BLACK SPRUCE STAND DYNAMICS

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ABSTRACT

This paper describes a simulation model reproducing the development over time of a coniferous forest. The purpose of the model is to test the dynamic effects on total volume and tree dimensions of such silvicultural activities as thinning, and fertilizing. Cause and effect relationships in the forest system are presented in the shape of a dynamic model, a multiloop feedback system. In this case, forest growth is viewed as a state which is determined by an accumulation process controlled by total volume (ft^3/acre) and stand density (number of trees/acre).

In addition, the development over time in an undisturbed forest or in stands affected 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 two main advantages:

1) any behavior or response of the forest can easily be visualized on graphics
2) 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.

The silviculture 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*, (Dynamics of Forest Stands) a model for simulating black spruce forests in Quebec resembles 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 (1975) 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 nonlinear feedback systems, containing multiple loops. Even when we possess an excellent knowledge of the various parts of a given system, it is usually impossible 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 (Forrester, 1976 and 1977), which is of very special value because

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*DYPEUFOR: Dynamique des Peuplements Forestiers

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 can improve 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 treatments 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 cu ft/acre, and not in equivalent dollars. This is intented to preserve the possibility of studying the relationships among the different loops of DYPEUFOR.
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.

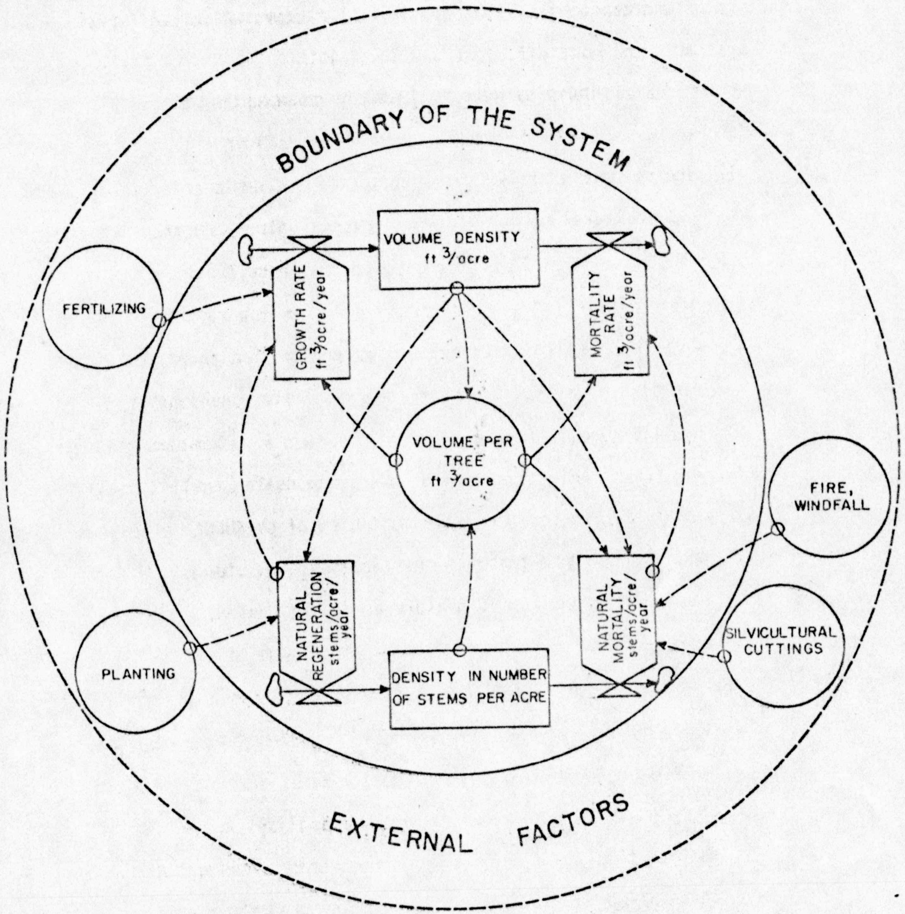

Figure 1: DYPEUFOR networks with their main internal and external elements

COMPONENTS OF DYPEUFOR

The dynamic simulation model discussed herein comprises three main components: natural regeneration, growth and natural mortality. Figure 2 clearly illustrates the roles of these in conjunction with the impact of external factors such as planting and cutting.

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 (Vezina 1975).

On the basis of earlier studies we hypothesized that the forest area would be 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 (Vezina 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.

Number of Seeds germinated

The regenerative process should allow for new seedlings to

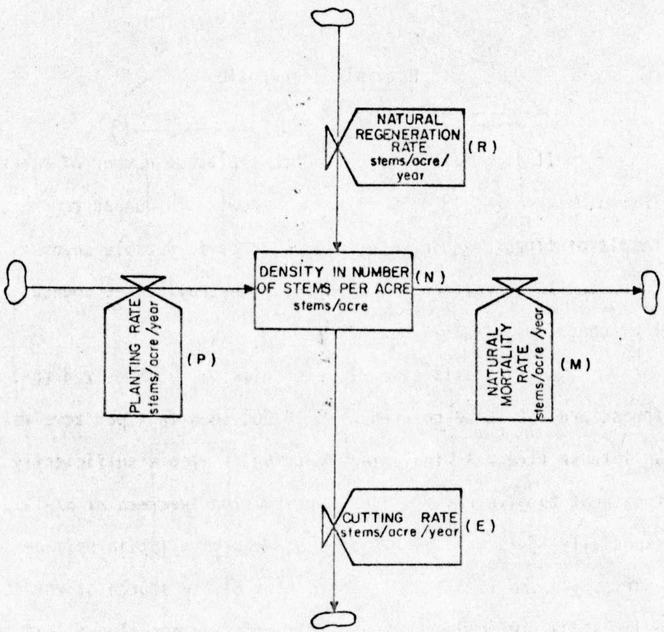

Figure 2: Principal rates determining the number of stems per acre per year

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:

$$\begin{bmatrix}\text{Regeneration} \\ \text{rate in} \\ \text{number of} \\ \text{stems per acre}\end{bmatrix} = \begin{bmatrix}\text{Number} \\ \text{of seeds} \\ \text{produced} \\ \text{per acre}\end{bmatrix} \times \begin{bmatrix}\text{Germination} \\ \text{rate}\end{bmatrix}$$

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 (Canadian Forestry Service, 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 3. At its optimum, the stand produces up to a million viable seeds per acre per year.

b) Germination rate (survival)

The germination rate is observed to change as cover closes in black spruce stands. The ratio of standing volume on maximum volume being a measure of stand's closure, determines the germination rate of seeds (figure 4). The explanation for maximum volume will be given in the section on Growth Increments.

Layering

In general, black spruce does not reproduce well sexually, but does reproduce well vegetatively, by means of layers. In a

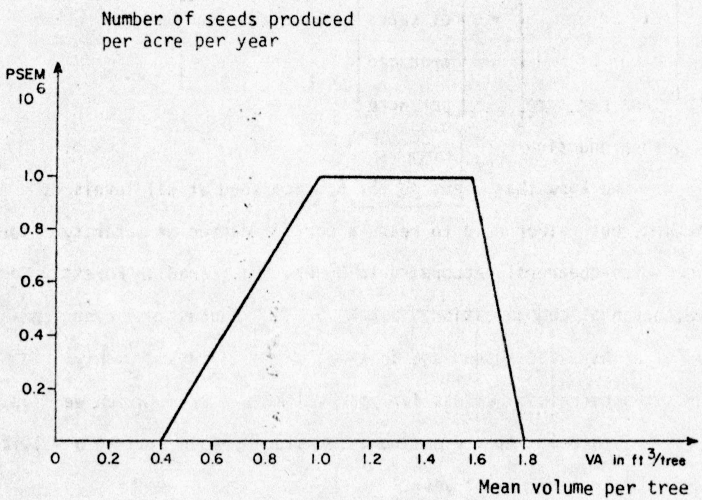

Figure 3: Number of seeds produced per acre per year as a function of the mean volume per tree

