Simulation of Forest Development

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Simulation of Forest Development

Presentations from a symposium held in Saariselkä, Finland, October 12-14, 1991

Hannu Salminen & Tuija Katermaa
Editors

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The symposium "Simulation of forest development" studied different aspects of biological modelling and computing. Present articles deal with traditional growth and yield studies, process-based ecophysiological simulation, carbon balance and carbon allocation, and soil acidification models. In addition, systems analysis modelling, information systems methodology, object-oriented modelling, and massively parallel computing are introduced as new approaches to simulation of complex domains. No general agreement of how to describe and model forest system were achieved, although increasing technical facilities for building complex systems will narrow the gap between different simulation approaches.

Key words: simulation, forest development, carbon balance, acidification, growth and yield, object-oriented, parallel computing.

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Contents

Preface

The symposium "Simulation of forest development" brought together Finnish modellers of forest processes from various disciplines. The goal of the symposium was exchange of ideas on modelling tree and forest stand development and to explore the possibilities of using the methods of information systems science in it. Different aspects of simulation and modelling were covered in 12 presentations, 4 workshop sessions, and a general discussions.

The four workshop sessions concentrated on the needs for a simulation system. Each group had to study the problem from a different perspective.

Group A discussed the needs of forest management planning and forestry practice imposed on simulation models. They mentioned several models which should be included in a simulation system. New models to be built deal with, for instance, the early development of trees, birth, death, peatland growth and yield, forests in Northern Finland, and multiple-use forests (parks, recreation areas etc.). Better models for describing the technical quality of stems are needed. It should also be possible to make the estimation of stem distribution tables more accurate by means of additional local measurements. Furthermore, all models should also be logical outside their normal application area. From the practicing forester's point of view, the models should also be as user-friendly as possible.

Group B presented the needs of system developers and growth modellers. According to them, to develop a system, both the need and the purpose for it must exist. Further, to facilitate communication among modellers and with the users of the system, common terminology and concepts have to be defined. This could be assisted by the formation of a common forestry repository.

Once the need has been recognized, tools and data are necessary to build a system. Lack of reliable component models is an obstacle to the development of simulation systems. It is difficult to judge the usefulness of models coming from different sources and representing different traditions of modelling. Agreed general guidelines to test models would increase their usefulness as components of a simulation system.

Group C covered some needs of forest health monitoring studies. Health studies diagnose disturbances and deviations in the development of forests. They concetrate on finding the causal relations and making risk assessments. In addition to stand models, robust tree-based models with 24-hour time intervals are needed. Especially in entomology, object-oriented modelling is to be preferred.

Group D defined the needs of ecological research and process-modellers in three paragraphs, which clarified the relations between traditional growth and yield and ecophysiological process-based studies. The group stated their mistrust in a universal simulation system meeting everybody's needs, because different models are built for solving different problems. Such a universal approach also necessitates a high level of standardization

and that, in turn, presupposes a good knowledge of the phenomenon under study. Furthermore, group D did not think that carbon balance models will be usable in forest management planning in the near future, since they produce mere relative rather than absolute figures. Process-based modellers offer qualitative forecasts for planning of field experiments, overall shapes for growth and yield models, and rugged versions of process models (long-term trends, essential factors affecting growth, rules of thumb e.g. the 3/2-square-law). Ecological research does need some information from growth and yield research; proper development series including different components of trees, leaf-area-indices and natural losses. These series should preferably begin from the year 0. In addition, process models need calibration data from long term field experiments and from very old field experiments.

In past decades, there has been a serious gap between traditional growth and yield modellers and process modellers. The growing need for more accurate and flexible models, and the availability of better tools and methodologies for constructing complex systems and processing large data sets, will lead to better co-operation between researchers representing different traditions of modelling.

Mr Risto Sievänen originally presented the idea for holding this symposium. He developed it further with Dr Hannu Saarenmaa and Mr Hannu Salminen. The symposium was funded by The Finnish Academy and organized by Mr Hannu Salminen at the Rovaniemi Research Station of the Finnish Forest Research Institute. Mr Martti Varmola, an experienced organizer, gave valuable advice. Mrs Helena Poikajärvi and Mr Jouni Hyvärinen took care of the practical matters. Mr Juha Huhtala and Mr Eero Siivola helped with technical arrangements.

The lay-out was designed and the reports were made up by Ms Tuija Katermaa, who also assisted in the editing work. My sincerest appreciation to all mentioned.

Nine out of the invited twelve speakers delivered their report also in the written form. In addition, two other reports were contributed; one from the opening session (page 7) and one without a presentation in symposium (page 49).

Rovaniemi, March 31, 1992

Hannu Salminen

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Growth and yield models in simulation: Some historical perspectives

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Modelling paradigms

Predictions of future forest growth have traditionally been based on past growth. Historical bioassay models (HB) are constructed from field measurements with statistical methods. This is probably the best approach to yield prediction if the future growing conditions are the same as those of the past and time span is moderately short. The record of past growth integrates the effects of all the factors that have influenced the trees on the site over the entire rotation. Growing conditions are summarized in the site index and in some climate indicators (temperature sum etc.). If fertilization and draining are excluded, the physical environment may be assumed to be constant. A model selection criterion is the goodness of fit of the model to the data. A primary interest is stand development with time. Since the early 1970's, new approaches have emerged. One way to increase the explanatory power of the model is to base it, instead of property-time, on property-property relations. Different kinds of interdependencies (competition-density, self-thinning, height-diameter etc.) offer more knowledge on which to base predictions (Leary 1988).

Assmann (1970) concluded that forest yield should be predicted by explanatory models showing how the process influencing determinants of forest growth will change in the future, instead of using past tree growth. Since then, several process-based growth models have been constructed. The importance of these approaches becomes emphasized in a situation where environmental changes, especially man-caused, are more rapid than ever.

The difficulty in constructing process-based forest growth models is in how to choose proper level of detailness. If a model is too simple to account for all the significant factors, it is inflexible, while choosing too complicated model components will lead to extremely complex systems, which then are difficult to apply in practice. It is also possible that the chosen factors fail to account for all major growth determinants that may change in the future, and the model is as short-lived as HB-models (Leary 1988).

In theory, process models can be applied to forecast growth and yield under different future conditions. Lack of adequate calibration data, poor understanding of how to build a complex and flexible information system, and limited computing facilities have prevented process models from being accepted as tools for forest management planning. All of these constraints can be more or less overcome, although there is still some essential knowledge yet to be discovered, especially in below-ground processes.

Using growth and yield models in simulation

The development of forest stands consists of many concurrent processes. Combining development algorithms and programs with real or artificially generated data in a computer system (i.e. simulation) is useful in managing complex systems. It is also possible to make experiments and test theories as well as predict forest development far to the future in simulated forests. Simulation of forest development has usually been based on either statistical or process models.

According to Kimmins et al. (1988), the hybrid simulation approach involves combining HB and process simulation approaches and uses the major strength of each approach to compensate for the major shortcoming of the other. FORCYTE-11 simulation system uses HB-models to forecast growth in stable conditions and process models to predict the effect of future environmental changes and to modify the results of the HB-models.

In FORCYTE-11, both model-types (HB and process) are in different modules. If "data structures" in a simulation system are imitated from nature, it is possible to apply a wide range of development models at the same time and in the same system in at least three ways: in basic growing actions, as controllers monitoring each other in parallel use, or in combination (e.g. feeding parameters to each other). Flexibility for the system could be achieved through object oriented approach.

Future directions

A vast amount of different kind of growth and yield models has been constructed during the past decades. Each of them has more or less knowledge built in to it. The use of these models can be supported with large data sets and remote monitoring systems. In theory, all data, knowledge and information we have should be always available for decision making and research. On of the "bottle-necks" of intelligent forecasting and planning systems seems to be the integration of knowledge representing different levels and coming from different sources.

Computers offer such an integration platform, and information system science has methodologies and tools for representing complex systems.

The questions to be asked include; What is the domain we are interested in? What are the 'things' (objects, entities etc.) in it? What are the attributes and behaviour/functions of the 'things'? and What are their relations to each other? (Shlaer & Mellor 1989).

Managing complex systems requires formal, well defined approaches. Jeffers (1978) introduced systems analysis as a research strategy for ecological sciences. Lately, general paradigms of artificial intelligence and information systems has been adapted into forest research (e.g. Bossel & Schäfer 1990, Kaila & Marshall 1992, Kolström 1989, Moore 1990, Plant & Stone 1991, Saarenmaa 1990). Growth and yield modellers should consider the object-oriented approach as a potential way of presenting systems. It is obvious that innovative generation of simulation systems using the techniques of artificial intelligence, GIS and OO-approach, will arise before the end of this decade.

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Growth models for predicting stand development

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Introduction

Models are made for describing reality, growth models for predicting stand development or explaining the effect of single predictors on it. Predictions needed in forest management must be at the right level both regionally and over a long-term time horizon. The latter demand is very difficult to fulfill. The ongoing environmental change makes accurate long-term predicting of stand development impossible when using traditional growth models.

The history of growth modelling

Yield tables are the simplest way to predict stand development by age. The first Finnish yield tables are those drawn up by Blomqvist in 1872. Today, yield tables are available for natural and planted, thinned and unthinned Scots pine, Norway spruce and birch stands (Koivisto 1959, Vuokila & Väliaho 1980). Most of the tables are made by smoothing data from temporary plots. Thus, the tables do not describe the development of stand characteristics in one stand, but they only show the mean of a large, heterogenous material. This must be taken into consideration when comparing simulated stand development to yield tables.

The use of regression analysis since the beginning of the 1960´s has made it possible to examine tree and stand growth as a function of characteristics other than age. In regression models, growth variation is evidenced by tree and stand variables correlating with growth. Although independent variables are not the real causes of increment, choosing variables is made keeping causality in mind.

The aim of process models is to describe the biological processes behind tree growth. The models result in biomass produced by photosynthesis. This biomass will be allocated betweed different parts of the tree. The main advantage of a process model is the possibility to test the effect of changing environment on tree growth, if the necessary processes are included in model. The problem with process models is their need for complex measurements and computer capacity on practical level, which makes

them unsuitable for use in forest management calculations. In the near future, the so-called hybrid models (which attempt to combine the simplicity of regression models and the causality of process models) will be the most promising way to bring these models closer to one another.

Growth models for single trees or the whole stand?

In the oldest Finnish growth models (Kuusela & Kilkki 1963), the relative volume increment of a stand depended on stand variables like age, stem volume, site type and the mean dimensions of the trees. Growth models for the whole stand were easy to use in forest management in which only ocular estimation of stand characteristics was made. Tree models were believed to be of minor value because of restrictions in computer capacity and the unknown diameter distribution of the stand. The weakness in the use of stand models is the fact that the allocation of growth to different dimensions is unknown.

During the recent years the prediction of stand growth has been based almost exclusively on tree models (Mielikäinen 1985, Pukkala 1988, Ojansuu et al. 1991). The reasons for this include improved computer capacity and models for predicting stand diameter distribution using easily measurable stand characteristics (Päivinen 1980).

Growth models for single trees are divided into two groups: 1. distance-dependent and 2. distance-independent models. Distance-dependent (spatial) models presuppose that the coordinates of single trees are known or they can be generated by computer (Pukkala 1988). Using tree coordinates, it is possible to estimate variables to describe competition between trees. The so-called competition indices are usually based on tree size and distances between individual trees.

Distance-dependent competition variables do not lead to a marked increase in the accuracy of stand-level growth predictions. The stand basal area and the relative size of trees are almost as effective independent variables as the most complicated competition indices. Distance-dependent growth models show their strength when they are used to simulate stand development after exceptional stand treatments. The effect of strip roads and row thinnings, as well as the development of uneven-aged stands, can be mentioned as examples.

Simulating the development of uneven-aged stands presupposes first a variety of tree models to describe the regeneration and early growth of plants based on the production, spreading and germination of seeds. The main task of the tree growth model is to predict the reaction of trees after very exceptional thinnings. The simulation of logging includes the moving of machines in the stand and the calculation of logging costs and damages caused by them.

Challenges of growth modelling in the near future

It is important that a stand simulator can simulate the development of real single stands in a realistic way. This sets high demands on the accuracy of all models in areal and treatmental respect. The worth of a simulator that is able to describe only the mean development of a yield table is like that of a hand-drawn line on paper. A growth researcher is mainly interested in modelling the causes of variation around the mean development. Thus, the growth models must fit with empirical data. The data can be the basis of modelling itself or test material for a theoretical model.

The changing environment is one reason why earlier yield tables or growth models are not capable of predicting future stand development. The effect of changes in the atmosphere and climate can be positive, negative or both at the same time.

The safest, but at the same time the most expensive way of taking the risk of possible growth trend into consideration is to make predictions only for short periods into the future and to make new yield models at short intervals based on new data. A more tempting way to solve the problem is to try to use climatic variables as predictors in the models. Models with causality are better suited for careful extrapolation of stand development, too. These models must, however, fit with existing and measurable data of today.

A compromise of the methods mentioned above is to be seen in traditional growth models that are constantly calibrated according to continuously measured data. These models, too, must be rebuilt after a certain number of years. At present this method is best suited to forest management where predictions do not reach very far into the future.

The peatlands of Finland consist of a very heterogenous group of growing conditions. Ditching, fertilization, thinning and nutritional problems make growth predicting very complicated. Modelling tree growth on peatlands is a demanding challenge of the near future.

Despite numerous experiments in young stands, modelling regeneration and the early development and mortality of young plants is still limited. The early development of trees is, however, one of the key factors in predicting stand production over the whole rotation. That is why modelling of young stands is one of the most urgent tasks of today.

The simulation of stand growth

Individual models describing small fractions of stand growth each get their value only if they are put together to predict the development of different stand characteristics. The complexity of a complete stand simulator is characterized in Figure 1. Stand treatment is the only one among many factors affecting tree growth that can be studied by field experiments. The

effects of changes in soil and atmosphere, as well as genetics, are still far from being solved in growth modelling. In addition to tree growth, different kinds of damage, the quality of stems and the technology of wood processing and transport also influence the economy of timber growing.

At present, the simulator most applied in Finnish forestry is Mela (Siitonen 1983). It has been used in predicting the timber production potential of the whole country. Some new simulators are under construction at the Finnish Forest Research Institute and at universities, too. The programming of new simulators is no longer the biggest problem. The greatest gaps still exist in growth modelling, i.e. the substance of simulations.

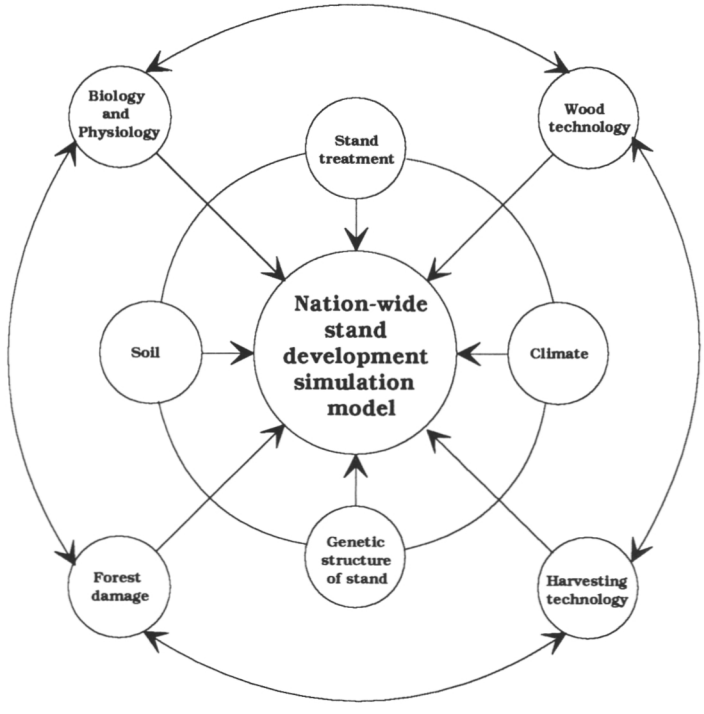

Figure 1. Basic idea of a nation-wide simulation model (Vuokila 1986).

