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Wood resource dynamics in the Scandinavian forestry sector

Virkesbalansens dynamik i den skandinaviska skogsnäringen

Edited by

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Abstract

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The Scandinavian forestry sector is facing a major challenge. After a century of rapid growth—both in forestry and the forest products industry—the sector is approaching a situation where rapid growth will no longer be possible simply because most of the annual forest growth is already being utilized. One may choose to let the forces of the free market shape the transition from rapid growth to moderate growth. *Or one may choose to pursue policies that are intended to improve the transition in one way or another.*

Wood Resource Dynamics *(i.e. this volume) describes the historical background for the current situation, both concerning the supply of and demand for wood and concerning existing legislation and management practises. The volume further describes the problems caused by slow growth in the forestry sector, and a discussion of the various policies that can be conceived to soften these problems.*

A system dynamics simulation model was developed to elucidate the likely future effects of the various policies. The volume proceeds to illustrate how this computer simulation model of the Scandinavian forestry sector can be used in discussions of long term policy for the forestry sector. The general applicability of the simulation model is being demonstrated by adapting the model to the case of Finland.

Finally, Wood Resource Dynamics *gives a short introduction to the system dynamics method for model building by presenting two applications to concrete, short term problems in the forestry sector—pulp inventory control and forest stand management.*

In this publication "forestry sector" refers to both forestry and the forest products industry.

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by Kjell Kalgraf

6.1 **Introduction**

This paper contains a description of a simulation model, which can reproduce the development over a period of time of certain main parameters in a forest stand, namely, volumetric density (m^3/ha) in respect of the standing volume, tree density (number of trees per hectare), the annual natural regeneration (number of trees per hectare per year), the annual natural thinning in respect of trees (number of trees per hectare per year) and of volume (m^3/ha per year). The model has been conceived to test the dynamic effects on volumetric density and the mean tree dimension (m^3/tree) of activities such as thinning, fertilization, spraying and ditching.

The cause-and-effect relationships in a stand have been captured in a system-dynamics model in which the forest is seen as a feedback-loop system. Increment is seen as a cumulative process that is determined by the state of the stand and governed by the volumetric density and tree density. As in a real stand the model generates the development over a period of time in an untreated stand by internal mechanisms in the system. When the stand is subjected to activities emanating from outside the stand, the development will be different. The relationship between such activities and development in the stand is studied in simulation experiments, whereby a computer is used to solve the set of simultaneous differential equations that determine the development of the system. When presented in graphical form, the simple cause-and-effect structure is able to serve as an aid to communication between professionals and laymen in matters pertaining to forestry.

System-dynamics symbols

The variable for the state or stocking of a stand, e.g. the standing volume of wood per unit area, is denoted by means of rectangular symbols □. Flows that produce a change in the state of the stand, e.g. increment, are denoted by arrows →. The mechanism that regulates the flow is denoted by the symbol ▭⋈. Flows to or from the surroundings are denoted by arrows that terminate in a cloud-like symbol ☁← where the cloud represents a source or a termination. A flow of information is denoted by a broken arrow ⇢. Auxiliary variables are denoted by means of circles ○, and constants by means of small circles bisected by a short, straight line –⊖–.

6.2 **The state of a stand**

The state of a stand can be described comparatively well by means of two variables: the commonest used are volumetric density and age, with age being related to the tree dimension. When the volumetric density and age are known, increment and natural thinning can be determined. Regeneration depends on the supply of seed, which may come from the stand itself or from neighbouring stands, and on the germinability of seed which depends mainly on volumetric density.

The processes of growth, natural thinning and regeneration change the state of a stand in such a way that during the next rotation these processes will be of a different magnitude. Thus, the system is a self-regulating one, in which the state of the forest determines a number of processes which, in turn, affect the state of the forest.

The basic concepts used in the model are as follows:

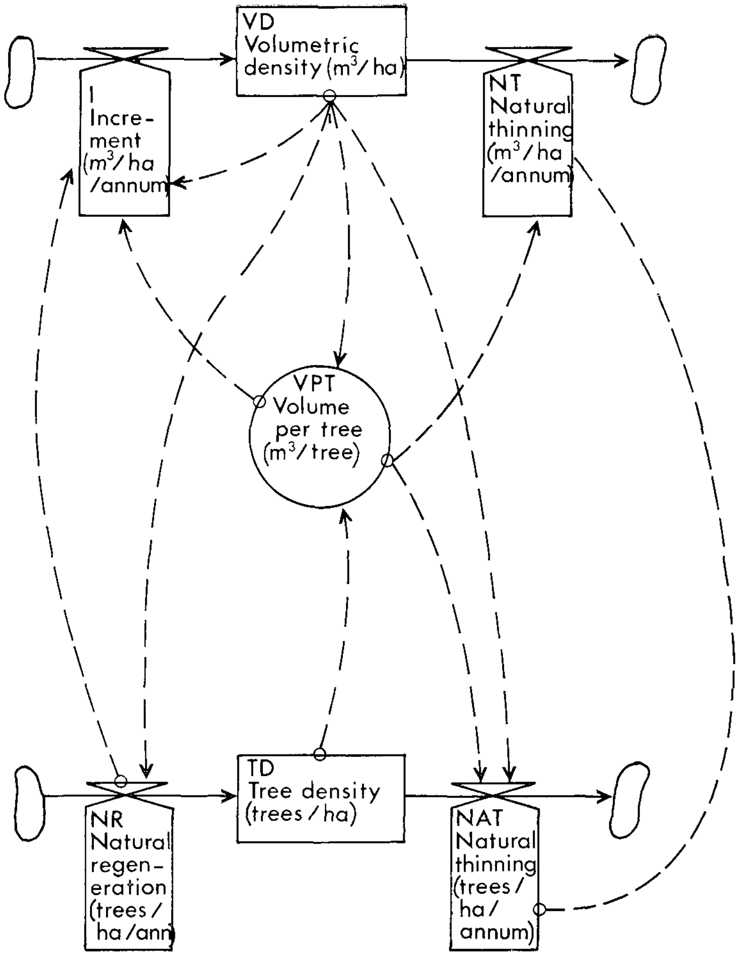

Figure 22. A schematic presentation of the interaction between volumetric density, tree density, natural regeneration, increment and natural thinning.

Volumetric density—which refers to the volume of all stemwood inside bark per unit area, expressed in m^3/ha.

Tree density—which refers to the number of trees per unit area, expressed in trees/ha.

Increment—which is the annual increase in volume inside bark of stemwood per unit area, expressed in m^3/ha per year.

Natural thinning—which is equivalent to the number of trees that die per unit area during a year, expressed in trees/ha per year.

Natural regeneration—which refers to the number of new trees per unit area appearing in a given year, having sprouted from seeds released in the stand itself or in neighbouring stands, expressed in trees/ha per year.

Thinning—which is the human activity involving the removal during a year of a given number of trees per unit area, expressed in (extracted) trees/ha per year.

Final felling—which refers to the felling of all remaining trees in a given area, with the possible exception of a number of seed trees, expressed in (extracted) trees/ha per year.

Of the above, volumetric density and tree density are variables describing the state of the stand. A broad outline of the relationships between the variables is presented in figure 22. As may be seen in the figure, volumetric density increases as a result of growth and decreases as a result of natural thinning. The tree density increases as a result of natural regeneration and decreases as a result of natural thinning. The extent to which increment, natural thinning and natural regeneration are in turn dependent on the state of the stand is indicated by the dashed information lines. Increment is dependent on regeneration (the additional volume contained in new seedlings each year), on volumetric density and on the volume per tree[1] (growth in respect of trees already established in the area). The effect of volume per tree reflects the effect of age on increment. Natural thinning is also dependent on volume density and volume per tree.[2] In the case of trees dying as a result of natural thinning, these create a loss of volume in the stand, which is dependent on the number of such trees and the volume per tree (which volume has a certain correlation with the average volume per tree in the stand). Natural regeneration is primarily dependent on the volumetric density of the stand, i.e. the germinability of new seed depends mainly on density, in so far as we assume that there is an abundant supply of seed that is largely determined by conditions outside the stand itself. The volume in the form of new shoots is small and only significant during the actual regeneration cycle, since it represents the initial volume in the cumulative process that builds up the standing volume.

In figure 22 several closed cause-and-effect chains can be distinguished:

- Volumetric density influences growth, which, in turn, influences volumetric density.
- Volumetric density influences volume per tree (age), which influences growth, which, in turn, influences volumetric density.
- Volumetric density influences natural thinning of trees, which influences the natural thinning volume, which, in turn, influences volumetric density.
- Volumetric density influences volume per tree (age), which influences natural thinning of trees, which influences the natural thinning volume, which, in turn, influences volumetric density.
- Tree density influences volume per tree (age), which influences natural thinning of trees, which, in turn, influences tree density.
- Tree density influences volume per tree (age), which influences growth, which influences volumetric density, which influences natural thinning of trees, which, in turn, influences tree density.
- Tree density influences volume per tree (age), which influences growth, which influences volumetric density, which influences natural regeneration, which, in turn, influences tree density.