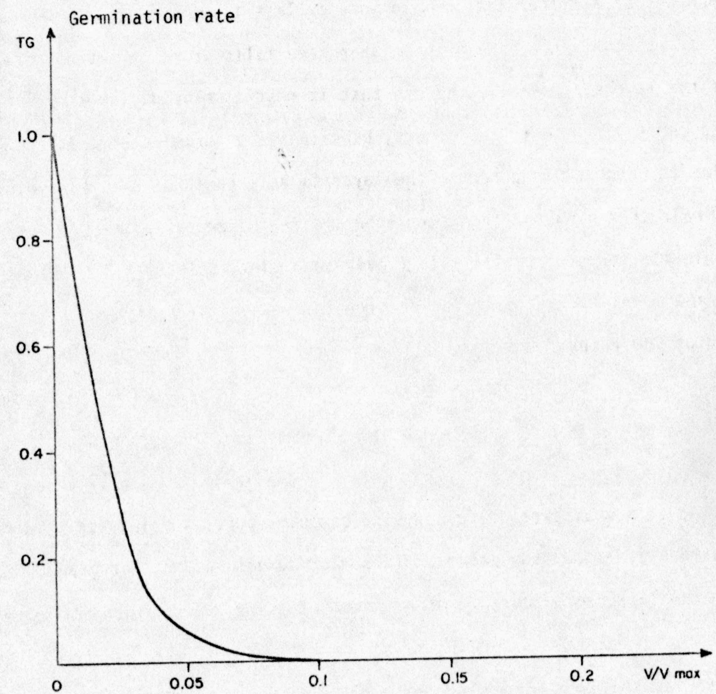

Figure 4: Relative germination rate as a function of the ratio V/Vmax

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 ft^3 for a class III site (Vezina and Linteau 1968). Therefore in the model each dead or fallen stem is replaced by a layer at the end of 100 years.

Growth Increments

A unit area of forest land cannot support a volume of wood greater than a maximum volume. This maximum volume Vmax corresponds to a completely closed cover. Volume growth depends among other things on the closure of the canopy. In an open stand with low density, where the volume V per acre is less than Vmax/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 Vmax/2. If in a denser stand, however, the volume V exceeds Vmax/2, the photosynthetic efficiency is reduced and everything else being equal, the volume growth is less than that of the stand where volume equals Vmax/2. We have just seen

that Vmax/2 serves as a reference value and that the ratio V/Vmax may be considered to be the relative crown closure.

Determination of the Maximum Volume Vmax and the Correcting Factor KCA

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:

$$\text{Vmax} = \left[\frac{\text{Area of one acre}}{\text{Area covered by the crown of the mean tree}}\right] \times \left[\begin{array}{l}\text{Mean}\\ \text{volume}\\ \text{per tree}\end{array}\right]$$

with

$$\left[\begin{array}{l}\text{Area covered by}\\ \text{the crown of the}\\ \text{mean tree}\end{array}\right] = \left[\begin{array}{l}\text{dbh of the}\\ \text{mean tree}\end{array}\right] \times \left[\begin{array}{l}\text{Correcting}\\ \text{factor}\\ \text{KCA}\end{array}\right]$$

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. Firsque, Canadian Forestry Service, 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. Factor KCA was determined from the normal yield tables of Vezina and Linteau (1968). 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. Table 1 gives the KCA values obtained for each pair dbh - number of stems, together with the corresponding volume per tree. Figure 5 shows KCA as a function of the mean volume per tree. After determining the factor KCA, mathematical transformations (see Ung et al 1978, pages 27-37 for details) allow us to obtain Vmax as a function of the mean volume per tree. Figure 6 illustrates this function.

Annual Growth of the Mean Volume per Tree

The calculation of annual growth of the mean volume per tree is based on the concept of the doubling time:

$$\left[\begin{array}{l}\text{Annual growth}\\ \text{of the mean}\\ \text{volume}\\ \text{per tree}\end{array}\right] = \left[\begin{array}{l}\text{Correcting}\\ \text{factor}\end{array}\right] \times \left[\frac{\log 2}{\begin{array}{l}\text{Doubling time}\\ \text{at 50\% of}\\ \text{Vmax}\end{array}}\right] \times \left[\begin{array}{l}\text{Mean}\\ \text{volume}\\ \text{per tree}\end{array}\right]$$

Figure 7 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 (1978) tables, to which was added the volume of nonmerchantable stems with a dbh less than four inches. From this figure 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. The details of

dbh in feet	number of stems per acre	KCA	Mean volume per tree
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 1: Values of factor KCA corresponding to various dbh and numbers of stems

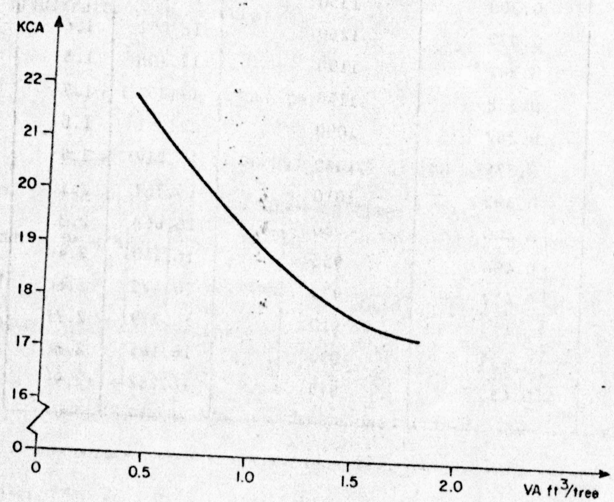

Figure 5: Factor KCA as a function of the mean volume per tree

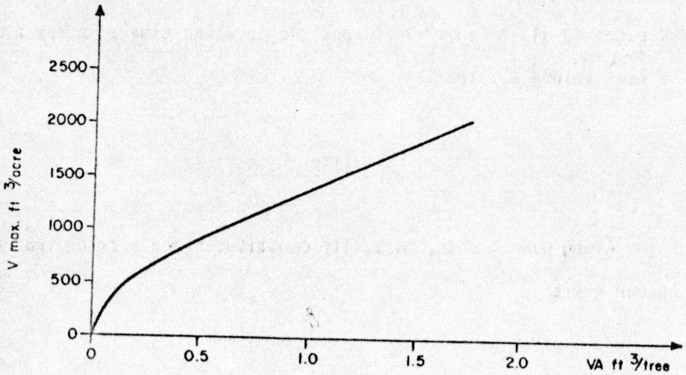

Figure 6: Vmax as a function of the mean volume per tree (VA)

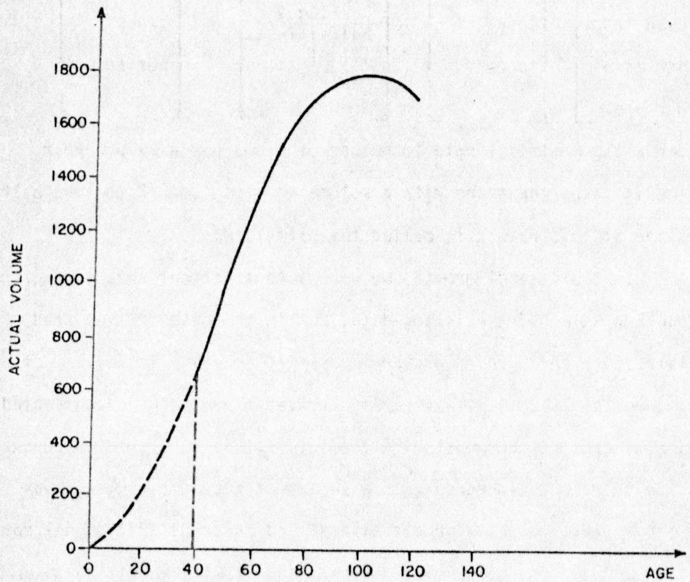

Figure 7: Variation over time of the total volume of a black spruce stand of site class III

the calculation of the doubling time are shown in Ung *et al* (1978, pages 40-41). Figure 8 graphs the doubling time as a function of the mean volume per tree.

Mortality

Along with growth, mortality constitutes the entropy indicator of our system.

Number of Dead Trees

The number of dead trees per year is calculated on the basis of the half-life concept:

$$\begin{bmatrix} \text{Number of} \\ \text{dead trees} \\ \text{per acre} \\ \text{per year} \end{bmatrix} = \begin{bmatrix} \text{Correcting} \\ \text{factor} \end{bmatrix} \times \begin{bmatrix} \dfrac{\log 2}{\text{Half-life at 50\% of Vmax}} \end{bmatrix} \times \begin{bmatrix} \text{Number of} \\ \text{trees} \\ \text{per acre} \end{bmatrix}$$

Consider x the mortality rate in number of stems per acre per year. The time it takes the stand with a volume equal to Vmax/2 to lose half its volume at this rate x is called the half-life.