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An aggregated, process-based stand growth model

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Introduction

The carbon balance approach to tree growth makes it possible to work on a very detailed level with regard to the processes generating tree growth. Consequently, the resulting growth model may be very complicated, it may have many parameters, and it may work with such short time steps that simulation over a period of a week consumes a considerable amount of computing time. It is a good means for studying the effects of physiological parameters and/or environmental conditions on forest growth rate. However, if the primary interest is only in the output of the growth process (stand and tree growth in terms of volume), then the above growth model may be too heavy for such purposes. One has to resort to other kinds of growth models, or the complicated process-based model has to be simplified.

The present paper gives a brief description of a model (Sievänen 1992) where the carbon balance approach (cf. Landsberg 1986) to tree growth has been used in a simple form which is makes it possible, on one hand, to keep the model simple for potential forest management applications and, on the other hand, to convey as much information as possible from the process level to stand growth level. The model is based on photosynthetic relationships and provides predictions in terms of tree dimensions. In it, simple expressions have been used for photosynthesis, other aspects of physiology, and tree structure. The model is formulated in continuous time to facilitate mathematical derivations. As a result of these derivations, the final growth model can be presented in a concise form, which also allows the parameters to be combined into fewer aggregated ones.

The carbon balance

In this model, a tree corresponds to a number of similar trees in the stand (members of a size class). Stand growth can be aggregated from the growth

of individual trees and the number of members in each size class. Distances between trees are not considered; hence, this model can be termed a distance-independent, individual-tree growth model.

The growth model of an individual tree is based on the standard carbon balance approach to tree growth (see e.g. Landsberg 1986) where the changes in the tree dry-weight W are determined by the balance between photosynthesis, P, maintenance respiration requirements, M, and senescence, S (of leaves, branches and fine roots):

$$\frac{dW}{dt} = P - M - S \tag{1}$$

The time resolution of the above equation is one year; that is, no within-year changes are included in the right-hand side terms. The tree is divided into five dry-weight compartments: foliage, branches, stem, stump with coarse roots and fine roots, with dry-weights W_f, W_b, W_s, W_u, and W_r, respectively.

Tree photosynthesis is expressed as a combination of tree photosynthesis in a closed stand, P_c, and photosynthesis of an isolated tree, P_o. It is assumed that there is a threshold leaf area, L_t, above which the stand can be regarded closed in terms of radiation interception and photosynthesis. If the stand leaf area, L_s, is less than L_t, then actual photosynthesis is a linear interpolation between P_c and P_o. These considerations yield:

$$P = \min[1, \frac{L_s}{L_t}] P_c + (1 - \min[1, \frac{L_s}{L_t}]) P_o \tag{2}$$

The closed and open condition photosynthesis rates are given by the equations

$$P_c = p_m \frac{L}{L_s} (1 - e^{-k_e L_s}) \tag{3}$$

$$P_o = p_m a_p k_e L \tag{4}$$

where p_m is the maximum photosynthetic production per unit ground area (which accounts for the effects of the photosynthetic properties of trees, amount of radiation and growth respiration), L is leaf area of the tree, and k_e is the light extinction coefficient.

The amount of annual maintenance respiration is assumed to be proportional to the respiring biomass (sapwood) in each compartment, W_{si}:

$$M = \Sigma r_i W_{si} \tag{5}$$

where r_i are parameters. The respiring biomass consists of foliage, branches, fine roots and sapwood in stem, and stump with coarse roots.

Senescence is treated in the similar manner, and it occurs in the foliage, branches, and fine roots, with parameters s_i:

$$S = \Sigma\, s_i\, W_i \tag{6}$$

The structural equations

To complete the growth model in terms of dry-weight requires that dynamical equations be specified for the compartments' dry-weights. This is usually accomplished by deriving partitioning coefficients of photosynthesis, and then establishing a carbon balance equation for each compartment. The values of the partitioning coefficients can be obtained, for example, from the requirements that the growth of various compartments obey equations which describe structural relationships in the tree (cf. Nikinmaa in this volume). Here also, such equations are specified which would allow derivation of the partitioning coefficients. This line is not followed, however. Instead, the structural equations are used to express tree growth in terms of diameter D (at relative height 0.2), height H and height of the crown base, H_c. The following is a summary of the structural equations.

First, the dry-weights of branches, W_b, and fine roots, W_r, depend on the dry-weight of the foliage, W_f. Furthermore, the dry-weight of the stump with coarse roots, W_u, depends on stem dry-weight, W_s. The relationships are expressed as

$$W_b = \alpha_b\, W_f^{\gamma_b}, \quad W_r = a_r W_f \quad \text{and} \quad W_u = a_u W_s \tag{7}$$

where a_b, g_b, a_r and a_u are parameters. The foliage mass is related to stem cross-sectional area at the crown base, $(p/4)D_c^2$, via the equation

$$W_f = \alpha_f \left(\frac{\pi}{4}\right) D_c^2 \tag{8}$$

where a_f is a parameter. The diameter at the crown base, D_c, can be obtained from D by using a taper function. Stem dry-weight, diameter and height are related via the equation

$$W_s = \rho v_s D^2 H \tag{9}$$

where v_s is a parameter and r the density of stemwood. Finally, it is assumed that the growth rates of the diameter and height are related by the function f_h which is defined by the equation

$$\frac{dH}{dt} = (e_1 + e_2\frac{H_c}{H})\frac{dD}{dt} = f_h \frac{dD}{dt} \tag{10}$$

where e_1 and e_2 are parameters.

With the aid of these equations, it is possible to make the necessary derivations to express tree growth in terms of diameter, D, height, H, and the height of the crown base, H_c, as follows:

$$\frac{dD}{dt} = \frac{\frac{P}{D} - (1-\frac{H_c}{H})\, D\, (m_f + m_s H) + c_f (\frac{D}{h})\frac{dH_c}{dt}}{c_f\left[2 - \frac{H_c}{H} + (\frac{f_h D}{H} - 1)\frac{H_c}{H}\right] + c_s (f_h D + 2H)} \tag{11}$$

$$\frac{dH}{dt} = f_h \frac{dD}{dt} \tag{12}$$

These equations comprise the dimensional growth of a tree in a stand when the height of the crown base and its rate of increase are determined at stand level (see below) and obtained as input for these equations. The parameters m_f, m_s, c_f, and cs are combinations of the carbon balance model parameters and the parameters in the structural equation (Sievänen 1992). They summarize the effects of physiological and biometrical properties of a tree on its growth. See Sievänen (1992) for a discussion of these.

Crown base, tree survival and stand growth model

In this model it is assumed (referring to an even-aged stand) that the height of the crown base is the same for all trees (except those for which the relative height of the crown base would exceed the maximum; their crown base is lower down). The recession of the crown base is treated in the present model as a stand process that is controlled by the crowding of trees; when crowding - measured as the stand basal area at the crown base - increases, the crown base recedes. This is accounted for by the equation

$$\frac{dH_c}{dt} = \max\,[\beta_c\,(G_c - G_{c0}), 0] \tag{13}$$

where G_{c0} is the critical stand basal area at the crown base at which crown base recession starts. Inspection of Eqn (8) indicates that the foliage mass of the stand is proportional to stand basal area at the crown base. It is thus

a substitute for foliage mass; hence, implicit in Eqn (13) is that the amount of foliage controls the recession of the crown base. The reason for using basal area instead of foliage mass is the desire to use solely dimensional variables in the model.

The number of trees in each size class is governed by the equation

$$\frac{dN}{dt} = \frac{-N}{1 + \delta_1 \frac{dD}{dt} + \delta_2 D^2} \qquad (14)$$

where N is the number of trees in a size class, and d1 and d2 are parameters. The term containing dD/dt in the denominator accounts for the tree vigour: large diameter growth rate makes the death rate smaller. The term with D^2 represents the fact that big trees tend not to die even if their growth rate is slow.

The above equations specify the growth model for an even-aged stand. When there are n size classes, the stand is described using the variables D_i, H_i and N_i, for each size class i = 1,..,n together with H_c. In other words, these are the state variables of the stand growth model. The dynamic equations for them are given by Eqns (11) - (14).

Concluding remarks

The equations (11) - (14) define a growth model for an even-aged stand. It is based on the functioning of individual trees. It contains a relatively low number of parameters which can be estimated using measurements of forest growth (Sievänen & Burk 1992a). Since both height and diameter of trees in the size classes is included in the model, it can provide much detail information about stands; for example, it is possible to predict the current stem volume yield by product class components from the value of the state.

Given the initial conditions (i.e. values of the state variables) and the parameter values, stand conditions can be simulated for any future time (within the rotation period). The initial conditions for a particular form of diameter distribution are not always available. In this case, it is possible to use a model for predicting a diameter distribution from stand level information; e.g. mean diameter, dominant height, and total number of trees. This widens the range of applicability of the stand growth model.

The model was tested using stand level data and it seems to reproduce the basic growth patterns in unthinned stands (Sievänen 1992). The model is under development, and it is being tested with treewise stand growth data (Sievänen & Burk 1992b). It is likely that some of its components will be replaced as it has turned out that they are not valid descriptions of real phenomena taking place in the forest. One such model component may be Eqn (13) for the rising of the crown base with the associated assumption of common height of the crown base. If the model is going to be applied to

mixed stands this model component has to be modified in any case. Other model components to be rigorously tested are photosynthesis, height growth, and tree mortality.

One possible application of the present model is to investigate the potential effect of certain environmental changes on stand growth. This is possible because many of the model's parameters have a biological meaning and represent a measure of some property. Changes in environmental conditions are likely to result in corresponding changes in these parameters. Examples of parameters that are likely to be affected by environmental changes are maximum photosynthetic production, leaf longevity and amount and productivity of roots.

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The allocation of carbohydrates

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Introduction

Allocation or partitioning of carbohydrates has a central role in process-based stand and tree growth models, (e.g. Thornley 1976, Hari et al. 1982, McMurtrie & Wolf 1983, Mäkelä & Hari 1986, Mohren 1987, Bossel 1986, Iserbrands et al. 1991). This is due to the direct influence that allocation has on the amount of productive organs in comparison to non-productive ones. For example, when McMurtrie & Wolf (1983) changed their partitioning coefficients for foliage, wood and fine roots from 20:20:60 to 30:30:40, the total stand biomass after 50 simulated years was about 30% more in the latter case than in the former one.

In the carbon budget models, allocation refers to the proportion of the carbohydrates that can be used for new growth of different biomass compartments after the respiration of already existing structures has been subtracted from the photosynthetically fixed carbon. Especially in models that use short time steps, the use of the concept allocation may be misleading. It forces us to view a plant as an entity having strategies instead of focusing on the processes bringing about growth.

As the growth and development of perennial plants is modelled with longer time steps, such as the growing season, then allocation or partitioning focuses on the slow, structural acclimation of the plant on the environmental conditions. Allocation in that case is the integral of various input-output processes and the associated intraplant regulation reflecting the genetic information of the plant. When the genetic information is viewed as a species strategy for survival, then the use of the term allocation may be, at least partially, justified. However, it is my opinion that much of the confusion could be avoided if we were to talk about different ways of modelling the growth of different parts of trees instead of allocation.

The growth of organs consist of differentiation of meristematic cells; their division and expansion and of the secondary cell wall thickening. Growth naturally depends on the availability of the building blocks of organic matter (i.e. carbohydrates and different other elements) normally called nutrients. The reactions require suitable environmental conditions; adequate water supply to act mainly as the media for the reactions and

acceptable temperature. On top of this, there are the growth regulators, or hormones, such as gibberellins, auxin and cytokinin, that play a very important role, especially in the phases of cell division and differentiation, carrying, among other things, positional information on the plant level and information about the growing season.

A realistic process-based growth model would require that we could quantify the effects of the above factors on the meristematic cells and how the different substances are transported within the plant. In trees it is not uncommon to have the main sites of the carbon fixation and nutrient uptake more than 50 meters apart from each other which are connected by two very different transport systems in phloem and xylem. The whole question is further complicated by the role of reserves and those substances that are retranslocated from senescing structures to still functioning ones.

Thus, the growth of a plant is a result of complex combination of interacting processes and it is most likely these processes that determine the main characteristics of plants. Despite the long tradition of plant physiology, we still do not understand many of the key processes involved to the point that we could distinguish the most important ones that would predict the major part of the outcome. However, for many reasons, there has been the need to be able to estimate the growth of plants based on their physiological functions.

The information base concerning the input- output reactions, especially those of foliage, has been rather good and it has facilitated the beginning of process-based growth modelling. On the other hand, the long tradition of dimension measurements in forestry provides us with quite a solid knowledge of the outcome of the growth processes in the conditions prevailing when the measurements were done. Thus, the poor knowledge of the processes controlling growth has led modellers to search for alternative methods to describe it as realistically as possible. It is most likely that since virtually all process-based models stem from the description of the input-output reactions, also the growth has become a process of partitioning or allocation.

Different approaches to model distribution of carbohydrates for growth

In the literature one can identify at least five different approaches to tackle the problem of allocation. Perhaps the most straightforward method is to use so-called allocation keys. Empirical constants are used (e.g. Thornley 1976, McMurtrie & Wolf 1983, Iserbrands et al. 1991), which can depend, for example, on the position of the trees in the stand (Hari et al. 1982) or the developmental stage or age of the stand (Mohren 1987). The use of this method is complicated by the limited data on allocation and, on the other hand, by the big variability of allocation depending on the environmental

conditions (e.g. Ingestad 1979, Linder & Axelsson 1982) or the size or age of the trees (Ovington 1957, Cannell 1985, Shepard & Ford 1986) and the tediousness of carrying out measurements on a large scale (Iserbrands & Dickson 1990, Arovaara & Ilvesniemi 1989).

Another possibility has been the assumption that there would exist certain allometric ratios between different parts of trees (Landsberg 1986). Generally it has been assumed that the size of one plant organ can be expressed in terms of size of another organ (Landsberg 1986, Santantonio 1990, Sievänen (1992)). If one is using biomasses then the ratio can be expressed as follows:

$$W_i = a\, W_j b \qquad (1)$$

where W stands for biomass of a compartment and a and b are empirical constants. If it is now assumed that the ratios remain unchanged from time to time, or the change is known, in which case it is possible to derive the distribution of total photosynthetic production for the different biomass compartments after respiration has been subtracted. Another way is to compare the different aspects of size as has been done in the pipe model by Shinozaki et al. (1964). A related approach is that used by Schäfer et al. (1990) where empirically derived amounts of biomass are used in different biomass compartments as a function of total stand biomass, which is then utilized as a "goal" for allocation.

