V,K/VM,K,0,1,7,,2)
T KMT=0/.4/.65/.9/1,8/7,8
R TPTI,KL=TABHL(TPTIT,TIME,K,0,10,2)
T TPTIT=0/0/0/0/0/0
R TETI,KL=CF,K+ETI,K
A CF,K=PULSE(TI,K/DT,REV,INT)
C REV=9999
C INT=999
A ETI,K=E1,K+E2,K+E3,K+E4,K
A E1,K=PULSE(E1TI/DT,E1A,INT)
C E1TI=0
C E1A=50
A E2,K=PULSE(E2TI/DT,E2A,INT)
C E2TI=0
C E2A=65
A E3,K=PULSE(E3TI/DT,E3A,INT)
C E3TI=0
C E3A=80
A E4,K=PULSE(E4TI/DT,E4A,INT)
C E4TI=0
C E4A=95
PRINT TI/V/VA/TMTI/TETI/AB/MAR/TRTI/TE
PLOT TI=TI/V=V/TRTI=TRTI/AB=TETI/E/AB=1
SPEC DT=1/LENGTH=200/PRTPER=1/PLTPER=4
RUN

```

Appendix 2: Version of DYPEUFOR used to simulate stand development without external action.



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```

L V=K*V+J+DT*(AB,JK=TE,JK=TM,JK)
N VEV1
C V1=10E-4
R AB,K=TI,K*A,K+VP*TPTI,JK+VSEM*TRTI,JK+(0,016*MAR,JK)
C VD=1E-5
C VSEM=1E-7
R MAR,KL=STEP((TETI,JK+TMTI,JK)+100)
A A,K*PA,K*VA,K
A PA,K*PA50,K*KA,K*FA
C FA=1
A PA50,K=LOGN(2)/D50,K
A D50,K=TABHL(D50T,VA,K,0,1,7,,1)
T D50T=0/9/11/13/14/17/18/19/21/23/27/31/37/45/56/70/84/98
A VA,K=V,K/TK,K
A KA,K=TABHL(KAT,V,K/VM,K,0,1,7,,2)
T KATE=1,2/1,12/1,04/.96/.88/.8
A VM,K=542608*EXP(-.305*LOGN(VA,K))/EXP(2*LOGN(KCA,K))
A KCA,K=TABHL(KCAT,VA,K,0,1,7,,1)
T KCAT=24,3/23,6/23/22,4/21,8/21,3/20,8/20,3/19,9/19,5/
X 19,1/18,8/18,4/18,1/17,8/17,8/17,5/17,3
R TE,KLBCF,K*VA,K+ETI,K*VA,K*GRAE,K
A GRAE,K=BCLIP(1,89,88,TIME*K*#IA+1)
R TM,KL=TMTI,JK*VA,K*GRAM,K
A GRAM,K=TA8HL(GRAMT,VA,K,0,1,7,,1)
T GRAMT=.8/.82/.84/.86/.88/.9/.92/.94/.96/.98/1/1,02/
X 1,04/1,06/1,08/1,1/1,12/1,14
L TI,K=TI,J+DT*(TPTI,JK+TRTI,JK+MAR,JK-TETI,JK-TMTI,JK)
N TISITI
C ITI=10000
R TRTI,KL=NSEM,K*TG,K
A NSEM,K=NMS#PSEM,K
C NMS=1E6
A PSEM,K=TABHL(PSEMT,VA,K,0,1,8,,2)
T PSEMT=0/0/0,.34/.66/1/1/1/1/0
A TG,K=CTG*TABHL(TGT,VA,K/VM,K,0,1,25,.0125)
T TGT=1,.6/.3/.1/.05/.01/.005/.001/.0005/.0001/.00005/1E-5/
X SE-6/1E-6/5E-7/1E-7/SE-8/1E-8/SE-9/1E-9/0
C CTG=.01
R TMTI,KLETI,K*DM,K
A PM,K=DM50,K*KH,K
A PM50,K=LOGN(2)/DV50,K
A DV50,K=TABHL(DVS0T,VA,K,0,1,7,,1)
T DV50T=5/14/26/40/60/70/85/110/144/235/280/320/344/350/344/
X 240/180/53
A KM,K=TABHL(KMT,VA,K/VM,K,0,1,7,,2)
T KMT=0/.4/.65/.9/1,8/7,8
R TPTI,KL=TABHL(TPTIT,TIME,K,0,10,2)
T TPTIT=0/0/0/0/0/0
R TETI,KL=CF,K+ETI,K
A CF,K=PULSE(TI,K/DT,REV,INT)
C REV=9999
C INT=999
A ETI,K=E1,K+E2,K+E3,K+E4,K
A E1,K=PULSE(E1TI/DT,E1A,INT)
C E1TI=800
C E1A=50
A E2,K=PULSE(E2TI/DT,E2A,INT)
C E2TI=300
C E2A=65
A E3,K=PULSE(E3TI/DT,E3A,INT)
C E3TI=0
C E3A=80
A E4,K=PULSE(E4TI/DT,E4A,INT)
C E4TI=0
C E4A=95
PRINT TI/V/VA/THTI/TETI/AB/MAR/TRTI/TF/GRAE
PLUT TI=T/V=V/TOTI=R/TMTIBM/TETI=E/AB=1
SPEC DT=1/LENGTH=200/PRTPER=5/PLTPER=4
RUN