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. 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

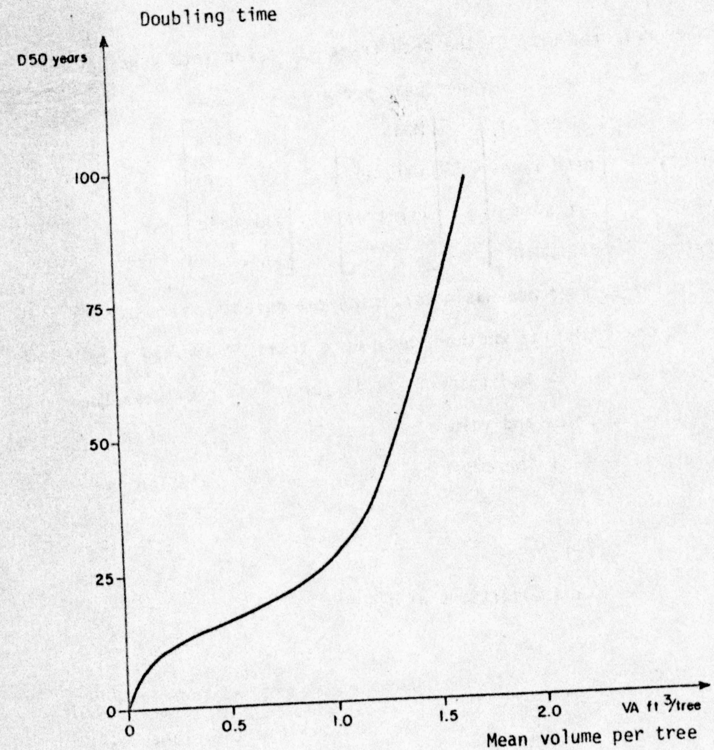

Figure 8: Doubling time as a function mean volume per tree

to the empirical data obtained by Boudoux (1978). Figure 9 shows the best half-life curve which we were able to obtain under the given constraints.

Volume of Dead Trees per Year

When relative size of the dead trees is taken into consideration, the volume of dead trees per year per acre is equal to:

$$\begin{bmatrix}\text{Volume of}\\ \text{dead trees}\\ \text{per acre}\\ \text{per year}\end{bmatrix} = \begin{bmatrix}\text{Number of}\\ \text{dead trees}\\ \text{per acre}\\ \text{per year}\end{bmatrix} \times \begin{bmatrix}\text{Mean}\\ \text{volume}\\ \text{per tree}\\ \end{bmatrix} \times \begin{bmatrix}\text{Relative}\\ \text{size of}\\ \text{the dead}\\ \text{trees}\end{bmatrix}$$

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 10.

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.

Density in Number of Stems per Acre

Stand density (trees/acre) is the result of regeneration and

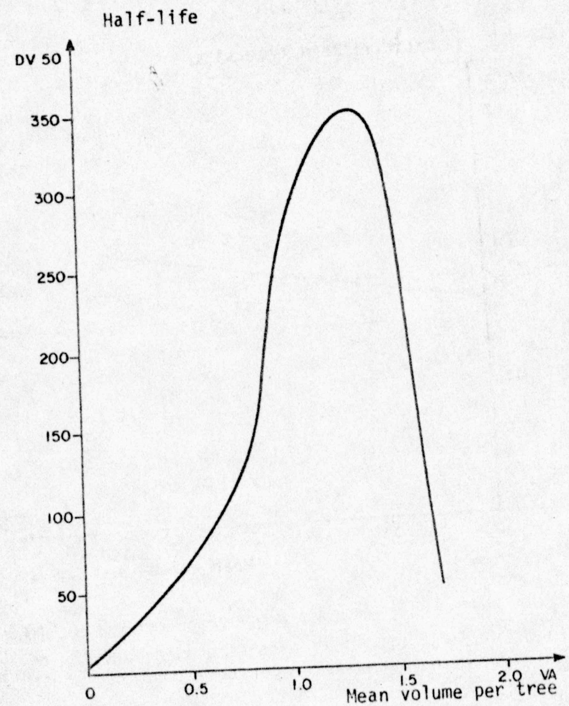

Figure 9: Half-life as a function of the mean volume per tree

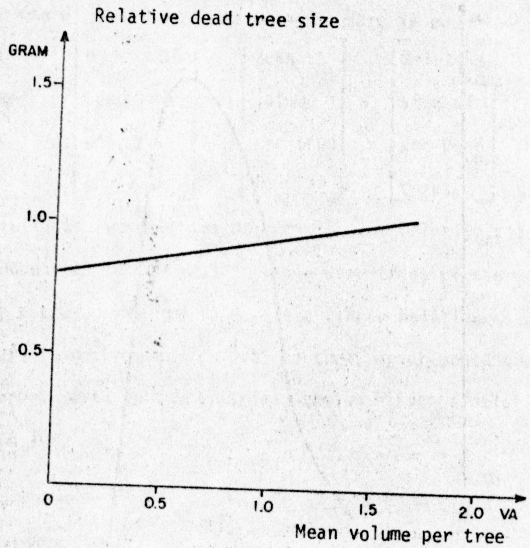

Figure 10: Relative dead tree size as a function of the mean volume per tree

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. The situation can be summarized by the equation:

$$\begin{bmatrix}\text{Number}\\\text{of trees}\\\text{at time}\\t\end{bmatrix} = \begin{bmatrix}\text{Number}\\\text{of trees}\\\text{at time}\\t\text{-}1\end{bmatrix} + dt\left\{\begin{bmatrix}\text{Annual}\\\text{planting}\\\text{rate}\end{bmatrix} + \begin{bmatrix}\text{Annual}\\\text{rate of}\\\text{sexual}\\\text{reproduction}\end{bmatrix} + \begin{bmatrix}\text{Annual}\\\text{rate of}\\\text{layering}\end{bmatrix} - \begin{bmatrix}\text{Annual}\\\text{cutting}\\\text{rate}\end{bmatrix} - \begin{bmatrix}\text{Annual}\\\text{mortality}\\\text{rate}\end{bmatrix}\right\}$$

Volume Density (cu ft/acre)

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

$$\begin{bmatrix}\text{Volume}\\\text{at time}\\t\end{bmatrix} = \begin{bmatrix}\text{Volume}\\\text{at time}\\t\text{-}1\end{bmatrix} + dt\left\{\begin{bmatrix}\text{Growth}\\\text{volume}\end{bmatrix} - \begin{bmatrix}\text{Cutting}\\\text{volume}\end{bmatrix} - \begin{bmatrix}\text{Mortality}\\\text{volume}\end{bmatrix}\right\}$$

Summary of relations

Figure 11 gives an overview of interactions of various internal variables in the DYPEUFOR simulation model. 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 (ft^3/acre) and that of the density in number of stems (number of stems/acre), the two being linked by the model's