The problem with this general method is that it relies heavily on the relative sizes of different components, which have to be empirically determined. On the other hand, it is still not clear how constant the relationships between different parts actually are, and how they are affected by different environmental conditions (e.g. Long & Smith 1988, Espinosa Bancalari et al. 1987, Geron & Ruark 1988). The good thing is that the model structures can be made rather simple and that this approach describes a great deal about the internal dynamics of forest stands (e.g. Sievänen (1992)).

A rather similar approach to that of the allometric ratios is the assumption of the functional balance between the parts of a tree. Basically, this approach rests on the assumption that the different structures within trees have certain primary functions and that the connections between the structures and functions are quantitatively known. It is then assumed that instead of always having constant ratios between the structures, the functions of different structures have to be in balance. Perhaps the most well known formulation of this principle, originally presented by White (1937), is the derivation of the shoot : root growth by Davidson (1969):

$$\mu_N W_r = \beta \mu_C W_s \qquad (2)$$

where μN and μC are the specific nitrogen and carbon assimilation rates, Wr and Ws are the shoot and root biomasses and ß is a parameter

describing the ratio between nitrogen and carbon used in structures. The weak point of this method is that it assumes that the nitrogen to carbon ratio would remain constant although it has been shown to vary (e.g. Ingestad 1979). Reynolds & Thornley (1982) developed a more detailed, dynamic model of the partitioning to shoots and roots, which accounted for the variation in the mentioned ratio, but which still described the functional balance. Mäkelä & Sievänen (1987) showed that the less the substrata can compensate each other in the structural growth, the more constant should the parameter β remain when changing the ratio $\mu N/\mu C$ in the optimum growth version of the Reynolds & Thornley model.

Later on, the implications of the pipe model approach were also used to derive growth between foliage, branches and stem (Mäkelä 1986, Valentine 1985, Hari et al. 1985). The functional interpretation of the pipe model could be that the foliage required for their mechanical and physiological support an infrastructure which consists of functional basic units and the amount of these units in any cross-section should be: a) proportional to the amount of foliage above the point and b) the structure of these units. A simplification of this would be that there is a constant ratio between the amount of foliage and the functional wood area below in branches, stem and transport roots, respectively (e.g. Mäkelä 1986) which yields the following equations:

$$A_s = n_s W_f \quad (3)$$
$$A_b = n_b W_f \quad (4)$$
$$A_t = n_t W_f \quad (5)$$

where A_i stands for the cross-sectional area of sapwood of a biomass compartment, i=f,s,b,t are the biomass compartments; foliage, branches, stem and transport roots respectively, n_i is the proportionating coefficient and W_i is the foliage biomass. Ludlow et al. (1990) have used a similar principle but they assumed that the new basal area growth would always be proportional to the new biomass formed above that point. In a way, this would resemble more the approach in which the growth of the stem depends on the photosynthetic capacity of needles above the reference height as first suggested by Pressler in the 1860's (cited by Assman 1970). The problems involved in using the pipe model related approaches are dealt with in more detail in the example of this kind of model given later on.

Perhaps a step towards a more mechanistic model would be that of the use of the so-called priority principle. Essentially, this approach assumes that different parts of trees have some predetermined maximal growth which is restrained by the availability of growth substances (e.g. Loomis et al. 1979). If the substratum supply (in carbon budget models the carbon supply) is not adequate to facilitate the growth of all compartments with their unrestrained growth rate, the substratum supply is limited according

to empirically derived "priorities" in which each class of organs is given a different response function for substratum dependence (cf. Loomis et al. 1979 p. 350). Thornley (1976) has explained the application of the Michaelis-Menten type functions for dependence between growth and substratum level. As these functions are compared between organs, one can derive the priority between organs (Loomis et al. 1979). This approach has been used to model the growth of agricultural plants, but Waring (1987) has derived the priorities for trees as well. Also Bassow et al. (1990) and Bossel & Schäfer (1989) used priority within the year. The main problem of this approach is that priority will most likely vary during the growing season depending on the internal regulation of the annual cycle and also depending on the different environmental conditions and the processes involved in this control that are not yet fully understood. Therefore, quite a lot of empirical work has to be done before the priorities in different conditions are known.

Perhaps the most mechanistic approach to the distribution of carbon is that of the transport resistance model by Thornley (1972). The transport resistance model assumes that the growth of different compartments (i.e. the substrate consumption) depends on the substrate supply at the growth location. The latter depends on the substrate uptake in that compartment or in some other compartment plus the transport between compartments. The transport rate, on the other hand, depends on the concentration difference between the compartments. Thus, one needs a description of the substrate uptake as a function of organ size and environment, substrate transport as a function of concentration difference between the compartments, and the properties of the transporting media and the substrate utilization as a function of the substrate supply.

According to the model, an equilibrium situation is reached when there is a balance between uptake, substrate consumption on growth, and transport rates between the compartments. Dixon et al. (1978) utilized basically the same approach to determine the distribution of carbohydrates in their stand model. The main problems of this approach are partially the same as in the previous approach. The rates of supply, transport and utilization are all affected by the internal factors controlling the annual cycle. On the other hand, too little is still known on how the substratum supply actually affects the activities on the cambial regions and, as was mentioned earlier, the transport system in trees can be quite complex.

The different approaches used are not necessarily contradicting ones and in many models several of the presented approaches can, in fact, be used (e.g. Schäfer et al. 1990). The use of the pipe model theory within the framework of functional balance for example, could also be interpreted as being an utilization of the observed empirical allometric ratios between different parts of trees. However, one can see that there is a general trend towards shorter time steps and perhaps more detailed hierarchy level of the models as one proceeds along the presented list. An exception is the use of the allocation keys, which are more reflecting of the poor present day

knowledge of the processes involved at any hierarchy level.

The change in hierarchy level also reflects the objectives of the models. The models by Sievänen (1992) and Ludlow et al. (1990) are clearly intended to be eventually used in the forest management decisions, whereas the very detailed models of Thornley (1972) and that of Ford & Kiester (1990) could serve more in helping one to understand the role of different processes in tree growth and perhaps to indicate the critical points where the present environmental change will affect tree functioning up to harmful limit.

Example of distribution of growth utilizing the functional balance principles

A biomass compartment growth model was constructed which followed the functional balance principle described in the previous chapter. The main difference with the outline was that the allocation between foliage and fine roots depended also on the amount of nutrients retranslocated from dying structures. In order for this to be included the functional balance had to be reformulated; the nutrient uptake and retranslocation from senescing structures would have to be equal to the amount of nutrients used up in the formation of new structures.

A couple of simplifying assumptions were made in the model. As pointed out by Mäkelä (1988), the specific nutrient uptake rate and the fine root specific senescence rate can compensate for each other in this type of approach. Therefore, they could be replaced by one parameter. This would mean that the root nutrient uptake efficiency describes the amount of nutrients taken up annually per unit amount of carbon. In other words, it is assumed that all the fine roots formed during one year would die during that year. On the other hand, it is also assumed that most of the retranslocated nutrients would come from the senescing needles. From these assumptions, the growth of new fine roots can be expressed as a follows:

$$\mu rmr = ßfmf+ßwmw+ßrmr-rtßfsf$$
$$<=>$$
$$mr = (ßfmf+ßwmw-rtßfsf)/(\mu r-ßr) \quad (6)$$

where μr is the annual nutrient uptake per unit amount of carbon used for fine roots, ßi is the nutrient concentration in the dry matter of different biomass compartments (here only foliage, wood and fine roots are considered, but the wood could also be further sub-divided into branches, stem and transport roots as is done in the model), mi is the new growing biomass of the different biomass compartments, rt is the parameter describing the retranslocation of nutrients from the senescing foliage, and sf is the

biomass of senescing foliage.

The allocation between the woody biomass and the foliage is done according to the pipe model principle (see derivation e.g. Mäkelä 1986 or Nikinmaa 1990). Based on that principle, the growth of woody tissue can be written as a function of growth of foliage as follows:

$$m_w = (h \cdot d/n)(m_f - s_f) + s_w \quad (7)$$

where h is the length of the woody path from foliage to fine roots, d is the density of wood, n is the proportionating coefficient between foliage biomass and stem cross-sectional area, and sw is the senescence of sapwood (i.e. the formation of heartwood). In the presented version of the model wood is sub-divided into branch, stem and transport root compartments, each of which have different proportionating coefficients.

The above equations can be joined together by the carbon balance (i.e. that the annual photosynthetic production is consumed by respiration and growth). Also, a storage component could be added into the analyses, which would yield the following formulation:

$$P - R = G_i(1 + rg_i + rm_i) + (T_n - T_o) \quad (8)$$

where P is the annual photosynthetic production of the tree, R is the maintenance respiration of the existing structures, G_i is the growth of different biomass compartments, rg_i and rm_i are the growth and maintenance respirations of the new growing structures, and T_n and T_o are the carbon allocated to being stored and the amount of carbon released from being stored. In the presented results, it is assumed that no net change occurs in the stored carbon; thus, the latter term can be omitted.

As can be seen from equation (7), one also needs to model the senescence of foliage, the growth in length of the pipe "infrastructure" and the turnover of sapwood into heartwood. In the presented model, a simple approach was used. Foliage mortality was simply assumed to be a constant proportion of the total foliage. For the height growth a model similar to that presented by Sievänen (1992) was used. In that model it was assumed that the ratio between height and diameter would remain unchanged in open grown trees and that stand density would modify this ratio. The density of the stand was described with the steepness of the light gradient of the tree crowns in trees of different sizes.

The turnover of sapwood into heartwood was assumed to be proportional to the amount of foliage dying below the new pruning limit of the trees. Additionally, a constant fraction of senescing foliage within the crown was assumed to be associated with the turnover of sapwood into heartwood. The pruning limit was assumed to depend on the production conditions at

the pruning limit of the trees (mainly depending on light) and the average production efficiency of the needles of the whole tree. The exact equations used to determine allocation as well as photosynthetic production, respiration, nutrient uptake and senescence, and whole tree mortality, are presented in detail by Nikinmaa & Hari (1992).

Simulation results

Some typical simulation results are presented in the following figures. A more detailed study of the model behaviour in different conditions is presented by Nikinmaa (1992). Figures 1 a and b show the development of the needle and stemwood biomass for Lapland (Muddusniemi), Southern Finland (Hyytiälä), East Karelia (Petrosavodsk) and South Russia. The simulations for the different locations were performed by using the same basic set of parameters and by then multiplying the functional parameters with the relative growing season length (1.0 for Hyytiälä). The functional parameters were the annual photosynthetic production of unshaded conditions, annual specific respirational losses of different parts of tree, and annual nutrient uptake efficiency per unit weight of carbon used to fine roots. In addition, the structural parameters (the n_i of the equations 3-5, average number of branches per whorl and the mortality of needles of different age classes) were changed according to the measurements performed in these locations.

When interpreting the results, it must be noted that the needle biomasses are the biomasses after the growing season (i.e. those from which the annual senescence has already been subtracted). The overall shapes of the curves both for needle mass and stem mass seem quite realistic. Albrektsson (1980) reports a sharper peak in the needle mass of young stands than was observed here. On the other hand, the model quite nicely predicts the much slower development of the northern stand as compared with the southern stands.

The simulated and observed growth of stands on different site types is compared in central Finland and in Lapland (figure 2a and b). The simulations were done so that the root nutrient uptake per unit weight was varied within the range that corresponded with the observed site type range while keeping the other parameters constant. In these simulations, both height and stem mass were used as the comparison criteria. The simulations were repeated for Lapland the same way as was explained earlier; i.e. by changing the structural parameters according to the measurements done in Muddusniemi and the functional parameters by multiplying the Hyytiälä values with the growing season length ratio between Muddusniemi and Hyytiälä (see Nikinmaa (1992)). In the simulations for Hyytiälä, my intention was not to obtain exactly the development observed by Ilvessalo (1920, based on temporary sample plots). I was more interested to see how well the model predictions corresponded with the shapes of the observed development curves.

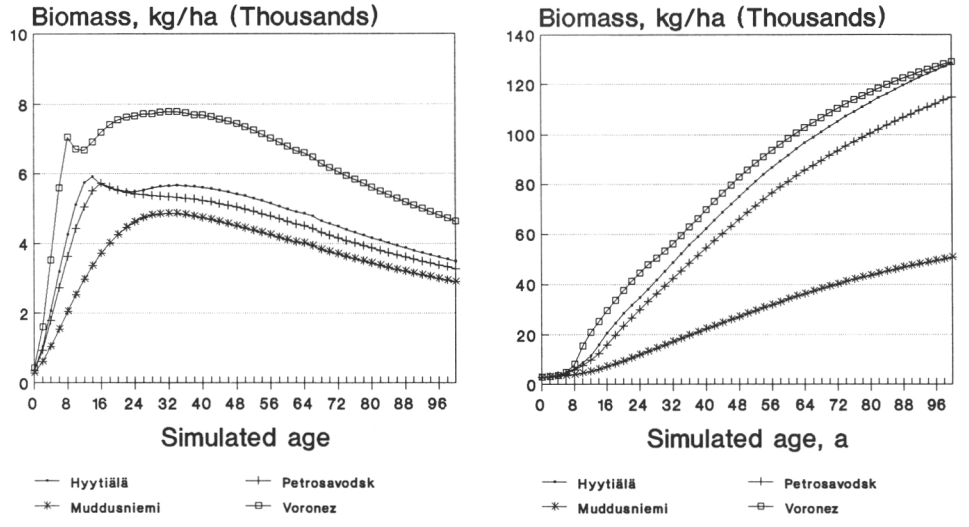

Figure 1. Simulated a) needle and b) stem dry mass development at four locations.

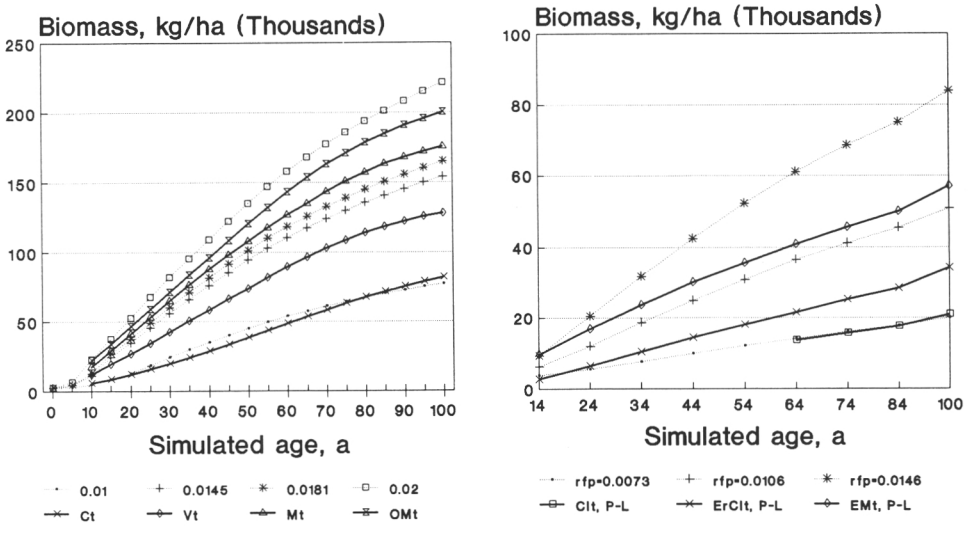

Figure 2. Comparison between simulated stem dry mass development assuming varied nutrient uptake per unit carbon consumed to fine roots and growth and yield table results for different site types at a) Hyytiälä (Ilvessalo´s yield tables for Southern Finland 1920) and b) Muddusniemi (Ilvessalo´s yield tables for Northern Lapland 1970).