A more detailed description of the way in which these feedback loops function in the model is presented in figure 23.

6.3 **Increment as expressed in the model**

Figure 23 will not be dealt with in depth,[3] but let us consider the concrete expression of increment. In the model increment (I) is the aggregate value of the number of trees (TD) multiplied by the increment per tree (IPT), plus the natural regeneration (NR) multiplied by the volume per seed (VS), plus the newly planted seedlings multiplied by the volume per seedling; thus

$$I = TD \times IPT + NR \times VS + P \times VP$$

Natural regeneration and planting are only relevant during the regeneration cycle. The increment per tree (IPT) is equivalent to the volume per tree (VPT) multiplied by the increment percentage (PI), i.e. $IPT = VPT \times PI$. The volume per tree is the relationship between volumetric density (VD)

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[1] Delbeck, K. 1965: Metoder for tilvekstberegninger i glissen skog. Melding fra Institutt for skogtaksasjon nr. 2—4, s. 5—47, Ås—NLH.

[2] Brantseg, A. 1961: Skogbestandets pleie. Skogbruksboka bind II, s. 355—384, Oslo.

[3] Readers interested in greater detail are referred to: Dynamikk i et Skogbestand, GRS 23, Gruppen for Ressursstudier, Oslo, 1975.

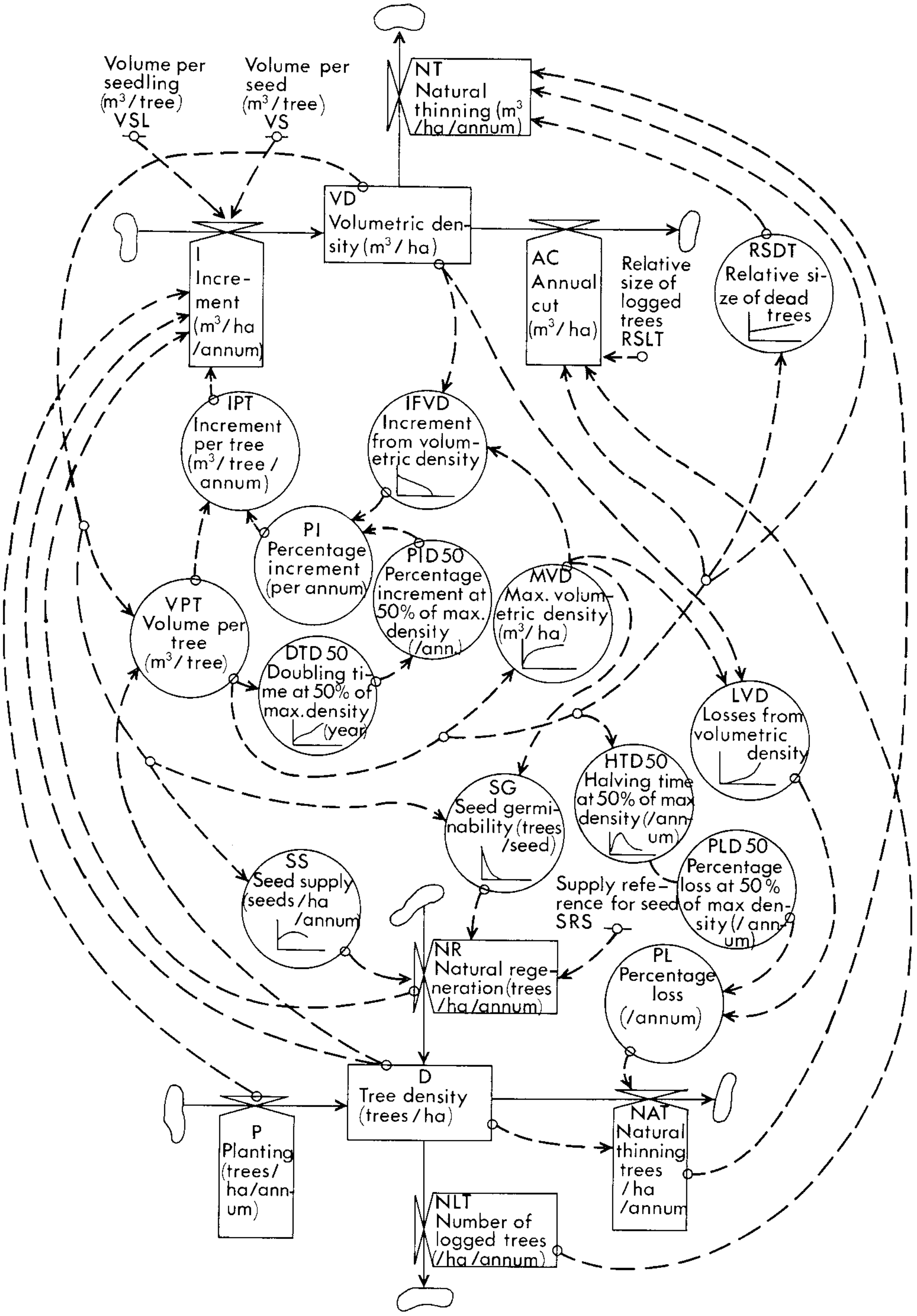

Figure 23. The DYNAMO flow chart for the forest increment model.

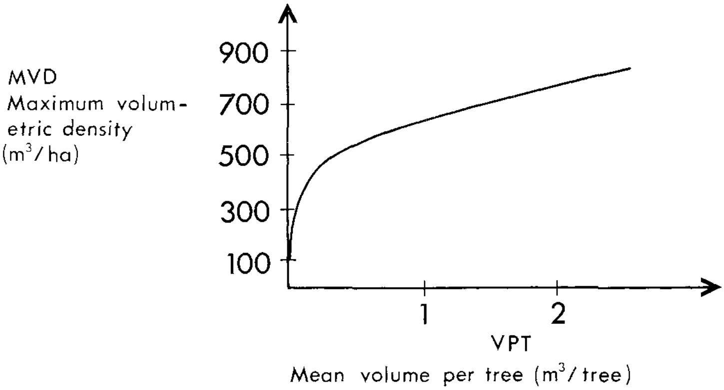

Figure 24. Assumed relationship between mean volume per tree and maximum volumetric density. (The figure is based on the graph published by A. Jørgensen Hope, Taksering av Sølvverksskogene 1931, together with the assumption that each tree requires an area equivalent to ten times that of its diameter in order to survive.)

and tree density (TD), i.e. VPT = VD/TD. The increment percentage is dependent on the volumetric density and the volume per tree (age). This relationship is roughly equivalent to a multiplicative expression of the interdependence of the effects of volumetric density and volume per tree, i.e. PI = PID50 × IFVD. The age effect is derived from the increment percentage at 50 % of the maximum volumetric density (PID50), which