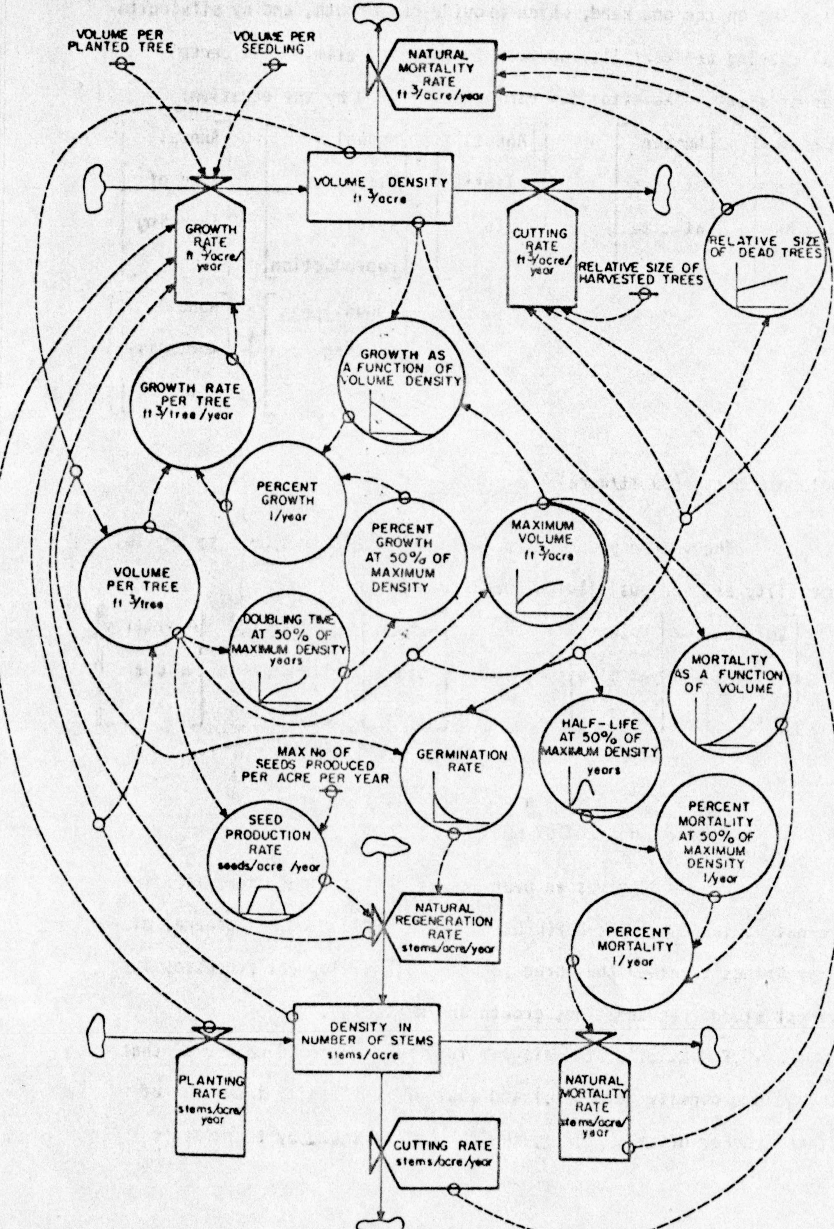

Figure 11: General *DYPEUFOR* diagram

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 percent of the maximum volume and the percent growth at 50 percent of the maximum density.

c) Mortality: the mean volume per tree is used in calculating the half-life at 50 percent 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.

RESULTS

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.

Figure 12 shows that in the regeneration phase the stand has a strictly positive material balance, characterized by 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

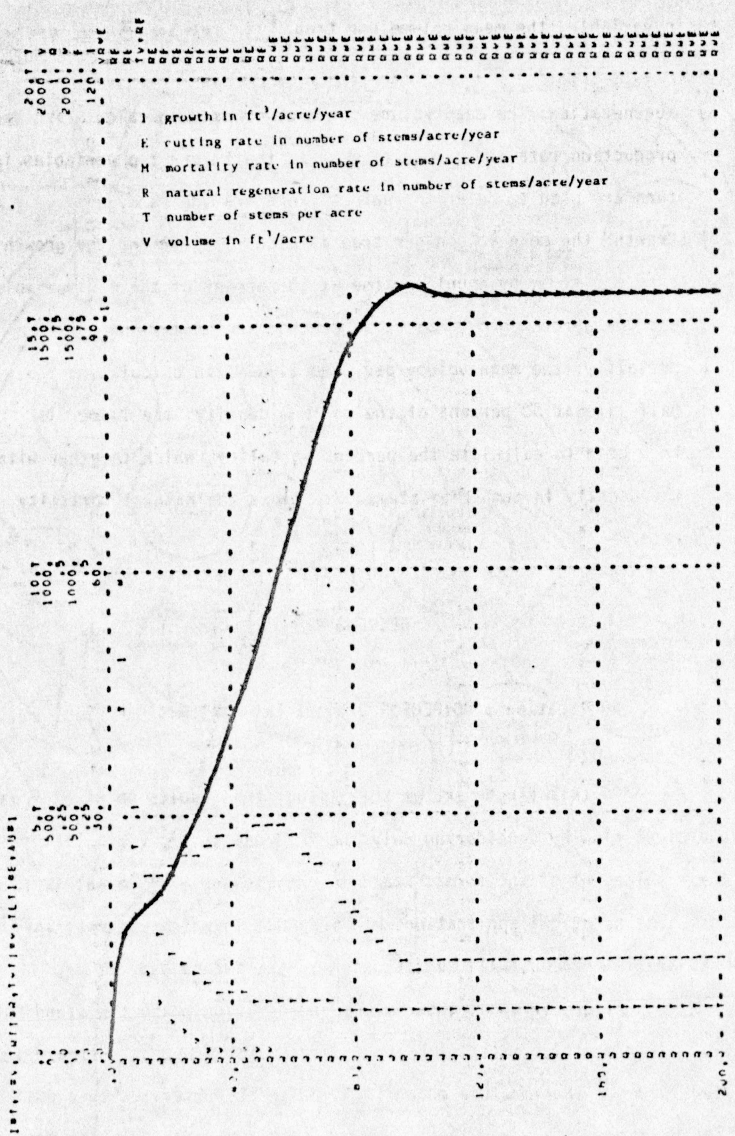

Figure 12: Simulation of stand development without external action

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.

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.

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. 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.

$$\begin{bmatrix}\text{Harvested}\\ \text{volume}\\ \text{at time}\\ t\end{bmatrix} = \begin{bmatrix}\text{Number}\\ \text{of stems}\\ \text{removed}\\ \text{by thinning}\\ \text{at time } t\end{bmatrix} \times \begin{bmatrix}\text{Mean}\\ \text{volume}\\ \text{per tree}\end{bmatrix} \times \begin{bmatrix}\text{Relative}\\ \text{size of}\\ \text{harvested}\\ \text{trees}\end{bmatrix}$$

Depending on the type of thinning, the relative size of harvested trees will be:

equal to 1 for a mixed thinning

less than 1 for a thinning from below

greater than 1 for a thinning from above

Figure 13 and table 2 show the results of two thinnings simulation: 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. These results and those of other types of thinnings are grouped in table 3. In general, the volume which can be harvested is low. A close study of the results shows that:

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

Treatments which Produce or Promote Growth

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

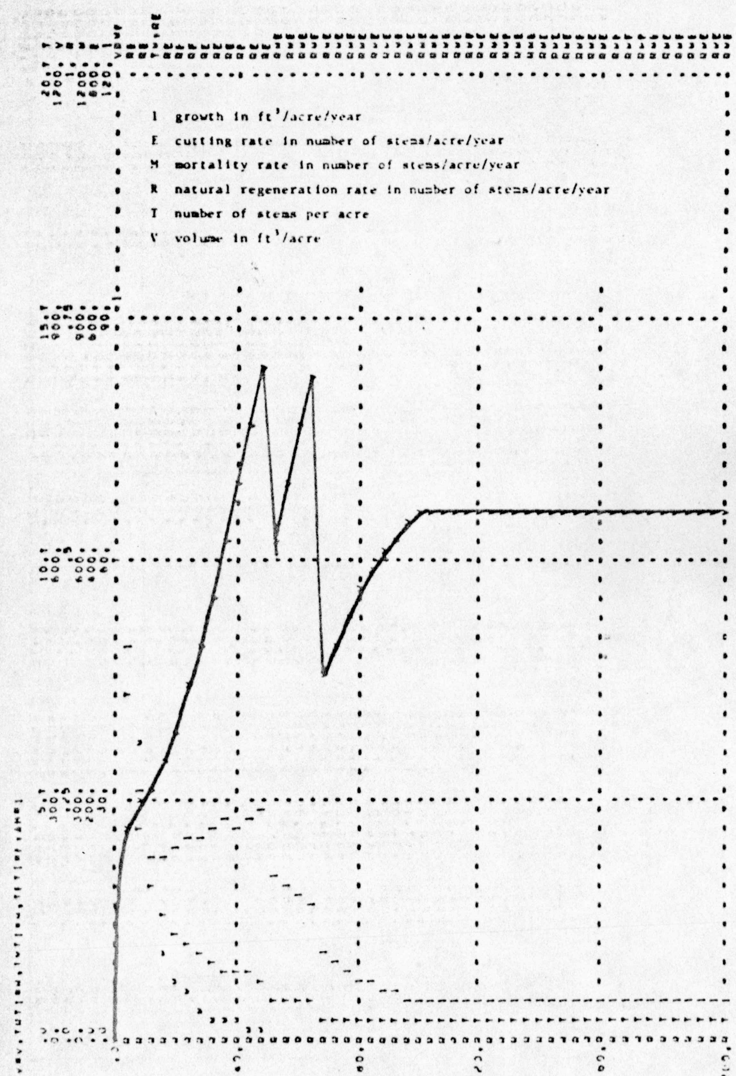

Figure 13: Simulation of stand development with two thinnings

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TIME E+00	TI E+03	V E+00	VA E+00	TMTI E+00	TETI E+00	AB E+00	WAR E+00	TRTI E+00	TE E+00	GRAE E+00
.0	10,000	.00	.0000	.41	.00	92,415	.0000	0.	.00	.8000
5.	6,137	278,96	.0455	756,04	.00	42,370	.0000	0.	.00	.8000
10.	3,674	306,79	.0835	254,68	.00	26,281	.0000	0.	.00	.8000
15.	2,716	337,75	.1244	123,46	.00	23,229	.0000	0.	.00	.8000
20.	2,211	389,39	.1761	75,33	.00	24,082	.0000	0.	.00	.8000
25.	1,889	453,03	.2398	50,12	.00	24,825	.0000	0.	.00	.8000
30.	1,671	524,92	.3142	34,76	.00	25,629	.0000	0.	.00	.8000
35.	1,521	608,54	.4001	24,09	.00	27,656	.0000	0.	.00	.8000
40.	1,408	697,97	.4958	20,46	.00	26,099	.0000	0.	.00	.8000
45.	1,314	783,68	.5962	16,17	.00	27,424	.0000	0.	.00	.8000
50.	1,243	878,97	.7070	11,73	500,00	28,775	.0000	0.	282,82	.8000
55.	.724	681,48	.9409	1,48	.00	19,341	.0000	0.	.00	1,2000
60.	.717	768,00	1,0704	1,24	.00	17,891	.0000	0.	.00	1,2000
65.	.712	847,11	1,1905	1,12	300,00	16,096	.0000	0.	428,60	1,2000
70.	.409	474,05	1,1602	.43	.00	10,300	.0000	0.	.00	1,2000
75.	.406	520,26	1,2800	.42	.00	8,997	.0000	0.	.00	1,2000
80.	.404	559,69	1,3841	.42	.00	7,730	.0000	0.	.00	1,2000
85.	.402	592,68	1,4741	.56	.00	6,666	.0000	0.	.00	1,2000
90.	.394	619,55	1,5531	.72	.00	5,966	.0000	0.	.00	1,2000
95.	.395	641,73	1,6247	.99	.00	5,471	.0000	0.	.00	1,2000
100.	.388	657,36	1,6933	2,35	.00	5,053	1,8399	0.	.00	1,2000
105.	.387	658,80	1,7008	2,72	.00	5,059	2,7171	0.	.00	1,2000
110.	.387	657,91	1,6982	2,60	.00	5,065	2,6255	0.	.00	1,2000
115.	.387	658,04	1,6984	2,62	.00	5,063	2,6121	0.	.00	1,2000
120.	.387	658,01	1,6984	2,62	.00	5,063	2,6170	0.	.00	1,2000
125.	.387	658,02	1,6984	2,62	.00	5,063	2,6155	0.	.00	1,2000
130.	.387	658,02	1,6984	2,62	.00	5,063	2,6160	0.	.00	1,2000
135.	.387	658,02	1,6984	2,62	.00	5,063	2,6157	0.	.00	1,2000
140.	.387	658,02	1,6984	2,62	.00	5,063	2,6157	0.	.00	1,2000
145.	.387	658,02	1,6984	2,62	.00	5,063	2,6157	0.	.00	1,2000
150.	.387	658,02	1,6984	2,62	.00	5,063	2,6157	0.	.00	1,2000
155.	.387	658,02	1,6984	2,62	.00	5,063	2,6157	0.	.00	1,2000
160.	.387	658,02	1,6984	2,62	.00	5,063	2,6157	0.	.00	1,2000
165.	.387	658,02	1,6984	2,62	.00	5,063	2,6157	0.	.00	1,2000
170.	.387	658,02	1,6984	2,62	.00	5,063	2,6157	0.	.00	1,2000
175.	.387	658,02	1,6984	2,62	.00	5,063	2,6157	0.	.00	1,2000
180.	.387	658,02	1,6984	2,62	.00	5,063	2,6157	0.	.00	1,2000
185.	.387	658,02	1,6984	2,62	.00	5,063	2,6157	0.	.00	1,2000
190.	.387	658,02	1,6984	2,62	.00	5,063	2,6157	0.	.00	1,2000
195.	.387	658,02	1,6984	2,62	.00	5,063	2,6157	0.	.00	1,2000
200.	.387	658,02	1,6984	2,62	.00	5,063	2,6157	0.	.00	1,2000

Table 2: Simulation of stand development with two thinnings

Description of treatment	Volume removed per acre ft³/acre	Volume removed per tree ft³	Age at which maximum volume is reached after thinnings	Maximum volume after thinnings ft³/acre (a)	Volume per tree relative to (a) ft³	Volume at 200 years ft³/acre	Volume per tree ft³	Total volume removed by thinnings ft³/acre
Mixed thinnings GRAE = 1 (*) 50 years, 500 stems 65 years, 300 stems	354 332	0.71 1.11	98	854	1.72	642	1.71	686
Thinning from below 300 stems GRAE = 0.8 50 years, 500 stems Thinning from above GRAE = 1.2 65 years, 300 stems	354 357	0.71 1.19	105	659	1.70	658	1.70	711
Mixed thinnings GRAE = 1 50 years, 200 stems 65 years, 200 stems	141 215	0.71 1.08	101	1191	1.67	1188	1.67	356
Mixed thinnings GRAE = 1 50 years, 200 stems 95 years, 100 stems	141 158	0.71 1.58	119	1280	1.66	1280	1.66	299
No treatment	-	-	100	1575	1.61	1567	1.61	

(*) GRAE: relative size of harvested trees

Table 3. Simulation of various thinning programs

a) 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. Consider the planting timetable shown in figure 14. The results of the simulation presented in figure 15 and table 4, show that this planting program is completely useless. It is made superfluous by the existence of a good natural regeneration in the first year (10,000 seedlings at the beginning of the simulation horizon). 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.

b) Fertilizing

Fertilizing can be introduced in the model by modifying the percent growth by a factor according to curve patterns such as those shown in figure 16.

Figure 17 and table 5 show the results of a fertilization according to pattern n^{o}1 which has an effect between 20 and 30 years. The results of simulations of various treatments are shown in table 6.

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^3/acre' that is, an improvement of 4.1 ft^3/acre in comparison with a non treatment policy. Further analysis of table 6 shows that pattern 2 seems to be better than