The application of the model for the conditions in Lapland was also a test for the model, since those values (from Ilvessalo 1970) represented a totally independent set of data which had not in any way been utilized when the model was fitted. As can be seen, the fit is quite satisfactory. It would have been interesting to see how well the model could have predicted growth in the South Russian conditions; unfortunately, no growth and yield data from there was available.

Figure 3 shows how the allocation changes with the development of the stand in the dominating trees. The main feature is the very strong shift from productive biomass (i.e. the foliage and fine roots) to woody biomass (stem, branches and transport roots) in the beginning of the stand growth which is then followed by a more or less stable phase. Especially the proportion allocated to stem increases first strongly and then starts to decline slowly. This follows as the total foliage is both growing and shifting strongly upwards. From the pipe model theory it then follows that the stem has to grow exponentially to maintain the structure. In nature, the changes may not be quite so strong since there is evidence that the xylem structure is also changing towards a more conductive one as the tree matures (Carlquist 1987). However, Ovington (1957), Cannell (1985), Albrektsson & Valinger (1985) and Mohren (1987) have reported results which would appear to support the simulated trend.

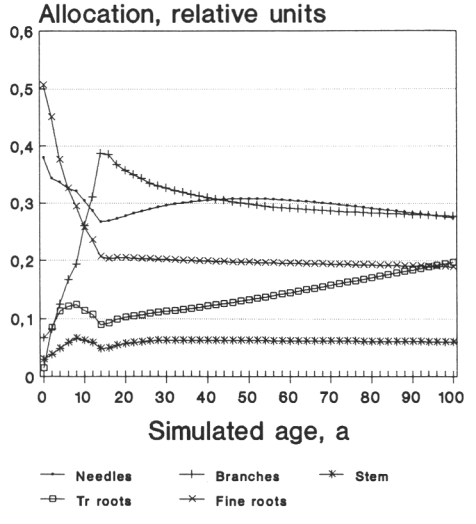

Figure 3. The development of carbon allocated to different biomass compartments of trees forming the dominating canopy.

Another strong change occurs in the proportion of fine root growth. From its initial high proportion, it comes down sharply, and stabilizes more or less at the same time as the canopy closes. The sharp drop can be explained by the decreasing ratio between the growth of new foliage and foliage senescence. This means that a bigger proportion of the total nutrient demand of the tree can be derived through internal circulation of the nutrients. However, it is also assumed that the nutrient availability per unit of soil volume will remain constant during the rotation.

As can be seen, there are numerous ways of deriving the growth of the different parts of a tree from its the photosynthetic production. While the presented approaches are all associated with the carbon balance models, they are used in models which have very different time scales and thus also different degrees of detail. As was mentioned earlier, the objectives of the model (i.e. the purposes for which it is intended to be used) also determine to a great extent which approach is rational to use when determining the growth of the different parts of a tree. The selection of the hierarchy level should be done so that it is in accordance with the time dynamics of the phenomenon which is intended to be analysed.

The carbon balance approach has been criticised and it has been said that growth is not that much carbon driven, but is merely controlled by the availability of nutrients at the shoot level. However, the presented example, which is clearly based from the carbon balance principle, can also be turned upside down to make it run on the nutrient balance principle. From equations (6) and (7) it follows that the growth of foliage depends linearly on the amount of nutrients available for growth of the above-ground parts. However, the slope of this dependence changes from year to year depending on the size of the woody part, its senescence and the senescence of foliage. This, of course, takes place within the limits of carbon availability.

It is clear that the nutrient dynamics within the tree are described very simplistically here. It is assumed that growth depends linearly on nutrient availability or (to use the carbon balance terminology) the nutrient concentration in the biomass remains constant. On the other hand, nutrient recycling is assumed to take place only from the dying needles. In addition, the structural growth of the below-ground parts is still rather coarsely modelled. Thus, more work is needed to improve the treatment of those parts in this approach.

Apart from nutrient dynamics, also height growth and turnover of sapwood into heartwood need more attention. In the case of the former, one possibility is to apply the optimality principle (Mäkelä & Sievänen 1992) or that combined with modular growth as described by Nikinmaa (1990) and Nikinmaa & Hari (1992). Heartwood formation is a more complicated matter, but the observations by Kaipiainen & Hari (1985) give a promising starting point.

Finally, as was mentioned earlier on, the pipe model theory only coarsely approximates the functions of woody material. As shown by Hari et al. (1986), there are strong changes in the ratio between the needle biomass

and sapwood cross-sectional area in Scots pine when moving from the smallest twigs to the main stem and transport roots. These observations coincide with the hypothesis about the hydraulic architecture of trees as proposed by Zimmermann (1983) and later by Tyree et al. (1985) which being mainly based on the observations made by Huber already at the beginning of the century (Zimmermann 1983) and later on by other authors for different species (e.g. Ewers & Zimmermann 1984). According to that hypothesis, the woody structure is constructed in such a way that the resistance imposed on the water flow is at its highest in the distal parts of the "pipes" which then guarantee that (in case of severe water stress) the cavitations would be restricted mainly to these regions thus securing stem conduction. This theory is supported by the observation of Sanio in the nineteenth century (according to Aloni 1987) that the tracheidal size normally increases when going from distal parts of branches to the lower part of the stem. Thus, the pipe model theory should be modified to also include these ideas if the functional aspect of the woody growth is to be used.

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Forest soil acidification models

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Introduction

The soil stores nutrients and water essential for tree growth. It modifies the chemical composition of rain water on its way to groundwater and surface waters. The soil is thus an important link between the atmosphere, vegetation and surface waters, a link which cannot be ignored when modelling forest growth or surface water chemistry under changing atmospheric conditions. This paper presents the basis of soil models, gives a brief overview of selected soil acidification models, and raises some questions that need to be addressed in the future.

Soil processes and a changing environment

The soil is a system of three phases: solid, aqueous and gaseous. The largest element pools are found in the solid mineral and organic fractions of the soil. The amounts of elements adsorbed to the mineral and organic surfaces are one to three orders of magnitude smaller than those. The pools of elements dissolved in soil solutes or in gaseous form are again one to three orders of magnitude smaller than those adsorbed to the surfaces. Only the elements in free-ion form in the soil solution, and adsorbed to the large reactive surfaces of the solid phase, are directly available to plants. The proportions of elements stored in the different pools change over time. This happens as a result of the transport of elements through soil with water and air, and the concurrent transfer of elements between the storage pools by biogeochemical soil processes. There is a large variation in the time scales of the soil processes. Chemical equilibria are more or less instantaneous processes, whereas the changes in the hydrological and heat regimes show diurnal and annual cycles. Growing vegetation and changes in land use influence soil chemical and hydrological properties on time scales of decades to centuries, whereas soil formation operates over thousands of years. The study of the complex biogeochemical interactions that generate

certain conditions for tree growth, and give rise to a certain composition of the leachate to surface waters, is facilitated by the use of dynamic process-oriented models, especially now as we face a changing environment.

Forest ecosystems are experiencing manifold environmental changes, both natural and anthropogenic. A growing forest stand induces changes in the cycling of nutrients and in the rates of evapotranspiration and percolation. Forestry management practices (e.g., ditching and clearcutting) amplify these changes. The external load of acidifying substances that originates in the burning of fossil fuels alters the chemical properties of forest soils, and may lead to unfavourable growth conditions through increased concentrations of aluminum and increased leaching of calcium and magnesium. Coupled with an increased deposition of nitrogen, these changes can result in nutrient imbalances. Changes in global climate may, in Finland, be reflected in warmer annual average temperatures, dryer summers and wetter winters. This would also imply chemical changes in soils and changes in the composition of leachates from soils.

Forest soil acidification models

The lack of long-term quantitative time series of soil chemical properties has contributed to the preference for the process-oriented, non-statistical approach in soil systems modelling. Often the testing of soil models has to be performed in the light of water quality data and laboratory experiments. The basic components of soil models are the transport of elements, mainly in water, and the retention/release of elements by the soils through various biogeochemical processes (Fig. 1). Terrestrial models, designed for studying forest growth, mostly focus on carbon and nitrogen cycling and include soil processes such as litter formation and decomposition, mineralization, root nutrient uptake. Soil acidification models, the main interest of this article, describe cation exchange, weathering, precipitation and dissolution reactions.

Roughly a dozen different attempts to simulate the acidification of soils have been made since the late 1970's (Table 1). Reuss (1980) formulated the ideas upon which many later soil acidification models are based. His model was one of the first that utilized established principles of soil chemistry to predict the most likely effect of rainfall acidity on leaching of base cations from noncalcareous soils. The model (Reuss 1980) is based on the assumption of there being a chemical equilibrium between solution ions and adsorbed ions. The sorption processes considered are SO_4^{2-}-adsorption and Ca^{2+}-H^+ exchange. In solution, the equilibrium concentrations of H^+, Al^{3+} and HCO_3^- are calculated. Furthermore, to preserve electroneutrality of the solution, the total equivalents of cations (Ca^{2+}, Al^{3+}, H^+) and anions (SO_4^{2-}, HCO_3^-, Cl^-) must be equal. With this model, Reuss (1980) predicted that changes in soil acidity and base cation status may occur much later and continue far longer than the major acid input, due to the dampening

effect of the soil's SO_4^{2-} adsorbing properties. The model results also confirmed that soils well supplied with bases are more susceptible to base loss. Model simulations by Reuss & Johnson (1985) showed that, whereas the pH of the soil solution (at elevated $(CO_2)_g$ levels) will be only moderately affected by an increase in strong acid anions, the pH of the leachate (after CO_2 equilibration) will be strongly affected. This is a good example of how models can advance science: with a simple modelling exercise Reuss & Johnson (1985) solved the apparent paradox of how acid deposition on naturally acid soils can lead to stream water acidification.

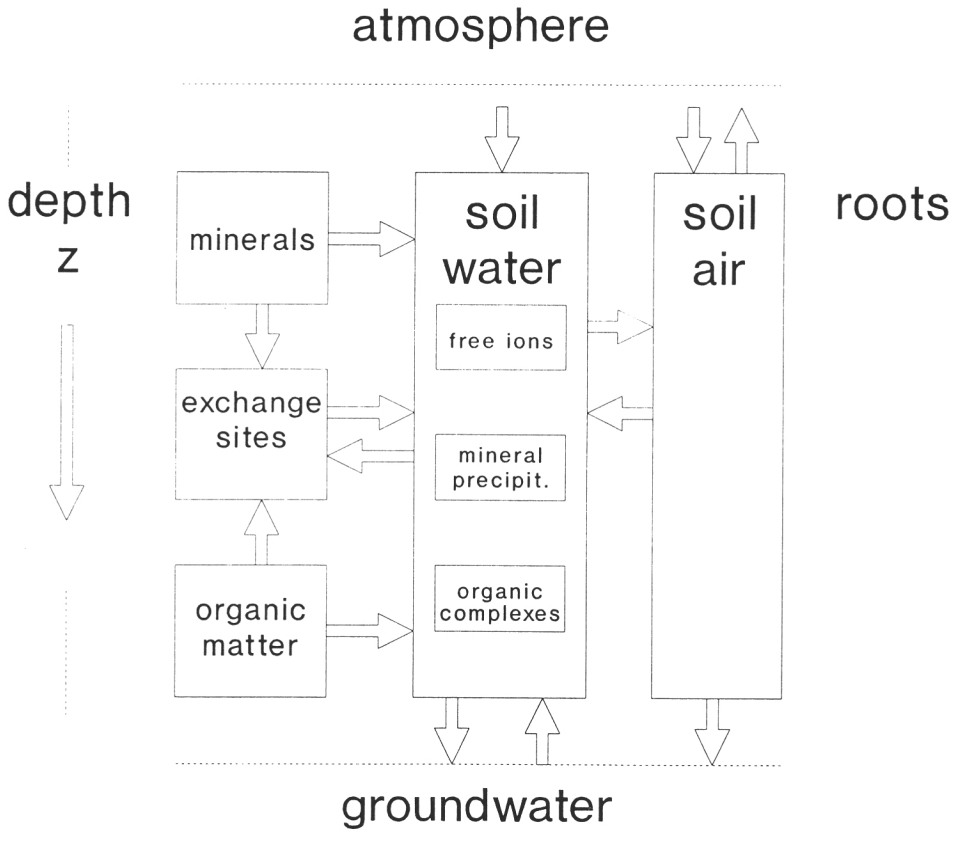

Figure 1. Basic components of soil models.

Table 1. Selected forest soil acidification models.

	Characteristics	Model	Main reference
1)	Basic equilibrium model		Reuss 1980
2)	Streamwater chemistry	Birkenes	Christophersen et al. 1982
3)	Soil and lake steady-state		Arp 1983
4)	Kinetic model		Oksanen et al. 1984
5)	Distributed kinetic model		Holmberg 1984
6)	Lumped equilibrium model	MAGIC	Cosby et al. 1985
7)	Integrated lake watershed model	ILWAS	Gherini et al. 1985
8)	Kinetic lumped model		Holmberg et al. 1985
9)	Decision support framework	RAINS	Kauppi et al. 1985
10)	Kinetic weathering	PROFILE	Sverdrup & Warfvinge 1988
11)	Kinetic lumped multi-layer	ETD	Nikolaidis et al. 1988
12)	Kinetic lumped model		Gobran & Bosatta 1988
13)	Finnish integrated	HAKOMA	Johansson et al. 1989
14)	Lumped kinetic one-layer	MIDAS	Holmberg et al. 1989
15)	Lumped equilibrium one-layer	SMART	De Vries et al. 1989

Short-term variations in streamwater chemistry in response to acid deposition were first modelled by Christophersen et al. (1982). Their model was calibrated and tested with precipitation and runoff data from Birkenes, southern Norway, for the years 1973 to 1978. The Birkenes model is based on a two-reservoir hydrologic model, which predicts quickflow from the upper soil horizons and baseflow from the lower reservoir, using data on precipitation and mean daily temperature. The chemical submodel accounts for adsorption, desorption and mineralization of SO_4^{2-}, the concentration of which is assumed to determine the sum of concentrations of the cations H^+, Ca^{2+}, Mg^{2+} and Al^{3+}. The partitioning of cations is calculated by assuming equilibrium between $Al(OH)_3$ and H^+, and Al^{3+}, and by assuming the relationship between Ca^{2+}, Mg^{2+} and H^+, to be controlled by cation-exchange equilibrium according to the Gapon equation.

The assumption of there being an equilibrium cation exchange was abandoned by Oksanen et al. (1984). They developed a dynamic model describing the kinetic exchange of monovalent cations (K^+, Na^+), divalent cations (Ca^{2+}, Mg^{2+}) and protons (H^+), in which the reaction rate is proportional to the amounts of the reacting ions. The time constants of the exchange are evaluated from experimental data. Ionic concentrations in equilibrium are related as in the Vanselow equation. Convective flow of water in the soil profile controls the transport of ions between consecutive soil layers, 1 cm thick. The applicability of the model is hampered by the non-constant nature of the ion-exchange coefficients.