```

Appendix 3: Version of DYPERFOR used to simulate stand development with a thinning from below of 500 stems at 50 years and a thinning from above of 300 stems at 65 years.



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```

L V@K#V+J+DT*(AB,JK=TE,JK=TM,JK)
N V@V1
C VI=10E-4
R AB,KL=T1,K#A,K+VP*TPT1,JK+VSEM#TRTI,JK+(0.016*MAR,JK)
C VP=1E-5
C VSEM=1E-7
R MAR,KL=STEP((TETI+JK+TMTI+JK),100)
A A*K#PA,K*VA,K
A PA,K#PA50,K#KA,K#FA
C FA=1
A PA50,K=LOGN(2)/DS0,K
A DS0,K#TABHL(DS0T,VA,K,0,1,7,1)
T DS0T=0/9/11/13/14/17/18/19/21/23/27/31/37/45/56/70/84/98
A VA,K#V,K/TI,K
A KA,K#TABHL(KAT,V,K/VM,K,0,1,7,1)
T KAT=1,2/1,12/1,04/,96/,88/,8
A VM,K#542608*EXP(.305*LOGN(VA,K))/EXP(.2*LOGN(KCA,K))
A KCA,K#TABHL(KCAT,VA,K,0,1,7,1)
T KCAT=24,3/23,6/23/22,4/21,8/21,3/20,8/20,3/19,9/19,5/
X 19,1/18,8/18,4/18,1/17,8/17,8/17,5/17,3
R TE,KL=BCF,K*VA,K+ETI,K*VA,K*GAE
C GAE=1
R TM,KL=TMTI,JK*VA,K*GRAM,K
A GRAM,K#TABHL(GRAHT,VA,K,0,1,7,1)
T GRAHT,8/,82/,84/,86/,88/,9/,92/,94/,96/,98/1/1,02/
X 1,04/1,06/1,08/1,1/1,12/1,14
L TI,K#TI,J+DT*(TPT1,JK+TRTI,JK+MAR,JK=TETI,JK=TMTI,JK)
N TI=T1
C ITI=10000
R TRTI,KL=ENSEM,K*TG,K
A NSEM,K#NMS*DSEM,K
C NMS=1E6
A PSEM,K#TABHL(PSEMT,VA,K,0,1,8,1)
T PSEMT=0/0/0/,34/,66/1/1/1/1/0
A TG,K#CTG#TABHL(TGT,V,K/VM,K,0,1,25,.0125)
T TGT=1,6/1,3/1,1/05/.01/.005/.001/.0005/.0001/.00005/1E-5/
X 5E-6/1E-6/5E-7/1E-7/5E-8/1E-8/5E-9/1E-9/0
C CTG=.01
R TMTI,KL=TI,K#PM,K
A PM,K#DM50,K#KM,K
A PH50,K=LOGN(2)/DV50,K
A DV50,K#TABHL(DV50T,VA,K,0,1,7,1)
T DV50T=5/14/26/40/60/70/85/110/144/235/280/320/344/350/344/
X 240/180/53
A KM,K#TABHL(KMT,V,K/VM,K,0,1,7,1)
T KMT=0/,4/,65/,9/1,8/7,8
R TPT1,KL=TABHL(TPT1,TIME,K,0,0,0,0)
T TPT1=0/0/0/0/000/500/500/500/500/0
R TETI,KL=BCF,K+ETI,K
A CF,K#PULSE(TI,K/DT,REV,INT)
C REV=9999
C INT=999
A ETI,K#E1,K+E2,K+E3,K+E4,K
A E1,K#PULSE(EITI/DT,EIA,INT)
C E1T=0
C E1A=50
A E2,K#PULSE(E2TI/DT,E2A,INT)
C E2T=0
C E2A=65
A E3,K#PULSE(E3TI/DT,E3A,INT)
C E3T=0
C E3A=80
A E4,K#PULSE(E4TI/DT,E4A,INT)
C E4T=0
C E4A=95
PRINT TI/V/VA/TMTI/TETI/AB/MAR/TRTI/TE/TPT1
PLOT TI*T/VA/V/TRTI*B/R/TMTI*B/M/TETI*B/AB*B
SPEC DT=1/LENGTH=200/PRTPER=5/PLTPER=4
RUN

```

Appendix 4: Version of DYPEUFOR used to simulate stand development  