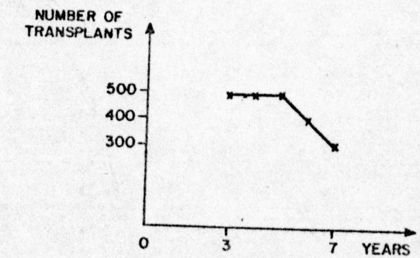

Figure 14: A planting timetable

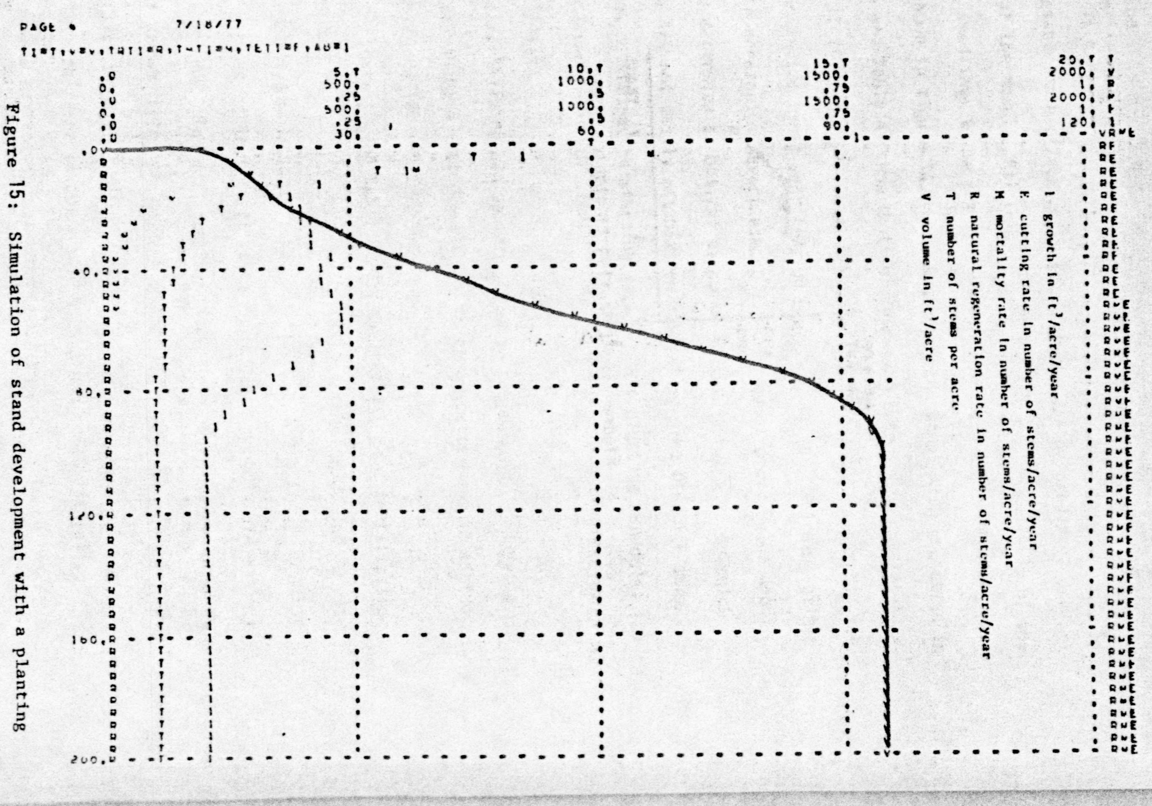

Figure 15: Simulation of stand development with a planting program

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TIME E+00	TI E+03	V E+00	VA E+00	TNTI E+00	TETI E+00	AB E+00	MAR E+00	TRTI E+00	TE E+00	TPTI E+00
.0	10.000	.0	.0000	.4	0.	92.415	.0000	0.	0.	.00
5.	6.990	284.2	.0407	1046.4	0.	47.329	.0000	0.	0.	500.00
10.	4.363	308.4	.0707	386.5	0.	30.611	.0000	0.	0.	.00
15.	3.001	327.9	.1093	159.8	0.	23.179	.0000	0.	0.	.00
20.	2.371	371.0	.1565	89.4	0.	23.849	.0000	0.	0.	.00
25.	1.993	430.7	.2161	58.1	0.	24.633	.0000	0.	0.	.00
30.	1.742	499.7	.2866	40.0	0.	25.225	.0000	0.	0.	.00
35.	1.570	577.9	.3681	27.3	0.	26.952	.0000	0.	0.	.00
40.	1.447	668.2	.4617	21.8	0.	26.648	.0000	0.	0.	.00
45.	1.346	753.0	.5594	17.6	0.	26.926	.0000	0.	0.	.00
50.	1.267	844.2	.6565	13.1	0.	28.372	.0000	0.	0.	.00
55.	1.209	946.1	.7827	9.5	0.	28.585	.0000	0.	0.	.00
60.	1.170	1054.3	.9013	5.6	0.	28.377	.0000	0.	0.	.00
65.	1.144	1165.4	1.0188	4.6	0.	25.912	.0000	0.	0.	.00
70.	1.122	1266.7	1.1291	4.1	0.	23.752	.0000	0.	0.	.00
75.	1.102	1355.6	1.2304	3.8	0.	21.103	.0000	0.	0.	.00
80.	1.083	1430.8	1.3212	3.8	0.	18.539	.0000	0.	0.	.00
85.	1.064	1491.4	1.4015	3.7	0.	16.292	.0000	0.	0.	.00
90.	1.043	1537.3	1.4733	4.8	0.	14.166	.0000	0.	0.	.00
95.	1.017	1563.2	1.5369	5.7	0.	12.738	.0000	0.	0.	.00
100.	.988	1574.3	1.5942	6.3	0.	11.689	6.1338	0.	0.	.00
105.	.987	1577.3	1.5975	6.3	0.	11.747	6.3074	0.	0.	.00
110.	.987	1579.4	1.5997	6.4	0.	11.720	6.3574	0.	0.	.00
115.	.987	1580.6	1.6012	6.4	0.	11.701	6.4169	0.	0.	.00
120.	.987	1581.5	1.6020	6.5	0.	11.691	6.4616	0.	0.	.00
125.	.987	1581.8	1.6024	6.5	0.	11.686	6.4836	0.	0.	.00
130.	.987	1582.0	1.6026	6.5	0.	11.684	6.4944	0.	0.	.00
135.	.987	1582.1	1.6027	6.5	0.	11.683	6.4996	0.	0.	.00
140.	.987	1582.1	1.6027	6.5	0.	11.682	6.5021	0.	0.	.00
145.	.987	1582.2	1.6027	6.5	0.	11.682	6.5033	0.	0.	.00
150.	.987	1582.2	1.6028	6.5	0.	11.682	6.5038	0.	0.	.00
155.	.987	1582.2	1.6028	6.5	0.	11.682	6.5041	0.	0.	.00
160.	.987	1582.2	1.6028	6.5	0.	11.682	6.5043	0.	0.	.00
165.	.987	1582.2	1.6028	6.5	0.	11.682	6.5043	0.	0.	.00
170.	.987	1582.2	1.6028	6.5	0.	11.682	6.5043	0.	0.	.00
175.	.987	1582.2	1.6028	6.5	0.	11.682	6.5043	0.	0.	.00
180.	.987	1582.2	1.6028	6.5	0.	11.682	6.5043	0.	0.	.00
185.	.987	1582.2	1.6028	6.5	0.	11.682	6.5043	0.	0.	.00
190.	.987	1582.2	1.6028	6.5	0.	11.682	6.5043	0.	0.	.00
195.	.987	1582.2	1.6028	6.5	0.	11.682	6.5043	0.	0.	.00
200.	.987	1582.2	1.6028	6.5	0.	11.682	6.5043	0.	0.	.00

Table 4: Simulation of stand development with a planting program

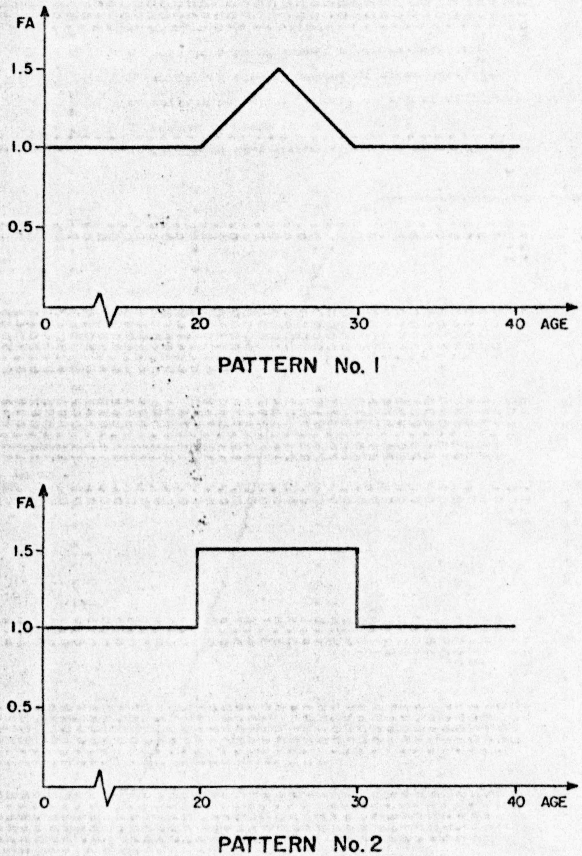

Figure 16: Curve patterns illustrating the effect of fertilizing on growth between 20 and 30 years