A modified version of Oksanen's model (Holmberg et al. 1985) was later simplified to deal with only one soil layer and the exchange of Ca^{2+}+Mg^{2+} and H^++Al^{3+}. In this model, cation exchange is described by kinetic equations that correspond to the Gaines-Thomas equilibrium, and the

equilibrium between H^+ and Al^{3+} in solution is calculated from the dissolution of aluminum hydroxide (Holmberg et al. 1989). The model has been used to explore possible paths of recovery of soil base saturation following decreased acid deposition (Holmberg 1990).

The MAGIC model (Cosby et al. 1985) describes soil water and streamwater chemistry based on soil cation exchange, dissolution of aluminum hydroxide, and solution of carbon dioxide. Cosby et al. have extended the conceptual approach by Reuss & Johnson (1986) to include Mg^{2+}, K^+, Na^+, F^-, NO_3^- and Cl^-, and to include important complexation reactions involving dissolved aluminum (such as hydration and complexation with SO_4^{2-} and F^-). Soil cation exchange is described using Gaines-Thomas expressions. The chemical concentrations are calculated from equilibrium expressions. A regionalized version of MAGIC, in which the model is incorporated into a Monte Carlo simulation framework, has been successfully used to reproduce the observed distributions of water quality variables derived from a regional survey of lakes in southern Norway (Cosby et al. 1989).

As a result of the Integrated Lake-Watershed Acidification Study (Goldstein et al. 1985), a general mechanistic theory of lake-watershed acidification that takes into account the production and consumption of acidity by watershed processes, as well as atmospheric inputs of acidity, was formulated in model form. The ILWAS model (Gherini et al. 1985) routes precipitation through the forest canopy, soil horizons, streams and lakes using mass balance concepts and equations which relate flow to hydraulic gradients. The concentrations of H^+, Ca^{2+}, Mg^{2+}, K^+, Na^+, NH_4^+, Al^{3+}, SO_4^{2-}, NO_3^-, Cl^-, F^-, inorganic and organic aluminum complexes, organic acids and dissolved organic carbon are simulated. Mass transfer of these components between gas, liquid and solid phases is formulated in kinetic and equilibrium expressions.

The soil submodel of the RAINS model (Kauppi et al. 1985, Alcamo et al. 1987) is based on the concept of buffer ranges (Ulrich 1983). Acid stress, input from the atmosphere, changes in soil pH, and the amount of exchangeable bases according to equilibrium expressions, specific for each buffer range. The buffer ranges are characterized by soil pH, mineral weathering rate and the amount of exchangeable base cations. In the Finnish integrated acidification model (Johansson et al. 1989), the RAINS soil impact model is implemented to simulate the development of base saturation under various scenarios of acid deposition. For small values of base saturation, however, the model is not realistic because of the linear expression describing cation exchange.

The PROFILE model (Sverdrup & Warfvinge 1988) simulates the concentrations of the major anions and cations in soil solution in equilibrium with silicate weathering, cation exchange and biochemical processes. The weathering rate is calculated using a separate model, which takes into account the exposed surface area of the mineral, the activity of the species in solution, partial pressure of carbon dioxide in solution, the soil moisture content and the fraction of the year when the ground is not frozen. Temporal development of soil solution chemistry is calculated by incorpo-

rating the equilibrium model in a dynamic framework (SAFE).

The ETD model (Nikolaidis et al. 1988) is based on the principle of continuity for alkalinity. It includes a general hydrologic submodel which accounts for snowmelt, interflow, overland flow, groundwater flow, frozen ground processes, seepage, and evapotranspiration. The alkalinity balance is affected by cation exchange, chemical weathering, sulfate sorption, and sulfate reduction in lake sediments. The model is driven by daily input data on precipitation, evaporation, acidity, SO_4^{2-} and Cl^- deposition.

The model of Gobran & Bosatta (1988) uses the approximate kinetics method by Bosatta (1983) to calculate the concentration of ions at any equilibrium point. This method mimics the kinetics of the chemical reactions. The chemical reactions accounted for are carbon dioxide dissociation, aluminum dissolution and hydrolysis, Ca^{2+}-Al^{3+}, exchange, and SO_4^{2-} adsorption and precipitation. Leaching occurs at a rate that is determined by the element concentrations and the constant specific leaching rate. Gobran & Bosatta (1988) define t_{Al}, the time at which the shift to Al dominance in soil solution occurs, as the time at which the fraction of Al equivalents in the soil solution is 0.5. They select t_{Al} as a measure of the soil's sensitivity against depletion of cations, and define the soil leaching sensitivity as the inverse of t_{Al}. In their model results, soil leaching sensitivity increased with the rate of percolation of water and with decreasing CEC. By analyzing the model's behavior under different acid deposition regimes and different values of the key parameters, the authors conclude that pH is not an appropriate variable to be used as an indicator of soil changes.

The SMART model (de Vries et al. 1989) simulates base saturation, pH, the concentrations of divalent cations, Al^{3+}, NH_4^+, NO_3^-, SO_4^{2-} and HCO_3^- in soil solution. It is based on a set of equilibrium expressions, which describe carbonate weathering, silicate weathering, aluminum hydroxide weathering, cation exchange, nitrification, immobilization and uptake, and a set of mass balance equations, which describe the flow of anions and cations through the soil. Simulations with SMART give results that are consistent with Ulrich's concept of buffer ranges, but they indicate that cation exchange is important over a wider range of soil conditions than Ulrich (1983) suggested. The model's response depends mainly on the soil's initial conditions: the amount of calcium carbonate in calcareous soils and the amount of exchangeable base cations in slightly acid soils.

Table 2 summarizes some general properties of the selected forest soil acidification models listed in table 1. Most of the models are one-layer, lumped parameter models, with static hydrology. In the majority of the models, forcing functions or equilibrium equations are used to describe cation exchange, weathering, aluminum chemistry, sulfate adsorption and the biological cycle. No model in operation today calculates using distributed variables and parameters. Very few use kinetic formulations for the chemical processes. Only four models include nitrogen chemistry and organic compounds.

Table 2. General properties of selected forest soil acidification models. Numbers refer to models in Table 1.

	Lumped		**Distributed**	
	One-layer	**Multi-layer**		
Variables and parameters	1,3,8,9,12,13 14,15	2,4,6,7, 10,11	5	
	Static	**Dynamic**		
Hydrology	1,3,4,6,8,9,10 12,13,14,15	2,5,7,11		
	Forcing function	**Equilibrium**	**Kinetic**	**Not included**
Cation exchange	3,9,13	1,2,6,7, 10,15	4,5,8,11 12,14	
Weathering	3,5,6,9, 13,14,15	1,2	7,10,11	4,8,12
Biol. cycle	5,6,7,8,10,13 14,15			1,2,3,4,9 11,12
Aluminum chemistry		1,2,6,9,10, 13,14,15	7,12	3,4,5,8,11
Sulfur adsorption	1,2,6,7 11,15		12	3,4,5,8,9,10 13,14
Nitrogen chemistry	6,15		7,10	1,2,3,4,5,8,9 11,12,13,14
Organic compounds		6,7,10		1,2,3,4,5,8,9 11,12,13,14,15

Comparing models

A Nordic project was conducted to compare the performance of four models at three sites with differing acidification histories (Wright et al. 1991). The sites are Birkenes, southern Norway, acidified already in the 1950's; Stubbetorp, east central Sweden, with a present day stream pH of 6, and in the process of acidifying; Yli-Knuutila, southern Finland, with a good resilience to acidification. The four models (MAGIC, SAFE, SMART, MIDAS) were calibrated to present-day soil and stream chemistry. Four different deposition scenarios were used to predict soil base saturation and streamwater chemistry up to the year 2040 (Wright et al. 1991).

For Birkenes, all models indicated that a reduction of more than 55% in sulphur is needed for the soil base saturation to recover. A likely future acidification of soils and waters at Stubbetorp was predicted by all models with all scenarios. All models gave only small changes for the high base saturation values of the thick clay soils at Yli-Knuutila for all the scenarios.

Despite differences in predicted absolute values, the simulated trends were similar for all sites for all the scenarios.

In a series of papers documenting a rigorous comparison of ETD, ILWAS and MAGIC, Rose et al. (1991a) point out the importance of ensuring that the models to be compared are sufficiently different and not only different formulations of the same hypotheses. Only then can agreement between model results increase our confidence in the models (Rose et al. 1991a, Rose et al. 1991b, Cook et al. 1992). They developed a collection of rules and algorithms to transform a common set of information into the specific input values for each of the models. Thus they were able to avoid the effect of investigator-dependent configuration and calibration procedures on the model results. By analyzing mass-balance budgets for acid neutralizing capacity, they evaluated the relative importance of the soil processes included in the three models. Through Monte Carlo analysis, they identified the sources of the variability of the predicted acid neutralizing capacity. They concluded that the three models are structurally different and that predictions of changes in acid neutralizing capacity were more similar than the predicted absolute values.

Future development

In order to assess the influence of forest land use, acid deposition and climate change, a better knowledge of the behavior of organic matter, N, Al and Fe in forest soils is needed. Quantitative estimates of the amount and the quality of organic matter in Finnish podzolic soils are still few. The importance of organic matter in retaining Ca^{2+} and Mg^{2+} through cation exchange is well known, but detailed knowledge of how the cation exchange capacity of organic matter changes is lacking. Also, the rates of organic matter decomposition, mineralization and nitrification under varying field conditions are poorly known. The fate of aluminum and iron in forest soils is of importance when assessing the combined effect of the changing environment. Not enough is known about the ability of Al^{3+} and Fe^{3+} to form organic complexes and the role of these ions in cation exchange. The mechanisms of feedback from soil chemistry to root functioning and uptake are still unclear, and therefore lacking in all models. Until these questions have been properly addressed by soil science, so that they can be included in the models, forest soil models will continue to fail in some conditions.

Process-oriented models are today the best tool for exploring the impact of different deposition and climate change scenarios. As regards acidification, modelling can provide an insight into the combined effect of sulphur and nitrogen deposition on soil chemistry and through that on water quality and forest growth. In view of a future climate change, soil models can illustrate the water quality consequences of changing hydrological and

temperature regimes. We cannot, however, rely on the predicted absolute values. Instead, more emphasis should be put on studying the sources of the variability in the predicted values and trends.

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Response of the boreal forest ecosystem to changing climate and its silvicultural implications

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Background to the study and the study problem

In Finland, the future mean annual temperature is expected to be two to three degrees higher than the present values, the temperature rise being the greatest in winter with a consequent lengthening of the thermal growing season. Furthermore, the annual precipitation will nearly double, the increase being at its greatest during wintertime. The climatic change increases the uncertainty of the future management of the forest ecosystem.

This study aims at outlining the ecological and silvicultural implications of the changing climate with regard to (i) how the expected climatic change could modify the functioning and structure of boreal forest ecosystem, and (ii) how the silvicultural management of the forest ecosystem should be modified in order to maintain sustainable forest yield in changing climatic conditions. The biological and silvicultural implications of the computations are utilized in outlining the options for timber production in changing the conditions based on model computations.

Outlines of modelling

The model is based on the assumptions that the climate change has direct effects on (i) the amount of radiation and its distribution into direct and diffuse radiation, (ii) the air temperature and its annual and diurnal distribution, (iii) the amount of precipitation and its distribution into rain and snow, and (iv) the wind velocity and its variability. Similarly, the climate change is assumed to modify indirectly (i) air humidity, (ii) soil temperature, (iii) availability of soil water, and (iv) availability of nutrients. The availability of nutrients will be modelled based on the annual time step. In other cases, the time step will be matched as closely as possible with time constant of the process, the shortest time step being one hour (Fig. 1).

The physiological processes of the plants link the plant community and the environment with each other, the linking factors being photosynthesis, respiration, transpiration, nutrient and water uptake and acclimation. All linking factors act the year-round, acclimation being the process copying the other processes into the annual cycle of the climate.

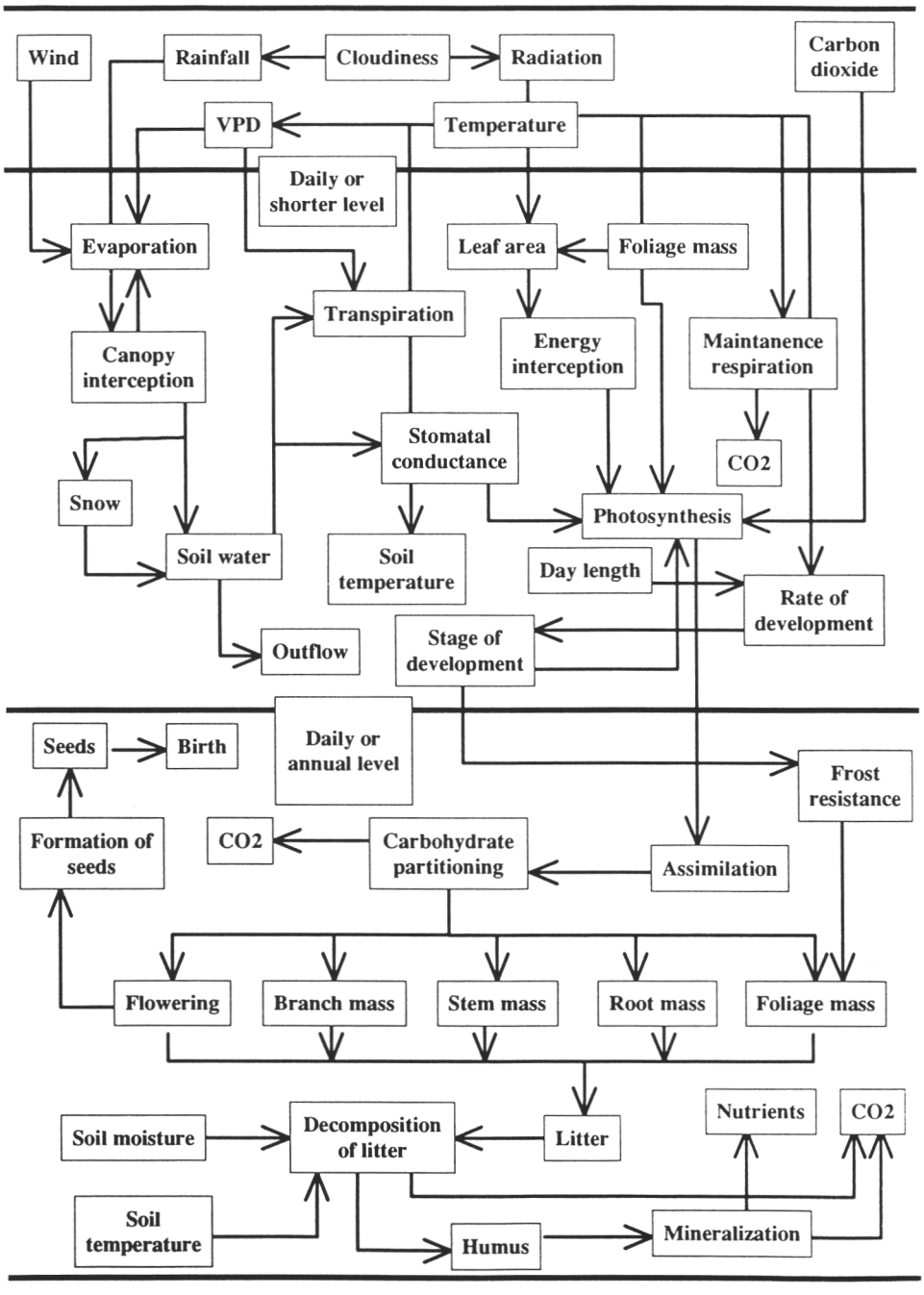

Figure 1. Outlines of the processes used to model the interaction between trees and the climate and the soil.