 with a planting program of 500 stems at 3, 4, and 5 years,  
 400 stems at 6 years and 300 at 7 years.



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```

L V=K*BV+J+DT*(AB,JK=TE,JK=TM,JK)
N VBV
C V=10E-4
R AB,KL=T,KA,K+VP*TPTI,JK+VSEM*TRTI,JK+(0,016*MAR,JK)
C VDE=5
C VSEM=1E-7
R MAR,KL=STEP((TETI+JK+TMTI+JK)+100)
A A,KBDA,K*VA,K
A PA,K*PA50,K*KA,K*FA,K
A PA,KB20*EXP(1+1)*RAMP(0.1*PER)*RAMP(0.2,PER+5)
X RAMP(0.1,PER+10)
C PER=20
A PA50,KBLOGN(2)/D50,K
A D50,K*TABHL(D50T,VA,K,0,1,7,,1)
T D50T=0/9/11/13/14/17/18/19/21/23/27/31/37/45/56/70/84/98
A VA,K=V,A,K/TI,K
A KA,K*TABHL(KATI,V,K/VM,K,0+1,,2)
T KATB1,2/1,12/1,04/,96/,88/,8
A VM,K=542608*EXP(-305*LOGN(VA,K))/EXP(2*LOGN(KCA,K))
A KCA,K*TABHL(KCAT,VA,K,0,1,7,,1)
T KCAT=24/3/23,6/23/22,4/21,8/21,3/20,8/20,3/19,9/19,5/
X 19,1/18,8/18,4/18,1/17,8/17,8/17,5/17,3
R TE,KL=CF,K*VA,K+ETI,K*VA,K*GAE
C GAE=1
R TM,KL=TMTI,JK*VA,K*GRAM,K
A GRAM,K*TABHL(GRAM,V,A,K,0+1,7,,1)
T GRAMT=8/,82/,84/,86/,88/,9/,92/,94/,96/,98/1/1,02/
X 1,04/1,06/1,08/1,1/1,12/1,14
L TI,K=TI,J+DT*(TPTI,JK+TRTI,JK+MAR,JK=TETI,JK=TMTI,JK)
N TIBITI
C ITI=10000
R TRTI,KL=NSEM,K*TG,K
A NSEM,K=NMS*DSEM,K
C NMS=1E6
A PSEM,K*TABHL(PSEM,T,VA,K,0,1,8,,2)
T PSEM=0/0/0/0/,34/,66/1/1/1/1/0
A TG,K=CTG*TABHL(TGT,V,K/VM,K,0,1,25,,0125)
T TGT=1/,6/,5/,1/,05/,01/,005/,001/,0005/,0001/,00005/1E=5/
X SE=6/1E=6/5E=7/1E=7/5E=8/1E=8/5E=9/1E=9/0
C CTG=.01
R TMTI,KL=TI,K*PM,K
A PM,K=PM50,K*KM,K
A PM50,KBLOGN(2)/DV50,K
A DV50,K*TABHL(DV50T,VA,K,0,1,7,,1)
T DV50T=5/14/26/40/60/70/85/110/144/235/280/320/344/350/346/
X 240/180/53
A KM,K*TABHL(KMT,V,K/VM,K,0+1,,2)
T KMT=0/,4/,65/,9/1,8/7,8
R TPTI,KL=TABHL(TPTI,TIME,K,0,10,,2)
T TPTI=0/0/0/0/0/0
R TETI,KL=CF,K+ETI,K
A CF,K=PULSE(TI,K/DT,REV,INT)
C REV=9999
C INT=999
A ETI,K=E1,K+E2,K+E3,K+E4,K
A E1,K=PULSE(E1I/DT,E1A,INT)
C E1I=0
C E1A=50
A E2,K=PULSE(E2I/DT,E2A,INT)
C E2I=0
C E2A=65
A E3,K=PULSE(E3I/DT,E3A,INT)
C E3I=0
C E3A=80
A E4,K=PULSE(E4I/DT,E4A,INT)
C E4I=0
C E4A=95
PRINT TI/V/VA/TMTI/TETI/AB/MAR/TRTI/TE/FA
PLOT TI/TBV/TRTI/AB/TMTI/AB/TETI/AB
SPEC DT=1/LENGTH=200/PRTPER=5/PLTPER=4
RUN

```

Appendix 5: Version of DVREUFOR used to simulate stand development with a fertilizing program having an effect between 20 and 30 years.