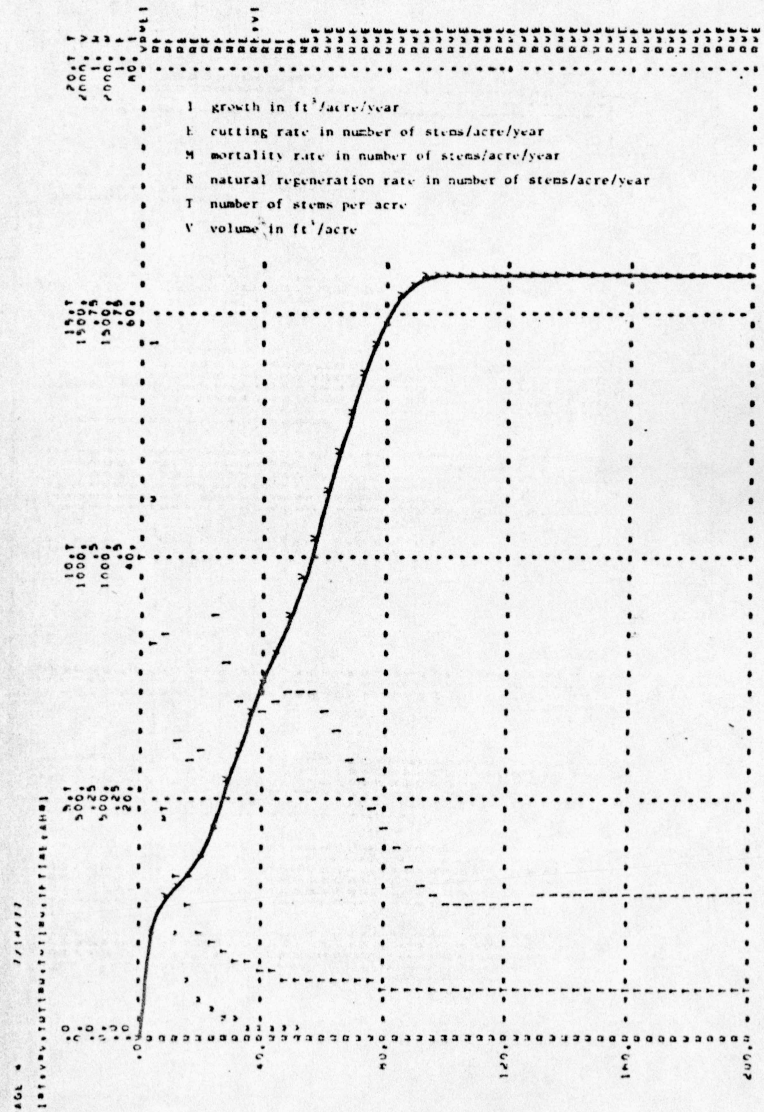

Figure 17: Simulation of stand development with fertilizing

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TIME E+00	TI E+03	V E+00	VA E+00	TWTI E+00	TETI E+00	AB E+00	WAR E+00	TRTI E+00	TE E+00	FA E+00
.0	10.000	.0	.0000	.4	0.	.000	.0000	0.	0.	.0000
5.	7.116	263.7	.0371	978.3	0.	48.939	.0000	0.	0.	1.0000
10.	3.978	301.2	.0757	303.5	0.	28.318	.0000	0.	0.	1.0000
15.	2.855	329.9	.1155	139.8	0.	23.098	.0000	0.	0.	1.0000
20.	2.293	377.8	.1648	82.2	0.	23.909	.0000	0.	0.	1.0000
25.	1.942	464.0	.2390	55.0	0.	37.912	.0000	0.	0.	1.5000
30.	1.704	571.3	.3352	36.5	0.	27.007	.0000	0.	0.	1.0000
35.	1.547	655.4	.4236	26.1	0.	27.945	.0000	0.	0.	1.0000
40.	1.426	739.9	.5190	21.3	0.	26.864	.0000	0.	0.	1.0000
45.	1.329	875.4	.6210	16.2	0.	28.234	.0000	0.	0.	1.0000
50.	1.258	922.1	.7332	11.6	0.	29.126	.0000	0.	0.	1.0000
55.	1.207	1026.4	.8503	7.4	0.	28.821	.0000	0.	0.	1.0000
60.	1.176	1138.9	.9686	5.3	0.	27.188	.0000	0.	0.	1.0000
65.	1.151	1244.5	1.0812	4.6	0.	25.138	.0000	0.	0.	1.0000
70.	1.124	1339.5	1.1862	4.1	0.	22.606	.0000	0.	0.	1.0000
75.	1.109	1420.8	1.2812	4.0	0.	19.921	.0000	0.	0.	1.0000
80.	1.089	1487.5	1.3657	3.9	0.	17.381	.0000	0.	0.	1.0000
85.	1.069	1540.5	1.4410	4.8	0.	15.187	.0000	0.	0.	1.0000
90.	1.042	1571.3	1.5086	6.2	0.	13.418	.0000	0.	0.	.9999
95.	1.012	1585.0	1.5667	6.1	0.	12.246	.0000	0.	0.	.9999
100.	.980	1588.7	1.6219	7.4	0.	11.282	6.9106	0.	0.	.9999
105.	.979	1580.1	1.6133	6.9	0.	11.499	6.9907	0.	0.	.9999
110.	.980	1575.9	1.6085	6.6	0.	11.555	6.6782	0.	0.	.9999
115.	.980	1574.1	1.6064	6.5	0.	11.580	6.5534	0.	0.	1.0000
120.	.980	1573.2	1.6054	6.5	0.	11.592	6.4982	0.	0.	1.0000
125.	.980	1572.8	1.6050	6.5	0.	11.597	6.4728	0.	0.	1.0000
130.	.980	1572.6	1.6048	6.5	0.	11.600	6.4610	0.	0.	1.0000
135.	.980	1572.5	1.6047	6.5	0.	11.601	6.4555	0.	0.	1.0000
140.	.980	1572.5	1.6047	6.5	0.	11.602	6.4528	0.	0.	1.0000
145.	.980	1572.5	1.6046	6.5	0.	11.602	6.4516	0.	0.	1.0000
150.	.980	1572.5	1.6046	6.5	0.	11.602	6.4510	0.	0.	1.0000
155.	.980	1572.5	1.6046	6.5	0.	11.602	6.4507	0.	0.	1.0000
160.	.980	1572.5	1.6046	6.5	0.	11.602	6.4506	0.	0.	1.0000
165.	.980	1572.5	1.6046	6.5	0.	11.603	6.4506	0.	0.	1.0000
170.	.980	1572.5	1.6046	6.5	0.	11.603	6.4506	0.	0.	1.0001
175.	.980	1572.5	1.6046	6.5	0.	11.603	6.4506	0.	0.	1.0001
180.	.980	1572.5	1.6046	6.5	0.	11.603	6.4507	0.	0.	1.0001
185.	.980	1572.5	1.6046	6.5	0.	11.602	6.4507	0.	0.	1.0000
190.	.980	1572.5	1.6046	6.5	0.	11.602	6.4506	0.	0.	1.0000
195.	.980	1572.5	1.6046	6.5	0.	11.601	6.4504	0.	0.	.9999
200.	.980	1572.5	1.6046	6.5	0.	11.600	6.4502	0.	0.	.9998

Table 5 : Simulation of stand development with fertilizing

Description of treatment and pattern number	Age at which the maximum volume is reached	Maximum volume (ft^3)		Volume at 200 years (ft^3)		Total volume removed by thinnings (ft^3)
		per acre	per tree	per acre	per tree	
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 Thinnings 50 years 200 stems-146 ft^3 65 years 200 stems-213 ft^3	121	1206.3	1.67	1206.3	1.67	359
11-19 #2 Thinnings 50 years 200 stems-156 ft^3 65 years 200 stems-221 ft^3	118	1207	1.67	1207	1.67	377
21-29 #1 Thinnings 50 years 200 stems-147 ft^3 65 years 200 stems-214 ft^3	122	1217	1.67	1217	1.67	361
21-29 #2 Thinnings 50 years 200 stems-156 ft^3 65 years 200 stems-222 ft^3	121	1226	1.67	1226	1.67	378

Table 6 : Simulation of various fertilizing programs

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. Figure 18 and table 7 give the results.

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 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 a forested area at a given moment.