The effects of different processes on community dynamics are extended over the life span of trees with a consequent output of the model in terms of the succession of the tree stand and the within-stand environment. In this context, the silvicultural management of the tree stand modifies directly and indirectly the community and, consequently, the growing conditions, thus enabling one to copy the forest ecosystem into the changing climate.

Outlines of the implementation

The study problem requires a model describing the effects of the climatic change on the functioning and structure of the boreal forest ecosystem and its silvicultural implication in terms of a proper management and the subsequent timber yield. Consequently, the model incorporates the following compartments.

Physical environment

The simulation of the weather pattern includes solar radiation, temperature, precipitation, air humidity, wind velocity and carbon dioxide concentration representing the annual and year-to-year variation around a given trend. Similarly, the simulation of the soil conditions includes temperature and water as determined by the physical structure of the soil profile. The nutrient pool available for tree growth is linked with the soil type and the quality and amount of organic matter and its decomposition.

Biological processes

The simulation of the recruitment of trees includes the formation and germination of seeds, the establishment and growth of seedlings as controlled by the physical conditions, and it is influenced by the presence of competing trees, ground vegetation and pathogenous organisms. The simulation of growth is based mainly on modelling principles, which allow the growth of individual trees being controlled by radiation, temperature, soil moisture and nutrient supply. A separate model for the growth and development of ground vegetation is prepared assuming that the tree layer controls the growth and development of the ground vegetation through the modification of their growing environment. The simulator for death is based on the modelling principles, which relate death to the growth efficiency and life span of trees. The simulation includes death due to strong winds and snow accumulation. Fungal and insect damages are modelled by assuming that the outbreaks of epidemics are a function of site factors, stand structure, the time elapsed from the preceding outbreak and random factors. The simulator for decomposition of litter and humus is based

mainly on the modelling principles, where the quality of litter and humus, soil temperature, moisture and nutrients are the factors controlling the decomposition rate.

Silvicultural management

Silvicultural management includes regeneration (natural, artificial), tending of the young stand (control of density and tree species composition), thinning, fertilization and soil treatment (scarification, control burning). All these measures change the structure of the forest ecosystem and, thus, result in changes in the processes (birth, growth and death) controlling the dynamics of the forest ecosystem.

Model input and output

The input of the model include the properties of tree stands in terms of the characteristics of the trees, soil, climate and management. Trees are characterized by species and diameter; these are used to derive the initial values of several other parameters of trees. Climate includes radiation, temperature, rainfall, and wind, and several other factors derivable from the above parameters. Soil is characterized by the chemical and physical properties of humus and mineral soil, these parameters being used to derive other parameters needed in simulation. In addition, the input of the model will include the management of a tree stand and soil as specified in different silvicultural measures.

The model is expected to produce the values of the parameters, which are further needed in evaluating the consequences of the changing climate for the dynamics of the forest ecosystem and the measures needed to adapt the silvicultural management with the changing conditions. The values of the different parameters can be further converted into the values of other parameters needed in evaluating of the effects of climate change on forest production.

The aim of simulating forest dynamics at a regional level requires from the model that it is capable of utilizing spatially differentiated information about the properties of the biological community and the physical environment. Therefore, the simulation model for the forest ecosystem will be a part of a larger system, which includes also systems to handle spatially organized data files. In this context, several data files on the properties of biological community and physical environment are used as input files, which are also capable of storing the output values of the simulation model for the forest ecosystem or its submodels.

Analyzing empirical stand development series in relation to simulated estimates of radiation interception: A new look at old data

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Introduction

When analyzing the dynamics of stand growth processes, it is useful to distinguish between four basic phases affecting biomass production: (1) supply rate of resources (radiation, water, nutrients), (2) resource capture, (3) efficiency of resource use in biosynthesis and (4) allocation of fixed carbon within trees. Traditionally, the emphasis in forest growth studies has been on monitoring biomass accumulation (phase 4) as a function of age. The results were formalized in the form of growth and yield tables, which express the development and growth potential of a particular genotype under a particular set of growing conditions. This approach is, however, inflexible and the predictions are true only if growth conditions remain unchanged. Accordingly, process-based mechanistic approaches have recently become more and more popular. Process models attempt to simulate the basic growth processes (in phases 1-4). However, building process models of entire ecosystems has proven to be an extremely demanding task, not least because of the gaps in the existing data basis.

When studying the relationships between biomass and production, the existing studies on stand development can, however, be further utilized by combining the empirical data from earlier studies with process models of forest functions (Kimmins et al. 1986). The idea is to compare the measured long-term stand development data (phase 4) against simulated estimates of resource supply and/or capture (phases 1 and 2, see Fig. 1). The advantage of this approach is that it allows one to analyze the implicit complexity of growth and yield data (trees integrate over the rotation all the effects of all the factors that determine their growth rate) in relation to the simulated behavior of some of the driving variables of forest production.

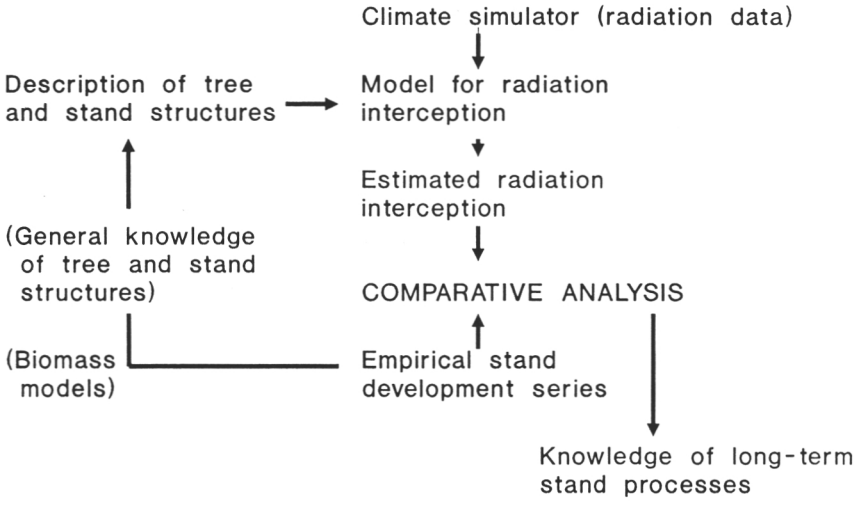

Figure 1. The basic components and steps of the analysis in which the measured long-term stand development data are compared against simulated estimates of radiation interception.

An example: stand development in relation to radiation interception

Although the central role of canopy characteristics and processes in forest production is widely acknowledged, relatively little is known about the long-term changes in total stand biomass, leaf mass (area) and radiation interception as related to production in northern Scots pine forests. One reason for this is that forest development, especially in northern latitudes, is an extremely slow process. Another reason is that many of the earlier studies focused on stemwood characteristics owing to their forest mensurational point of view.

The aim of the study (Kuuluvainen 1991) was to analyze the long-term development and relationships of three basic components of northern boreal Scots pine forest production: 1) needle biomass, 2) interception of photosynthetically active radiation (PAR) and 3) stemwood production. This was accomplished by completing Ilvessalo's (1937) classical study on the growth and development of Scots pine in central north Finland with a biomass equation and a process model of radiation interception.

Since the study by Ilvessalo (1937) did not take into account foliage characteristics, the needle biomass of the stands at a particular age was estimated using the needle biomass equation of Albrektson et al. (1984). After comparing the site descriptions of Albrektson et al. (1984) and those of the stand development series of Ilvessalo (1937), the rather fertile *Empetrum-Vaccinium* -site was chosen as the reference site type. This enabled one to outline the development of stand needle biomass in relation to other characteristics of stand structure and stemwood production over a period of 150 years, from stand age 50 to 200 years.

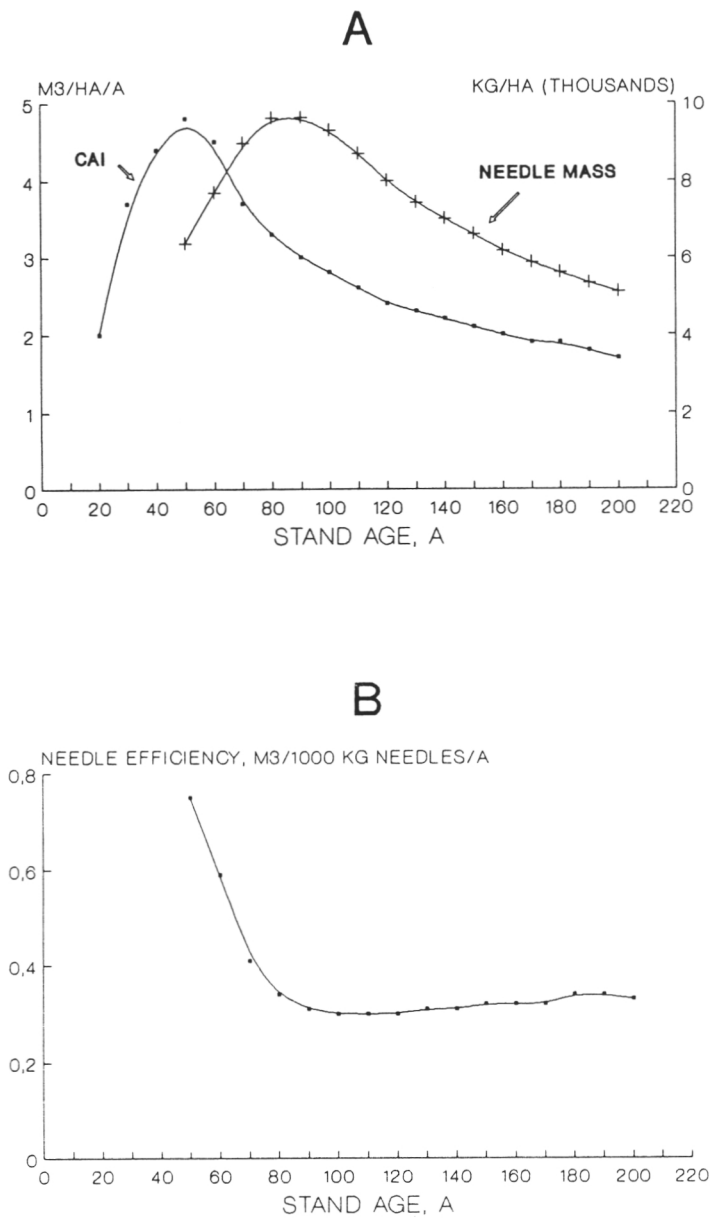

Figure 2(ab). Analysis of the development of specific properties of structure and productivity of Scots pine stands on *Empetrum-Vaccinium*-site type in northern boreal zone in Finland. (a) Simulated stand needle dry mass in relation current annual volume increment of stemwood excluding bark (CAI) as given by Ilvessalo (1937); (b) Needle efficiency in stemwood production, i.e. the annual amount of stemwood produced per unit needle mass (derived from curves in Fig. 2a).

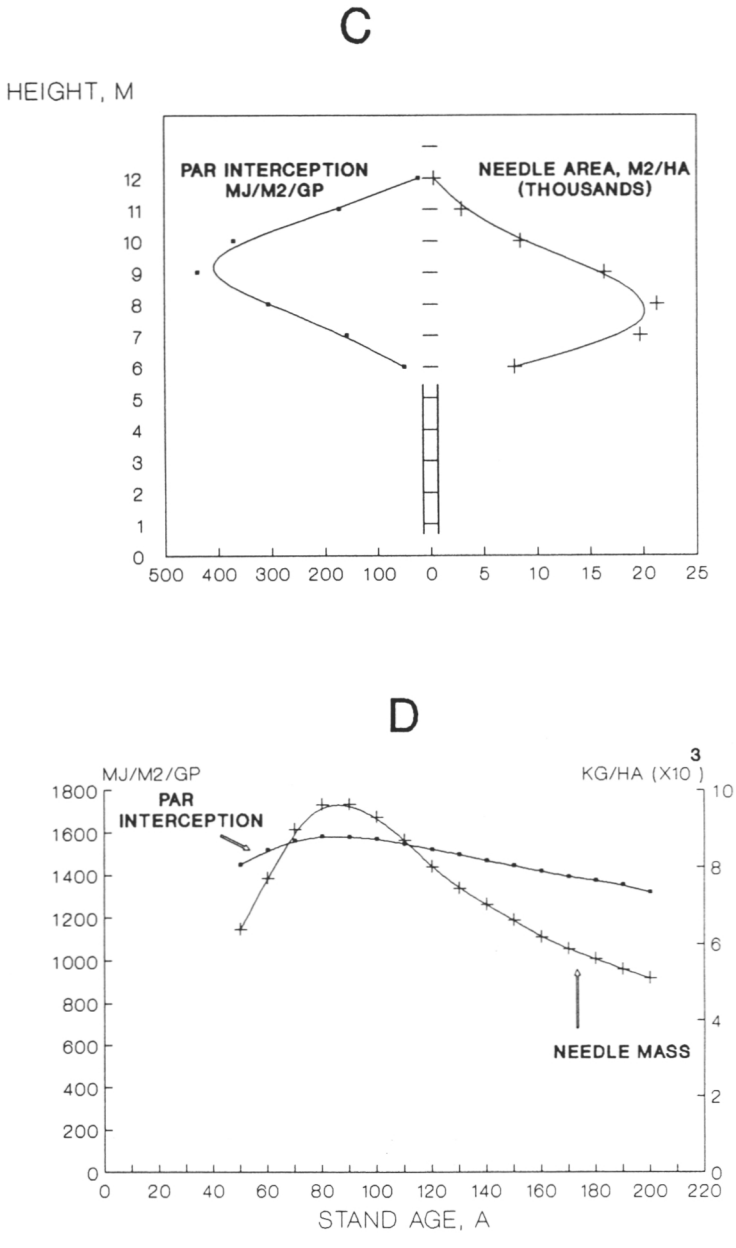

Figure 2(cd). Analysis of the development of specific properties of structure and productivity of Scots pine stands on *Empetrum-Vaccinium*-site type in northern boreal zone in Finland. (c) The simulated vertical distribution of needle area and interception of photosynthetically active radiation (PAR) during growing period (GP) at stand age 60 years; (d) The development of simulated annual PAR interception in relation to stand needle dry mass with stand age (Kuuluvainen 1991).