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```

L V=K*V+J+DT*(AB,JK=TE,JK=TN,JK)
N VSVI
C V1=10E-4
R AB,KLBTI,K*AB,K+VP*TPTI,JK+VSEH*TRTI,JK+10,0168MAR,JK
C VPATE=5
C VSENHIE=7
R MAR,KL=STEP1(TETI,JK+TMTI,JK)+100
A A,K*PA,K*VA,K
A PA,K*PAS0,K*KA,K*FA,K
A P00008TBP(100)*STEP(00,PER)*STEP(00,PER+10)
C #00010
A PA50,KBLLOGN(2)/D50,K
A D50,KTABHL(D50T,VA,K,0+1,7,,1)
T D50T=0/9/11/13/14/17/18/19/21/23/27/31/37/45/56/70/84/98
A VA,K*EV,K/TI,K
A KA,KTABHL(KAT,V,K/VM,K=0+1,,2)
T KAT=1,2/1,12/1,64/,96/,88/,8
A VM,K=542608*EXP(-.305*LOGN(VA,K))/EXP(2*LOGN(KCA,K))
A KCA,KTABHL(KCAT,VA,K,0+1,7,,1)
T KCAT=24,3/23,6/23/22,6/21,8/21,3/20,8/20,3/19,9/19,5/
X 19,1/18,8/18,4/18,1/17,8/17,8/17,5/17,3
R TE,KL=CF,K*VA,K*ETI,K*VA,K*RAE
C GRAEG1
R TH,KL=TMTI,JK*VA,K*GRAM,K
A GRAM,KTABHL(GRAMT,VA,K,0+1,7,,1)
T GRAMT=8//82//84//86//88//9//92//94//96//98/1/1,02/
X 1.04/1.06/1.08/1.1/1.12/1.14
L TI,KRTI,J+DT*TPTI,JK+TRTI,JK+MAR,JK=TETI,JK=TMTI,JK
N TIBITI
C ITIB10000
R TRTI,KLBNSEM,K*TG,K
A NSEM,KBNMS*DSEM,K
C NH5=1E6
A PSEM,KTABHL(PSEMT,VA,K,0+1,8,,2)
T PSEM=0/0/0/.34/.66/1/1/1/1/0
A TG,KBCTG*TABHL(TGT,V,K/VM,K,0+25,.0125)
T TGT=1/.6/.3/.1/.05/.01/.001/.0005/.0001/.00005/1E-5/
X 5E-6/1E-6/5E-7/1E-7/5E-8/1E-8/5E-9/1E-9/0
C CTG=.01
R THTI,KLBTI,K*PM,K
A PM,DPM50,K*KM,K
A PM50,KLOGN(2)/DV50,K
A DV50,KTABHL(DV50T,VA,K,0+1,7,,1)
T DV50T=5/14/26/40/60/70/85/110/144/235/280/320/344/350/364/
X 260/180/53
A KM,KTABHL(KMT,V,K/VM,K,0+1,,2)
T KMT=0/.4/.65/.9/1.8/7.8
R TPTI,KLBTABHL(TPTIT,TIME,K,0+10,,2)
T TPTIT=0/0/0/0/0/0/0
R TETI,KLRCF,K*ETI,K
A CF,KRPULSE(TI,K/DT,REV,INT)
C REV=9999
C INT=999
A ETI,K=E1,K+E2,K+E3,K+E4,K
A E1,KRPULSE(E1T/DT,E1A,INT)
C E1A=999
A E2,KRPULSE(E2T/DT,E2A,INT)
C E2A=999
A E3,KRPULSE(E3T/DT,E3A,INT)
C E3T=100
C E3A=80
A E4,KRPULSE(E4T/DT,E4A,INT)
C E4T=100
C E4A=95
PRINT TI/V/VA/TMTI/TETI/AB/MAR/TRTI/TE/PA
PLOT TIBT/VSV/TRT1BR/TMT1BH/TET1BE/ABR1
SPEC DT=1/LENGTH=200/PRTPER=5/PLTPER=4
RUN

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Appendix 6: Version of DYPLUFOR used to simulate stand development with a combined program of fertilizing at 10 years and mixed thinning of 200 stems at 50 years and 200 stems at 65 years.