decreases monotonically as age increases. The effect of volumetric density is derived from the increment percentage from volumetric density (IFVD), which also decreases monotonically as the volumetric density increases in relation to the maximum volumetric density in respect of the mean tree dimension that applies at a given time. The maximum volumetric density is equivalent to the density when increment is nil and which, characteristically, is greater in the case of large trees than in the case of small trees. Small shoots, for instance, will never be able to attain a volumetric density of 100 m^3/ha, regardless of how tight the seedling spacing is, although this volumetric density is easily reached naturally in sparse stands containing more-mature trees. The existence of a maximum volumetric density can be proved theoretically, although the density will be dependent on the height curve for the stand in question (the correlation between mean diameter and mean height). The curve in figure 24 is based on a special height curve and should therefore only be regarded as an approximation.

The increment percentage at maximum volumetric density will be nil. In reality stands can never achieve this particular density, since natural thinning increases sharply as the density approaches the maximum limit, with growth and natural thinning becoming balanced a good way below maximum volumetric density, as a result of which the density ceases to increase. Thus, to obtain a reference curve for increment percentage, we take one half of the maximum volumetric density as our point of departure. Thus, in practice the increment percentage can be determined by means of measurement in a stand with a density equivalent to half the maximum volumetric density. In the case of small trees, the increment percentage is considerable (100 % or more per annum) but falls sharply as the volume per tree increases. It seemed expedient, therefore, to work with a doubling time at 50 % of the maximum volumetric density, rather than with the increment percentage. The correlation between the two is:

Doubling time = (ln 2)/increment percentage, or

^{e}(Doubling time × increment percentage) = 2

(e = 2.71828 . . .)