Finally, a model outlined by Nilson (Hari et al. 1985) was used to simulate the interception of photosynthetically active direct and diffuse radiation (PAR) in the canopy during growing seasons. To facilitate this, the canopy structure was modelled by utilizing the computed needle masses and the stand characteristics given by Ilvessalo (1937). All the computations were carried out at latitude 67°, which approximately corresponds to the locations of Ilvessalo's (1937) sample tree stands in northern Finland. The growing season was assumed to range from the beginning of May to the beginning of October (Julian days 150-270). The poisson distribution of trees and Poisson distribution of foliage within the needle bearing crown volume was assumed.

Discussion: shortcomings and advantages of the method

The applied method enables one to analyze the pattern of stand development in relation to the most important driving variable of forest production, i.e. solar radiation. This kind of a long-term analysis would not be feasible otherwise. However, the method involves inevitable uncertainties. For example, no accurate method exists for the estimation of needle biomass, because both stem and needle characteristics are known to vary considerable in Scots pine (e.g. Bröms & Axelsson 1984). The needle biomass model of Albrektson et al. (1984) was selected, because the available Finnish needle biomass equation (Hakkila 1971) requires crown ratio (crown length/tree height) as an input variable, which was not measured by Ilvessalo (1937). Also the mean tree method may introduce some uncertainty to the stand-level needle biomass estimates (Zavitkovski et al. 1974).

When calculating radiation extinction, the canopy cover was assumed to be constant, although in reality the degree of canopy cover may change and it probably declines with stand age as the stand breaks up. Also, random tree distribution was assumed, which is apparently unrealistic especially in older stands. However, the effect of these factors on intercepted radiation is, although obvious, apparently rather small in fully-stocked coniferous stands (Pukkala & Kuuluvainen 1987).

In spite of these inevitable shortcomings of the method, the estimates of stand needle mass and PAR interception were regarded as being reliable enough for the present purpose for three reasons. Firstly, older naturally regenerated and undisturbed Scots pine stands in northern Finland are typically rather homogenous (Ilvessalo 1937). Secondly, the values for mean diameter and mean height, which were used as predictors in the needle biomass equation, were computed by weighing with basal area (Ilvessalo 1937); this method should lead to rather reliable results. Thirdly, although the actual values of needle mass and PAR interception may not be reliable, the long-term pattern of changes, of which we lack knowledge, should be predicted fairly accurately.

In conclusion, the assumptions needed for the calculations cause an inevitable shift from quantitative to more qualitative predictions. Therefore, the results presented, although valuable as such, can be taken only as first

approximations of the long-term relationships between the studied variables. The availability of a region- and site-specific needle biomass model, and additional information concerning tree and stand structures, would obviously have resulted in improved accuracy of the derived estimates.

Some conclusions

It is obvious that the presented method of analysis can produce such information of long-term stand dynamics as cannot be obtained otherwise. For example, the cited analysis of the long-term development of undisturbed Scots pine stands growing on *Empetrum-Vaccinium* -site types in the northern boreal zone demonstrates that, within their endogenous developmental cycle, these stands undergo periods of severe stress due to competition and, most probably, time-lags in the nutrient cycle (Pastor et al. 1987). It is well known that stressed trees have limited resources for defence and repair and are, therefore, more susceptible to pollution damage and various pathogens than unstressed trees. This emphasizes that endogenous changes in stand development should be taken into account when assessing pollution effects on tree growth (Loehle 1988).

The cited analysis further points out that the efficiency of foliage in radiation interception and/or biomass production could be a useful indicator in monitoring the development and stress stage of forest stands. The possibility of identifying stands undergoing severe stress would facilitate the implementation of silvicultural measures to diminish the stress and risk of damage due to air pollutants and/or biotic pathogens.

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The early development of pine plantation and its silvicultural implications: An on-going work

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Introduction

Artificial forest regeneration always leads to the establishment of both planted seedlings as well as naturally born seedlings. A stand composed of planted seedlings is usually the goal of artificial regeneration. Most of the naturally born seedlings are unwanted (shrubs etc.). Therefore, this is the stage at which the silviculturist has to ensure the future development of planted seedlings. The usual tending methods at this stage are cleaning, beating up, and controlling of ground vegetation. On the other hand, the silviculturist must have a goal for his decisions. Usually the silviculturist has in his mind a picture of the desired young stand. The stand might be 20 - 30 years of age, of a certain density, and with a certain mixture of tree species.

However, human decision-making can not take very many facts into account. It is also subjective by nature. Computer-assisted decision-making has advantages which improve human decision-making in this respect. It is capable of handling an unlimited amount of information, of picking out the essential facts from a vast amount of information, and of even solving problems by itself by using a knowledge-based model of the area (Kaila & Saarenmaa 1990).

A new area in ecological modelling is the use of the object-oriented approach in building simulation models. The object-oriented approach leads to constructive thinking by specifying objects having an internal structure and functioning. It allows definition of a problem in terms of actors (objects) and the communication of messages between them (Coulson et al. 1987, Cox 1986). Each biological object, such as a tree, can be considered as an 'actor' receiving messages, 'acting', and sending messages (Bossel & Schäfer 1990). Thus, the basic idea of an object is appropriate to a real stand, where there is a collection of objects (trees) and interactions between them (competition). The available techniques make simulation programming easier, and allow easier interfacing with graphics and other

support facilities (Tsatsoulis 1991).

In fact, the decision-maker is one actor in the system that describes the early development of a stand. The target for the decision-maker is to make a model of the stand. The decision-maker -object is doing model-based reasoning in his decision-making. This approach makes possible the presentation of in-depth knowledge of the system.

The aim of this study is (i) to build a simulation model of a pine plantation and (ii) to use the model in an expert system to define the actions needed during the early development of a pine plantation to achieve the target stand.

The stand model

The model has to respond to the following demand: a single tree spatial model having the development of sprouts and ground vegetation included. Sprouts and ground vegetation clearly influence the development of the planted pines.

The height growth (Y) of pine plants is carried out as a multiplicative model

$$Y = Y_0 Y_1 Y_2 Y_3$$

where Y_0 = potential height growth,
Y_1 = competition from neighbouring seedlings,
Y_2 = competition from sprouts, and
Y_3 = competition from ground vegetation.

The competition from neighboring sprouts for example is described in the way that Andersson (1982) describes it; i.e. as the basal area of neighboring sprouts nearer than 1 m. The most unknown competition factors is the influence of ground vegetation.

The modelling methodology is the concept of object-oriented analysis (OOA), design (OOD), and programming (OOP) (see e.g. Korson & McGregor 1990, Booch 1991). The object structures of Kolström (1991) and Kolström & Salminen (1991) are modified to respond to the needs of this typical situation.

Defining the needed actions in a young stand

The need for actions rises from two different types of situations. Firstly, the desired actions can be defined purely on the basis of the actual situation in the stand. Secondly, the needed actions can be defined on the basis of the actual situation in the stand and the intended structure of the stand in the near future (Fig. 1).

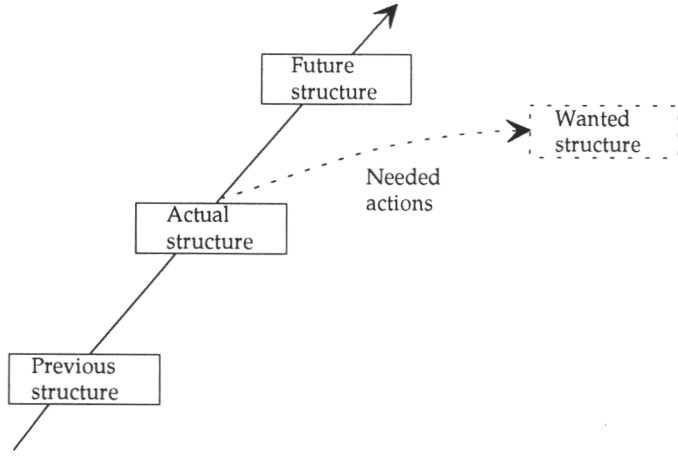

Figure 1. The effect of the past development in a stand and the silvicultural actions taken on the future development of a stand. A schematic presentation (Daniel et al. 1979).

Just as the model of the stand is a collection of different objects, silvicultural actions and cleaning models are presented as objects. The active object controlling these actions is the decision-maker object that can be presented as the agent "Forester". The "Forester" agent mimics the behaviour of a real forester in a real situation (for more about agents, see, for example, Minsky 1988).

Present situation of the project

The model of a pine plantation is now almost ready. The emphasis is at the moment on developing the "Forester" agent and the objects "Forester" needs in his decision-making. The system is done using the ProKappa expert system shell in a workstation. One aspect of the task is to make reusable elements in the way presented by Pratt et al. (1991).

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Stabilization and uncertain resources

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Introduction

Economic efficiency is the most common objective dealt with in the literature on the management of fluctuating resources (Clark 1985, Mangel 1985, Walters 1986). Stabilization of uncertain resources or resource economics has received relatively minor attention. (For general references on applying systems analysis modelling in ecological modelling and resource management, see Jeffers 1978, Edelstein-Keshet 1989, Getz & Haight 1989, Clark 1990, Braat & van Lierop 1987).

A resource management problem is a situation in which the management objective is to minimize fluctuations in resource stocks or animal populations. Such situations arise in different fields of resource and wildlife management. In resource management a manager may depress the stock fluctuations to increase the productivity and the economic security of the enterprises and the workers involved in the sector.

Let's look at the issue of stabilizing resources. System dynamics are modelled by discrete time models and the dynamics are affected by fluctuations. The realization of these fluctuations is not known at the time of decision making. Let's assume that no statistical description of the fluctuations is available or used in decision making. Let's assume, however, that the bounds of the uncertainties are known. Given these constraints, let's study the conditions under which it is possible to stabilize resource economics systems into certain "tubes" around the nominal solutions obtained in the absence of the uncertainties.

Resource model

Consider an uncertain density-dependent resource described by a difference equation of the form

$$N(k+1)=F[N(k),v(k,N(k),u(k))]+u(k), \qquad (1)$$

where k=0,1,... is the time, N(k) is the size of the resource stock at time k, F(.) is the growth function of the resource, and u(k) is the control during period [k,k+1]. A positive control (u(k) > 0) corresponds to stocking the resources, while a negative control (u(k)<0) means harvesting. The unknown function v(.), depending on time, stock level and harvest rate, represents the uncertainty or fluctuation related to the growth function of the resource (e.g., forest, fish, game, pests, etc.).

Let's assume that the fluctuation affecting the growth rate is bounded and satisfies

$$| v(k,N(k),u(k)) | < \bar{v} \tag{7}$$

where $\bar{v}$ are known.

The common choices for the (undisturbed, uncontrolled) growth function for the animal populations are as follows:

$$F(N(k),0)=N(k)(1+r(1-N(k)/K)) \qquad \text{(logistic growth)} \tag{2}$$

where r is the growth rate and K is the carrying capacity;

$$F(N(k),0)= \alpha\, N(k) \exp(-\beta\, N(k)) \qquad \text{(Ricker)} \tag{3}$$

where α and β are positive parameters; and

$$F(N(k),0) = \frac{\alpha' N(k)}{\beta' + N(k)} \qquad \text{(Beverton-Holt)} \tag{4}$$

where α' and β' are positive parameters.

Figure 1 illustrates the annual growth of an unharvested resource. The annual growth is now equal to F(N(k),v(k,N(k),u(k)))-N(k), where u(k)=0 for each k.

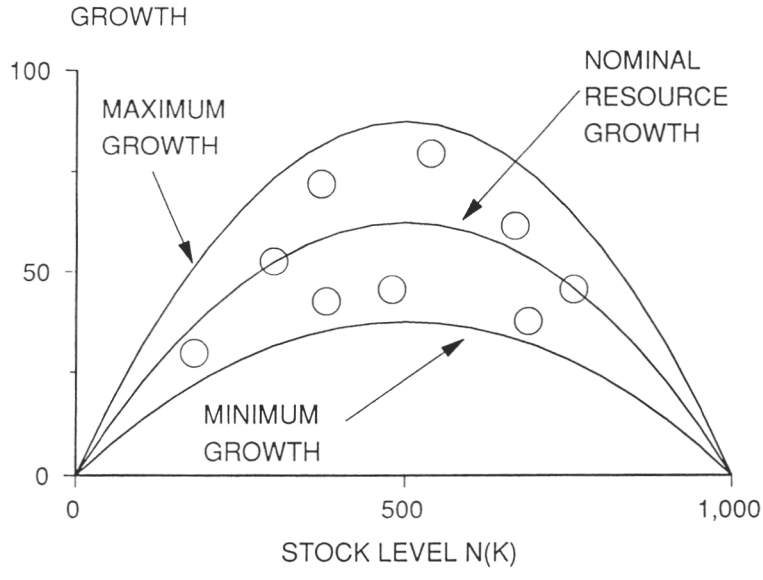

Figure 1. The resource growth fluctuates around the nominal resource curve in the set between the maximum and minimum growth curves. The figure illustrates the annual growth of an unharvested resource. The circles illustrate possible points in the set defined by the maximum and minimum growth curves.

Stabilization problem

Let's consider a resource management problem in which the resource growth fluctuates. The fluctuating growth can be modelled by assuming that the parameters of the models change from time to time.

- The management goal is to stabilize the resource level, or resource growth, to be near some chosen level.

- The desired level may have been derived for the optimization of revenue from fishery.

- However, the stabilizing goal need not be connected to optimal management of the resources. A need to stabilize fluctuations may also arise from other measures of management.

The usual assumption made in the resource management literature is that resource dynamics can be modelled perfectly, or at least that the statistical properties of the fluctuations are known (e.g., see Clark 1985, Mangel 1985, Walters 1986). Based on these assumptions, optimal harvesting strategies or other feasible management policies are determined in the form of memoryless state feedback policies of the form

$$u(k)=p(k,N(k))$$

Optimization is carried out by applying parameter and state estimation procedures together with dynamic programming algorithms. While being attractive as a theoretically sound method for designing management policies for uncertain resources, the attraction of the approach is reduced by the massive computational effort required for carrying out simulations. Typically, optimal harvesting strategies constitute management of the resource at some steady-state value, and adaptive management rules are used to refine this basic rule.

- Stabilization is computationally much simpler than dynamic programming.

Let's assume now that, instead of optimizing, the resource manager attempts to stabilize the resource, or the resource growth, around some constant steady-state stock level Ns. The choice of the target level Ns may be motivated by some optimization criterion. For example, the level may be determined by maximizing the sustainable yield from fishery. We shall treat the management problem as a stabilizing problem. Hence, the target level Ns will be considered here as a given value. No other explicit management criteria will apply.

Next, we define the nominal resource system by assuming that no (unknown) fluctuations are present in the system (1) - (2), i.e. $v(k,N(k),u(k))=0$ for all k, N(k), u(k). Thus, the nominal model of the resource growth corresponds to a deterministic growth curve around which the "real" resource growth is scattered.

- The nominal resource model is not a unique model and can be chosen by the resource manager.

In the absense of uncertainties, stabilization of the resource would be successful. The resource would be driven exactly to the chosen steady-state level Ns and kept there forever. Resource levels often tend to fluctuate, however, in which case resource managers may attempt to take these fluctuations into account in designing resource management schemes. A desirable management policy would be a harvest rate such that, for any disturbance function v(.), the equilibrium stock level Ns is asymptotically stable.

- Asymptotic stability requirements can be satisfied in some continuous time resource models (Corless & Leitmann 1985).

- Unfortunately, this goal is not achieved in discrete time models.