The importance of filling this gap, which is brought into

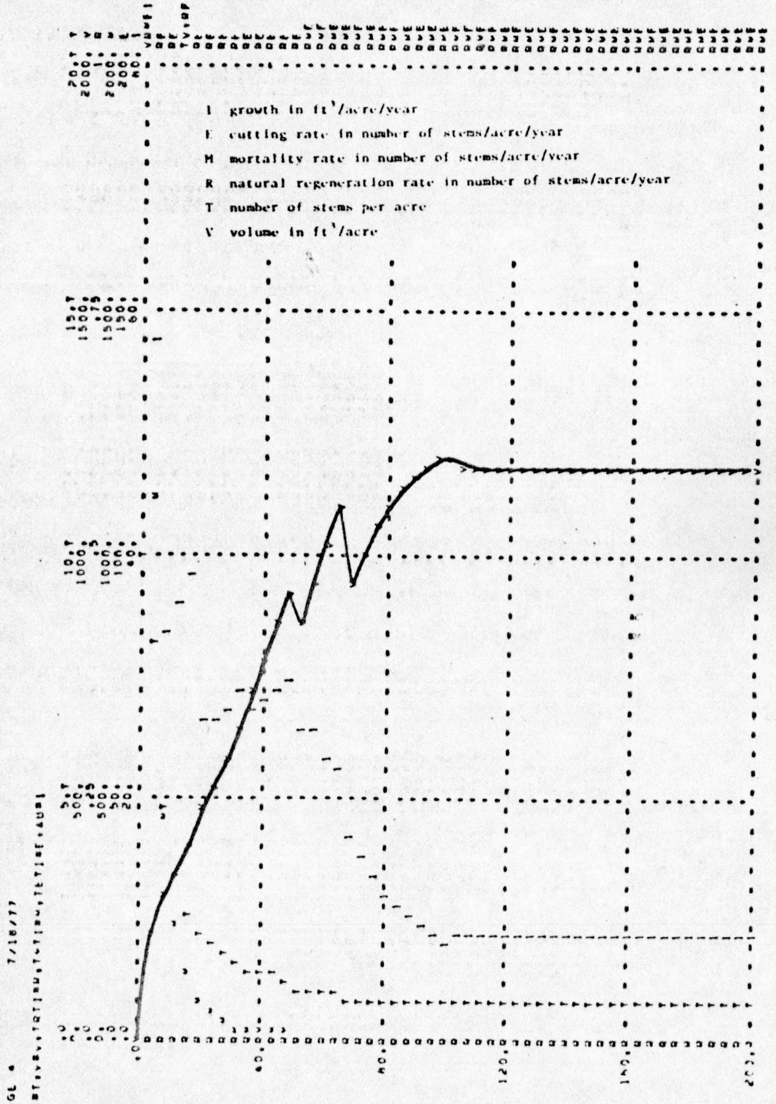

Figure 18: Simulation of stand development with a combined fertilizing and thinning program

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TIME E+00	TI E+03	V E+00	VA E+00	TMTI E+00	TETI E+00	AB E+00	MAR E+00	TRTI E+00	TE E+00	FA E+00
.0	10,000	.0	,0000	.4	.00	,000	,0000	0.	,00	,0000
5.	7,116	263,7	,0371	978,3	,00	48,939	,0000	0.	,00	1,0000
10.	3,978	301,2	,0757	303,5	,00	42,477	,0000	0.	,00	1,5000
15.	2,811	385,4	,1371	148,1	,00	37,651	,0000	0.	,00	1,5000
20.	2,219	487,4	,2197	83,5	,00	26,726	,0000	0.	,00	1,0000
25.	1,876	542,1	,2889	51,2	,00	26,625	,0000	0.	,00	1,0000
30.	1,661	613,1	,3690	32,8	,00	28,058	,0000	0.	,00	1,0000
35.	1,516	699,4	,4613	25,3	,00	27,498	,0000	0.	,00	1,0000
40.	1,400	780,9	,5578	19,9	,00	27,601	,0000	0.	,00	1,0000
45.	1,311	869,6	,6635	14,7	,00	28,956	,0000	0.	,00	1,0000
50.	1,246	969,8	,7783	10,5	200,00	29,147	,0000	0.	155,66	1,0000
55.	1,017	917,9	,9024	3,5	,00	25,753	,0000	0.	,00	1,0000
60.	1,001	1025,8	1,0250	3,0	,00	23,575	,0000	0.	,00	1,0000
65.	,986	1124,2	1,1397	2,7	200,00	21,552	,0000	0.	227,94	1,0000
70.	,778	974,7	1,2523	1,3	,00	16,022	,0000	0.	,00	1,0000
75.	,772	1041,8	1,3499	1,3	,00	13,933	,0000	0.	,00	1,0000
80.	,765	1098,0	1,4353	1,5	,00	12,119	,0000	0.	,00	1,0000
85.	,757	1142,7	1,5104	2,0	,00	10,702	,0000	0.	,00	1,0000
90.	,746	1176,8	1,5775	2,3	,00	9,756	,0000	0.	,00	1,0000
95.	,733	1201,8	1,6400	3,4	,00	9,007	,0000	0.	,00	1,0000
100.	,709	1207,5	1,7021	8,0	,00	8,314	6,4096	0.	,00	1,0000
105.	,711	1185,0	1,6661	4,4	,00	8,664	4,5466	0.	,00	1,0000
110.	,711	1186,4	1,6680	4,5	,00	8,640	4,4741	0.	,00	1,0000
115.	,711	1186,9	1,6688	4,6	,00	8,634	4,5489	0.	,00	1,0000
120.	,711	1187,0	1,6690	4,6	,00	8,633	4,5607	0.	,00	1,0000
125.	,711	1187,0	1,6690	4,6	,00	8,633	4,5620	0.	,00	1,0000
130.	,711	1187,0	1,6690	4,6	,00	8,633	4,5621	0.	,00	1,0000
135.	,711	1187,0	1,6690	4,6	,00	8,633	4,5621	0.	,00	1,0000
140.	,711	1187,0	1,6690	4,6	,00	8,633	4,5621	0.	,00	1,0000
145.	,711	1187,0	1,6690	4,6	,00	8,633	4,5621	0.	,00	1,0000
150.	,711	1187,0	1,6690	4,6	,00	8,633	4,5621	0.	,00	1,0000
155.	,711	1187,0	1,6690	4,6	,00	8,633	4,5671	0.	,00	1,0000
160.	,711	1187,0	1,6690	4,6	,00	8,633	4,5621	0.	,00	1,0000
165.	,711	1187,0	1,6690	4,6	,00	8,633	4,5621	0.	,00	1,0000
170.	,711	1187,0	1,6690	4,6	,00	8,633	4,5621	0.	,00	1,0000
175.	,711	1187,0	1,6690	4,6	,00	8,633	4,5621	0.	,00	1,0000
180.	,711	1187,0	1,6690	4,6	,00	8,633	4,5621	0.	,00	1,0000
185.	,711	1187,0	1,6690	4,6	,00	8,633	4,5621	0.	,00	1,0000
190.	,711	1187,0	1,6690	4,6	,00	8,633	4,5621	0.	,00	1,0000
195.	,711	1187,0	1,6690	4,6	,00	8,633	4,5621	0.	,00	1,0000
200.	,711	1187,0	1,6690	4,6	,00	8,633	4,5621	0.	,00	1,0000

Table 7: Simulation of stand development with a combined fertilizing and thinning program

sharp focus by the DYPEUFOR global systems approach, and the considerable amount of research which remains to be done in order to throw light on this factor cannot be overemphasized.

Notwithstanding the lack of mortality data, the model's potential was tested using a number of scenarios. For the time being results are dependent on hypothetical values which may not completely reflect reality. It nevertheless remains true that DYPEUFOR is a valuable tool which could provide valuable information leading to sound forest management as soon as accurate and complete information on mortality is available. The determination by iteration of optimum combinations of duration, intensity and type of silvicultural treatments appears as one of the most promising applications of the model. A number of preliminary conclusions regarding fertilization and thinning have already been obtained in the course of this study. Furthermore, the interplay of 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 obtain an overview of the effects of any disturbance to the forest stand dynamics.

Finally, this model designed to permit a large degree of flexibility, enables us to gain a better understanding of the current state of forestry knowledge.

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