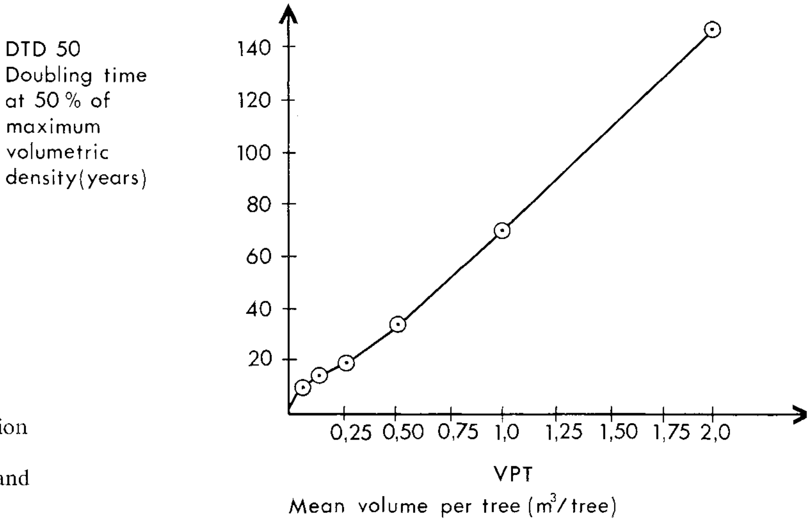

Figure 25. The assumed correlation between mean volume per tree and doubling time.

The doubling time is the time required for the volume per tree to double itself at a constant increment percentage. The course described by the doubling time is shown in figure 25.

The doubling time is extremely short in the case of small trees (high increment percentage) and increases rapidly (the increment percentage decreases rapidly). In the case of larger trees, the doubling time increases relatively evenly, i.e. the increment percentage decreases evenly. In an average, well-treated stand the volume per tree lies between nil and 0.5 m^3/tree, whereas in natural stands the volume per tree may be greater. The curve in figure 25 is partially based on data from real stands (in the normal area) and partially on estimates. The other effect of increment percentage stems from volumetric density. It is not the absolute value of volumetric density that is of importance but whether or not the volumetric density is large or small in relation to the maximum volumetric density for a given average tree dimension. As the volumetric density approaches the maximum, competition will become great and the increment percentage will fall towards nil. Conversely, when the volumetric density is low, competition will be less intensive and the increment percentage will increase. Generally speaking, the volumetric density in a stand will be around 50 % of the maximum value. The curve in figure 26 should be regarded as an approximation of the relationship between increment percentage and volumetric density. Measurements made in stands indicate that the curve in respect of normal values in the stands will be such that a 10 % reduction in the volumetric density will create an 8 % increase in the increment percentage.[4]

The dynamic effect of the correlation in figure 26 is that the system tends to keep the volumetric density at the reasonable level in comparison with the maximum density of the tree dimension concerned. Since the trees are growing, the maximum volumetric density will also increase and variations in volumetric density/maximum volumetric density will be small. In actuality it is the age effect that manifests itself and determines the increment percentage, unless of course drastic changes in the volumetric density/maximum volumetric density are effected by silvicultural operations such as thinning.

[4] Eide og Langsaeter, 1941: Produksjonsundersøkelser i østnorsk granskog. Meddelelser fra det norske skogforsøksvesen 7, s. 355—500, Ås—NLH.

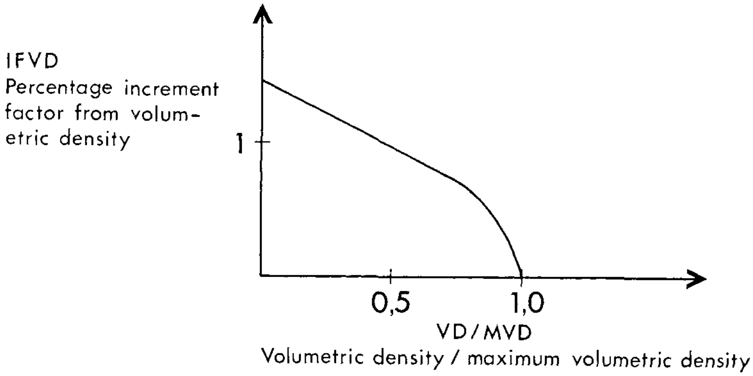

Figure 26. Assumed correlation between volumetric density and increment percentage.