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L V=K*V+J+DT*(AH,JK=TE,JK=TN,JK)
N V=V1
C VI=10E-4
R AH,KLETI,K*A,K+VP*TPTI,JK+VSEM*TRTI,JK+(0,016*MAR,JK)
C VSEM=1E-7
R MAR,KL=STEP((TETI,JK+TMTI,JK)+100)
A A,K*PA,K*VA,K
A PA,K*PA50,K*KAA,K*FA
C FA=1
A PA50,K=LOGN(2)/D50,K
A D50,K=TABHL(D50T,VA,K+0,1,7,,1)
T D50T=0/9/11/13/14/17/18/19/21/23/27/31/37/45/56/70/84/98
A VA,K=V,K/TI,K
A KA,K=TABHL(KAT,V,K/VH,K+0,1,7,,2)
T KAT=1,2/1,12/1,04/.96/.88/.8
A VV,K=542608*EXP(-305*LOGN(VA,K))/EXP(2*LOGN(KCA,K))
A KCA,K=TABHL(KCAT,VA,K+0,1,7,,1)
T KCATE=24,3/23,6/23/22,4/21,8/21,3/20,8/20,3/19,9/19,5/
X 19,1/18,8/18,4/18,1/17,8/17,8/17,5/17,3
R TE,KL=CF,K*VA,K+ETI,K*VA,K*GRAE
C GRAE=1
R TM,KLE=TMTI,JK*VA,K*GRAM,K
A GRAM,K=TABHL(GRAMT,VA,K+0,1,7,,1)
T GRAVIT=.8/.82/.84/.86/.88/.9/.92/.94/.96/.98/1/1,02/
X 1,04/1,06/1,08/1,1/1,12/1,14
L TI,KETI,J+DT*(TDTI,JK+TRTI,JK+MAR,JK=TETI,JK=TMTI,JK)
N TIBITI
C ITI=10000
R TRTI,KL=ENSEM,K*TG,K
A NSEM,K=NMS*DSEM,K
C NMS=1E6
A DSEM,K=TABHL(DSEM,V,VA,K+0,1,8,,2)
T DSEM=0/0/0/.34/.66/1/1/1/1/0
A TG,K=CTG+TABHL(TGT,V,K/VH,K+0,.25,.0125)
T TGT=1,.6/.3/.1/.05/.01/.005/.001/.0005/.0001/.00005/1E-5/
X 5E-6/1E-6/5E-7/1E-7/5E-8/1E-8/5E-9/1E-9/0
C CTG=.01
R TMTI,KL=TI,K*DM,K
A DM,K=PM50,K*KM,K
A PM50,K=LOGN(2)/DV50,K
A DV50,K=TABHL(DV50T,VA,K+0,1,7,,1)
T DV50T=5/14/26/40/60/70/85/110/144/235/280/320/344/350/344/
X 240/180/53
A KM,K=TABHL(KMT,V,K/VH,K+0,1,7,,2)
T KMT=0/.4/.65/.9/1,8/7,8
R TPTI,KLE=TABHL(TPTIT,TIME,K,0,10,2)
T TPTIT=0/0/0/0/0/0
R TETI,KL=MAX(CP,K+ETI,K*TI,K*CHA,K+000001)
A NO,K=0,5#NDISE()
A CHA,K=CLIP(CLIP(CLIP(.1,.01#NO,K,.99),.008#NO,K,.97),.
X ,001#NO,K,.94)+0#NO,K,.90)
A CF,K=PULSE(TI,K/DT,REV,INT)
C REV=9999
C INT=999
A ETI,K=E1,K+E2,K+E3,K+E4,K
A E1,K=PULSE(E1T/DT,E1A,INT)
C E1T=0
C E1A=50
A E2,K=PULSE(E2T/DT,E2A,INT)
C E2T=0
C E2A=65
A E3,K=PULSE(E3T/DT,E3A,INT)
C E3T=0
C E3A=80
A E4,K=PULSE(E4T/DT,E4A,INT)
C E4T=0
C E4A=95
PRINT TI/V/VA/TMTI/TETI/AB/MAR/TRTI/TE/CHA
PLOT TI*T/V*V/TRTI*B/R/TMTI*B/M/TETI*B/AB*B
SPEC DT=1/LENGTH=200/PRTPER=5/PLTPER=4
RUN

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Appendix 7: Version of DYPERFOR used to simulate the development of a stand affected by windfall, a stochastic phenomenon.