6.4 Other mechanisms in the model

Variables influencing increment also influence *natural thinning*. As far as *natural regeneration* is concerned, the supply of seed is governed to a large extent by neighbouring stands, whereas the viability of seeds will depend on the volumetric density/maximum volumetric density.[5] This means that regeneration will cease at comparatively low volumetric densities in new stands, since the maximum volumetric density will be low; on the other hand, regeneration in older stands may occur when the volumetric density is much greater, because the volume will then be concentrated to fewer and larger trees, with the result that new trees will have more room to grow between the old ones.

Checking of the dynamic development in the model is achieved by comparing the increment from the model with that determined by an increment formula.[6] The formula is based on data derived from stands of between 20 and 100 years old and may be written as follows:

$$I = \sqrt{TD} * 10^{-0,915 - 0,00113 * TD + (60,8)/(A + 50)} * e^{-60/VD}$$

where

I = increment (m^3/ha per annum)
TD = tree density (trees/ha)
A = age (years)
VD = volumetric density (m^3/ha) and
e = 2.71828.

When the model is run in the computer values will be obtained for TD and VD. If, at the start of the run, the trees are very young, the value of A can be selected to correspond to the time elapsing during the simulation, enabling current values of I to be calculated and then compared with the increment produced by the model. In the runs described in the following pages, the value of I and the increment produced by the model are shown. The two runs described were selected at random in order to illustrate the properties of the model.

Since there is a wide variety of increment formulae, it is difficult to find objective criteria for choosing between them. Nonetheless, we decided that it would be expedient to conduct the comparison using one of these increment formulae. An alternative method would have been to compare the results from the model with measurements made in a stand.

6.5 Model runs

The results of system dynamics runs are usually presented in the form of graphs, with time being plotted along one axis and the dimensions that are of interest plotted

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[5] Haugberg, M. 1962: Grunnlaget for skogens naturlig foryngelse. Skogbruksboka bind II, s. 143—157, Oslo.

[6] Andersson, S.-O. och Stålhandske, S.-I. 1974: Volymtillväxtfunktionen för tall i norra Sverige. Stencil Institutionen för skogsskötsel, Skogshögskolan.

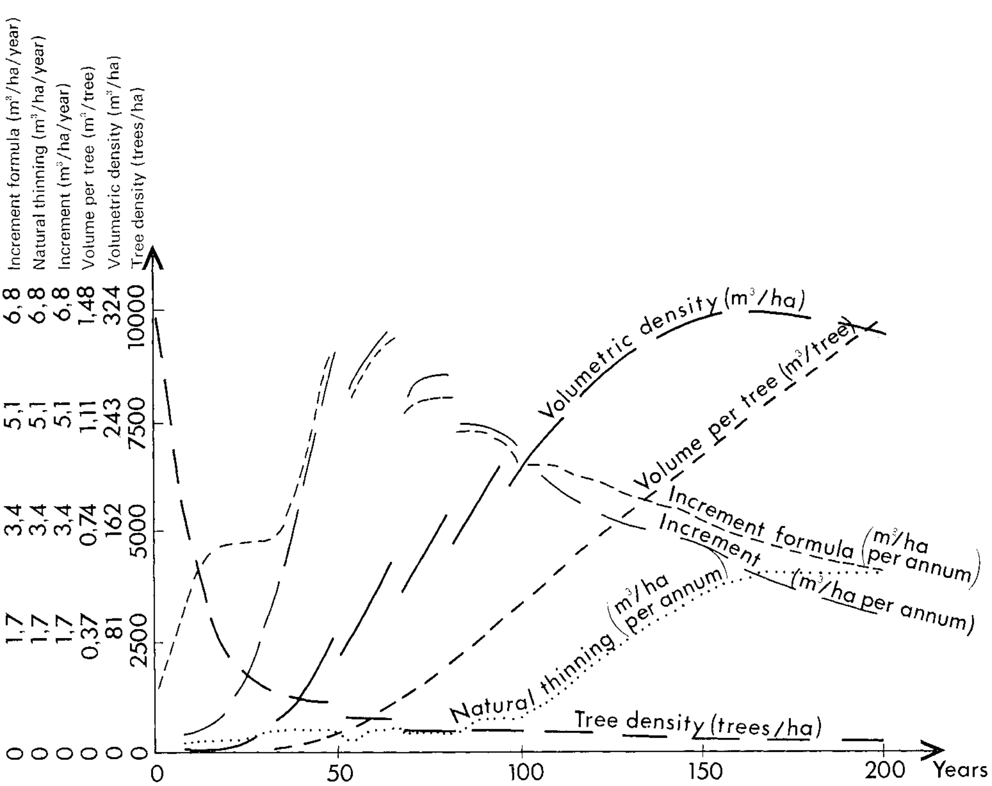

Figure 27. Thinning experiment.

along the other. One can choose which model dimensions should be plotted and can easily change them between runs. We have elected to plot volumetric density, tree density, volume per tree, increment and natural thinning, and also an auxiliary magnitude of increment derived from the increment formula in order to provide a gauge of the feasibility of the model development. We will deal with two model runs, one in which four thinnings are carried out and one in which we allow the stand to develop without the occurrence of events like windthrows and fires, until the stand matures into what may be called a forest in natural equilibrium.

6.6 The model stand with four thinnings

We start with a young stand with a volumetric density of 1 m^3/ha and with 10,000 trees/ha. Thinnings are carried out at age 50, 65, 80 and 95 years, with 300, 200, 100 and 50 trees/ha, respectively, being removed in a short period of time, and where the volume of the thinned trees corresponds to the average volume per tree in the stand. The results are presented in figure 27.

At age 50, the tree density falls rapidly towards 1250 trees/ha, whereas the volumetric density increases to 90 m^3/ha. Numerous weak trees (below the average size for the stand) will therefore be suppressed while the remaining trees will grow vigorously. Increment will increase sharply from an insignificant level to a level of about 6 m^3/ha per annum at about age 50.

The outcome of the first thinning will be a reduction in standing volume and tree density. Since the trees removed will be average-sized (although other assumptions can be tested), the volume per tree will not be affected. Increment, on the other hand,

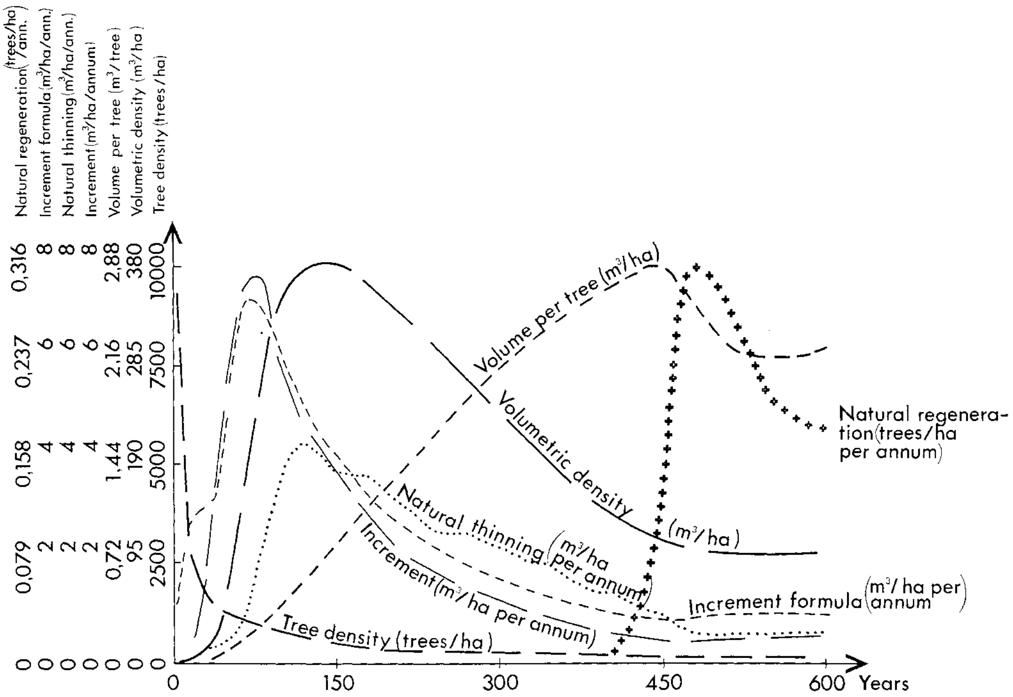

Figure 28. Development into natural forest.

will fall, even if the increment percentage rises owing to the reduction in volumetric density. This effect is normal. An increase in volumetric density implies an increase in increment within the normal range of variation in respect of volumetric density, even if the increase is of a slightly lower magnitude because of the fall in the increment percentage. Only when the volumetric density reaches considerable proportions will this relationship be reversed.

Subsequent thinnings will produce a corresponding effect: the volume will become concentrated to fewer and larger trees. After thinning, the increment percentage will rise, although, in time, when the trees have grown, the increment percentage will fall because of the age factor, while the mean volume per tree will increase slightly as if no thinning had been carried out. Thus, the standing volume in thinned stands will never obtain the same maximum value compared with that in unthinned stands.

There is relatively good agreement between the increment computed in the model and that derived from the increment formula; this is partly attributable to the fact that a deliberate effort was made to maintain consistency in the parameterization of the model. This is especially true of areas for which there are no known data. Consequently, the observed consistency merely demonstrates that paramaterization of the model is possible such that the model and increment formula will follow approximately the same development over a period of time. It is quite possible that the parameters used are not entirely reasonable in some areas compared with the situation in reality, but this can only be determined if the parameters are compared with data collected in an existing stand.

6.7 Model stands developing into natural forest

In this case we assume that no silvicultural activities will be carried out and that there will be no exogenous occurrences such as fires, windthrow, etc. The model commences with a volumetric density of 1 m^3/ha and 10,000 trees per hectare. The results are presented in figure 28.

Volumetric density will culminate after 130 years. By this time the trees will have grown so large that natural thinning will outstrip increment. The volumetric density will continue to fall because the trees will grow even larger. Finally, the forest will become so sparse that natural regeneration will start to occur, leading to a reduction in the mean volume per tree because of the small volume of the new trees. In time the forest will attain a balance in respect of increment, characterized by a relatively low volumetric density, and relatively few, albeit large, trees—a seemingly reasonable situation.[7]

6.8 **Comments**

A model of the type shown here is ideally suited as an instrument of communication. For example, the model could well be employed in training, in order to illustrate the important relationships existing in a stand. Moreover, the model should be suitable for use in talks between forestry experts on the one hand and laymen on the other.

It is possible to achieve quantitative accuracy with this type of model. However, if the numerical values are to be reliable, a considerable amount of work must be laid down on the determination of the model parameters in respect of given tree species and site quality indices. The model could then also be used to estimate quantitative changes resulting from given activities.

A clear limitation of the model is its ability to deal with simple stands only. Consequently, the evaluation of consequences in respect of larger forest estates is beyond the scope of the field of application of the model. Thus, the model is not suitable for determining the economic consequences in respect of larger forest estates, although obviously it could be coupled with a structure designed to calculate the economic consequences for a stand.

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[7] Huse, S. 1965: Strukturformer hos urskogsbestand i Øver Pasvik. Meddelelser fra Norges landbrukshøgskole, Vol. 44, nr 31.

Summary

"Forestry in Sweden during the industrial age" outlines the historical background to the situation facing the Swedish forestry sector at the beginning of the 1970s, namely, an imbalance between the supply of forest resources and the expansion of the forest products industry. A similar situation is also to be found in Finland and Norway.

"Transition strategies for the Scandinavian forestry sector" provides an account of the problems facing the forestry sectors in Finland, Norway and Sweden in the transition from a period of rapid growth to one of modest growth. With reference to a simulation model that has been constructed according to the method of system dynamics, the paper also describes some conceivable alternative courses of action for the sector and presents a synopsis of some tendencies that should be taken into account by the strategic planners.

"The transition from ample to scarce wood resources" demonstrates how the ability of the simulation model can be used in practice in a policy discussion. The paper describes a hypothetical discussion between representatives of the main groups affected by the transition. Accordingly, the parts include a director of a forest enterprise, an "ombudsman" or spokesman for the employees, a private woodlot owner and a member of parliament. The views put forward by the representatives help to promote knowledge and understanding of the transition problems.

"The SOS (Society and Forestry) model and the Finnish forestry sector" discusses the possibilities of using the SOS model to study the consequences for the Finnish forestry sector of constraints imposed by the supply of wood resources. To provide the necessary background, an account of the development of the Finnish forestry sector since 1945 is also included. There is an account of the reparameterization work and of the subsequent simulation run. Finally, a number of conditions that might be peculiar to the Finnish forestry sector when compared with the structure of the SOS model are discussed. The conclusion to be drawn is that the model structure is apparently of a sufficiently general nature for the model to be used in studies on the consequences of constraints on the supply of forest resources in the forestry sector of any individual Scandinavian country.

The last two papers provide examples of the system dynamics method. In addition, *"Stock fluctuations in the pulp industry"* serves as a complement to the long-term-oriented SOS model in that the article presents a system dynamics model of the production in Norway of bleached sulphite pulp and short term fluctuations in stock levels.

"The dynamics of a simple stand" describes the way in which i forest stand can be represented by means of system dynamics. The purpose is to show how a system dynamics model is constructed and how it functions.