- Yet, it is possible to decrease otherwise considerable fluctuations, which occur when the disturbances are ignored and only nominal controls are used.

The management goal of resource stabilization can be characterized formally by the concept of global uniform asymptotic stability of a set. For a system to be globally uniformly asymptotically stable about a set B it is required that, starting from any initial stock level, the resource can be driven arbitrarily close to the set B in finite time and to remain there for all future time. Thus, the management goal is to keep the resource fluctuations in the range defined by the set B, and to make this range B as small as possible.

Global uniform asymptotic stability of a resource system can be achieved using the min-max Lyapunov stability approach (Corless & Manela 1986, Kaitala & Leitmann 1989, 1990, 1991) in designing the management rules. The method is based on constructing Lyapunov functions to measure the "distance" of the resource system from the steady-state level. The management scheme is then constructed such that, given any admissible realization of the disturbance v(.), the maximum value of the Lyapunov function decreases during each time step as long as the attractive set has not been reached. This property assures the stability of the system: the fluctuations of the stock level are decreased such that, after some time, the stock level is "near" the attractive set B where it remains thereafter.

The theory has been reviewed by Corless & Manela (1986) and Kaitala & Leitmann (1989, 1990, 1991) and simulation examples are to be found in Kaitala & Leitmann (1989, 1990, 1991).

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Information system analysis and modelling: The problem of object identification

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Computerized modelling in forest research

The paper is targeted at that the part of the forestry community which is specialized and advanced in information systems and software applications development. The problem of object identification has been studied as an essential part of object-oriented system analysis (OOA); specific object-oriented programming questions are principally omitted. The three addressed aspects are: information systems analysis and design, software systems definition, and modelling.

Information systems and software applications development in the Finnish forest research have evolved through several distinguishable stages during the past three decades (Kaila & Saarenmaa 1990). Modelling and computing have been recognized as being a logically connected methodological pair since the early 1970's, when linear programming, dynamic modelling and systems theory were introduced to the community. Modelling was emphasized also when the artificial intelligence (AI) methodologies and expert systems development were subjects of closer look in the mid 1980's. Also, the utilization of the object-oriented methods supports modelling. The latest stage in the development process is the emergence of GIS (Geographical Information System) applications. At present, modelling, in association with remote sensing and GIS, is considered as "the future backbone" of the Finnish forest research information systems development policy.

Modelling with objects

The concept of modelling reality as sets of objects has theoretically evolved from studies of entity-relationship type (ER) (Codd 1970, Date 1986, Sundgren 1981) and artificial intelligence (AI) (Feigenbaum 1977). The first

[1] The study forms a part of the author's licenciate thesis for the Department of Information Processing Science of University of Oulu

is fundamental in the theory of database design and analysis. In 1981, Sundgren proposed the concept of object-system, which consisted of four basic components: objects, attributes, object relations and time. The components were defined as follows:

- Object: An object is some physical or abstract substance that has some importance to a stake holder or a stake holder group. Persons, companies, cars, traffic accidents and trade transactions are examples of objects.

- Attribute: An attribute is a thing that at a certain moment of time characterizes a single object or a group of objects that share the characteristic feature at the moment; e.g. "to be a person", "to be 25 years old", "to be called Nils", "to be a Finnish company".

- Object relation: An object relation is a thing that characterizes the relationship between two or more objects. For example: "a person is the father of a person", "a person is employed by a company", "a company produces a product", " a country exports some goods to an other country", "a country joins economical community".

- Time: Time is expressed as moments or intervals of time.

The concepts of object types and object instances were also present in these early definitions. According to Sundgren (1981), when a system is specified using the above framework, it is reasonable to use (general) object classes instead of individual objects. In this sense, the presented object-system model formalizes the conceptual analysis and resembles the normalized form of database design. An important contribution of the presented model was that, above the data model level, everything can be described utilizing only one systems element; i.e. object. In comparison to ER-model (Codd 1970, Date 1986), which is used for the normalized representations of static data contents of information system, the time component allows the design of dynamic system components.

Subsequently, this conceptual basis has been a subject of substantial evolution. The true origin of object-oriented thinking, that we practice today, is in the development of object languages and exercises with object-oriented applications. These were first discussed in association with the SIMULA language, and further developed within numerous software development environments (Smalltalk, C++, Ada, Actor, KEE and ProKappa). Object languages define objects with dynamic component and behaviour that creates entirely different conceptual setting for systems development. Relation-based data modelling (ER model) always needs separate application program, which leads to unwanted dualism preventing system modelling as one whole. The principles of encapsulation of methods and data structures into functional and separately controlled units (objects), inher-

itance of attributes and associations in the object class hierarchy, and message passing based communication between the object instances, allows the design of software application systems capable of reproducing the functions of the real world as they occur.

Information system design

The traditional information system design process is based on the ER type, and follows a few basic thinking patterns, which apply to the object-oriented approach as well (Shlaer & Mellor 1988, 1989). A common way to organize information systems development concepts is to make a distinction between the activities and the goals of IS analysis and design. The definitions of the IS environment, boundaries, main components, policies, functions, and products are outcomes of a definite analysis phase. IS analysis includes feasibility evaluation of the future system and planning of the needed development project. The resulting information system abstraction must focus and conduct the work in the following design activities.

Many theoretical approaches to OOA use the Structured Analysis methodology (DeMarco 1978, Korson & McGregor 1990, Yourdon 1990) as an important rudiment. In this methodology, the Information Systems and application Software (IS/SW) design is done using a specific set of formal tools that include data flow diagrams, data dictionary, process specifications, entity-relationship diagrams, state-transition diagrams, and resource allocation and scheduling charts for project management. The analysis proceeds by producing a series of systems models (abstractions) including an environmental model, a behavioural model and an user implementation model.

In Yourdon's (1990) terminology, the essential model contains the complete description of what the future system should do to satisfy the user. It consists of two major components; an environmental model and a behavioural model. The environmental model defines the boundary between the system and the rest of the world. The model gives to a systems analyst a way to figure out what kind of changes are needed to get a functional organization to work better, and what is the form of the ideal system. The environmental model includes a statement of the purpose of the system, context diagram and event list.

A behavioural model describes the required behaviour of the system, necessary for successful interaction with the system environment. Yourdon (1990) suggests dividing the behavioural model building into two phases; firstly, the building of a preliminary model, and then completing it. This division can be seen as an implementation of a determined iteration within the design process. The behavioural model is technically a first-draft data-flow diagram which is produced from the event list produced during the previous design phase.

Once the analysis phase is completed, the work continues into the phase

of application implementation. In Yourdon's (1990) terminology, this is the phase of design which will produce a systems-implementation model and a program-implementation model. Questions referring to this level are beyond the scope of this paper and the reader is encouraged to pursue the original references (Yourdon, 1990, Yourdon & Constantine 1989, Page-Jones 1988, Ullman 1988, Mellor & Ward 1986, Orr 1977, Jackson 1975).

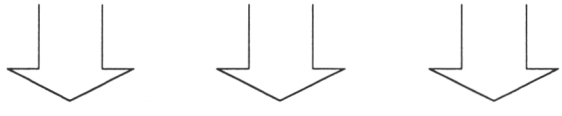
Object identification

Functional decomposition (top down) and linear progression assumed in the traditional information analysis are too simplistic patterns for complex object-systems definition (Henderson-Sellers & Edwards 1990, Iivari 1991). An object-system model should rather be seen as a result of conceptual analysis, which is concluded in an iterative way (Iivari 1991, Kaila & Marshall 1992). In a formal form, this abstraction collects the system's Universe of Discourse (UoD) (ISO-report 1982) of the application problem and lets the designer to use the object collection as a set of building blocks for any kind of application software development.

Even though we have the basic elements of the object model well defined, and even though modelling with objects seems to give us an easy and powerful tool for formalizing reality in the way that leads to reasonable software application specifications, there are some blind areas at the information systems development level. To date, there is no theoretically sound set of norms to control how the object-oriented analysis should be performed. In addition, it is still obscure how object-oriented programming project should be managed. Several competing methodologies are currently on the market (Coad & Yourdon 1990, Booch 1991). Especially CASE-technologies (Computer Assisted Systems Engineering) have produced multiform products that support either general or standardized application generation rules, or serve as build-in innovations in association with some particular application generation environments. Both approaches have their pros and cons; judgment is left to the reader.

With regard to object-oriented approaches, Iivari (1991) makes a distinction between the following three activity classes: information systems development, application software development, and development of reusable software components. In every case the concept of object identification is an essential part of the object-system definition process. Object identification means the definition process where the characteristics i.e. attributes, associations, methods and behaviour of an object class are defined. Iivari also suggests five useful general object types. All objects can be identified either as user, entity, event, information or interface objects. For technical support to object identification process, Iivari has organized the following conceptual framework (Fig. 1).

		1 Structure abstraction	2 Function abstraction	3 Behavior abstraction
I Organizational level	Ia Designed context	Organizational actors and positions Organizational channels	Organizational functions Input and output flows State/stores	Events Triggering conditions
	Ib Application concept	Users	IS services	IS use acts
II Conceptual/ Infological level	IIa Universe of Discourse	Object types, entity/event types Association types Attributes	Action/Operation types	Events Triggering conditions
	IIb IS applications	Information types	IS functions	Events Triggering conditions
	IIc User interface	Interface object types - application dependent and generic	Interface operation types - application dependent and generic	Interface acts
III Datalogical/ Technical level		Abstract machines and data Communication links - device dependent	DB/files, SW/program components, I/O data types and algorithms - device dependent	Events, control states, control rules, control state transitions and data processes



OBJECTS METHODS MESSAGES

Figure 1. Modification of the integrative framework for object identification (Iivari 1991).

Exercise: Objects of a Virtual Forest

In this last section of the text, we shall conduct a mental exercise to test Iivari's (1991) framework of object identification (Fig. 1). We shall to give some general level definitions to an imaginary, but familiar, concept denoted here by the term "Virtual Forest" (VF). (It should be pointed out that the author's intention is not to give an exhaustive declaration of the conceptual volume and content of VF). VF is a connotation of the concept of virtual reality (VR) (Huhtamo 1991).

In essence, VF is a set of super classes for a collection of reusable software components. It may serve the forest research community as an implementation of model repository, and it defines the general interface standards for model production.

At first, the proposed framework suggests to us to abstract the target system's structure on the organizational level. In this respect, we make the following definitions of candidate user objects:

- VF is a commonly known and shared platform for model implementations.

- It is actively developed and maintained by the knowledge engineers of a forest research unit.

- Direct users of the associated system are model developers and application programmers.

- Application users may have indirect access to VF.

The functionality of VF allows users to add models into the object-system. Application development based on object libraries must be directly supported.

- Information retrieval, controlled object extraction, and object deletions by authorized users are allowed.

VF forms a new logical resource for knowledge work. It serves as a forest and landscape simulator, cultivated electronic communication channel or software library. It has multiple interfaces for application integration and networks.

After the definition of organizational use acts (omitted here), we have specified the top level features of the demanded object-system. Thus, we have figured out the user object candidates, and defined the appropriate methods and messages in general.

Object identification on the conceptual/infological level produces definitions for the information contents of the object-system (UoD). Because VF is an application environment for different kinds of models, and many of the

models represent some specific methods of particular object types, the object selection of VF has to be flexible and include the following objects of entity and event types.

- The meta-abstraction of model produces a principal object into the system.

- The elementary object types of VF will be formed from sets of typical forest entities including trees, vegetation, growth sites, topology, etc.

- The set of basic events may include patterns for planning, growth, silvicultural treatments, harvesting, raw material transportation, land use etc.

The list of acceptable entities and events is unlimited because any change in aspect may produce an extra set of features.

One important feature of VF is its dynamic development or evolution. The system will grow and encounter changes in the course of time. Every included model is alterable and insertions of new models may cause changes in the overall behaviour of the object-system.

- The concept of time is characteristic for VF. The object type may have many different scale-dependent implementation forms.

Because we have assumed that VF will be rather a collection of reusable software components than a defined information system, the IS specifications will be very application dependent. We define the following general information object classes.

- I/O transactions, generic documents and queries may also have more general research related features.

- The implemented system may produce aggregated information through integrated statistical software, business graphics or image processing. For these purposes, certain data matrix object types may be useful.

The interface object types and associated function types are also application dependent and generic by default.

- VF should include a general pattern for graphical representation of forest information. Ability for 2, 3, and 4 dimensional projections is required.

- A general test bench for model fine-tuning, model browser and model dictionary of information contents should be added to the template of optional system services.

The object identification on the conceptual/infological level is completed by concluding the behavioural features of the object-system. Many of VF models are triggered by time, but it is only one aspect of object-systems behaviour. Mostly the objects are triggered by messages caused by events in other system components.

The last phase in our "first iteration of conceptual analysis" produces the datalogical/technical level abstractions of VF. The object-systems technical requirements will be defined, as objects of abstract machines, data base files and software components, considering the above organizational and logical boundaries.

- VF will be implemented in a host computer.

- The model developers and application programs will work at workstations. Graphical user interface and animation options are required.

- The user, or any other source of queries, may approach VF through a computer network. The LAN and WAN services offered may differ from each other.

VF's object repository and applications will be implemented in a specific message passing environment, indicating the need for an object-oriented application development shell. Modelling work may also be augmented by use of advanced hardware/software techniques; e.g. massively parallel computing, hypertext or multimedia. These options denote different abstraction for hardware/software structure. The functional as well as the associative behavioural features are highly dependent of the device platform.

Conclusion

Modelling has a close relationship with the object-oriented systems development. Object-oriented IS/SW development differs from traditional ER based information system approach. Also, the development of information systems, application software, or reusable software components differ from each other. Identification of candidate object types is essential in the object-oriented analysis. All objects can be identified either as an user, entity, event, information or interface object. Iivari's (1991) framework for object identification, rationalizes and supports analysis process of this class.

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Object-oriented topological simulation models of trees and massively parallel computing

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"If the only tool you know is a hammer, the rest of the world soon begins to look like a nail."
- Jan Aikins at International Joint Conference on Artificial Intelligence, 1987.

Introduction

Nowadays, simulation is achieved only through the use of computers. The rapid advancement of computer science has brought about a large amount of new technology that is now available for building applications. However, the thinking of forest modellers has developed under the influence of the tools known to them through experience. In terms of software, these include statistical methods, FORTRAN, and for some, differential calculus and dynamic models. In terms of hardware, there has been no choice other than serial machines.

An ideal simulation model resembles its natural counterpart by as many facets as is practical. Software for forest modelling should, therefore, have the abstraction capability to mimic the structure and functioning of trees and landscapes. Unfortunately, none of the methods mentioned above insists or supports any structure for the models. Eventually, this has led to difficulties in the reuse and sharing of models between research groups. The axiom "models should always be made for some purpose" has turned into "everybody makes his own models".

In nature, all the trees grow at the same time. In forest planning, many operations should be evaluated simultaneously. Thus, the hardware should allow parallel execution of the algorithms.

New solutions from software engineering have removed some of the limitations of the old tools. The most important technology is object-oriented programming which binds all functioning to some reusable structure. Hardware, of course, will always impose some limit on processing speed, but even today 10 000 MFLOPS and 10 000 MIPS on parallel simulation are achievable.

This paper describes an attempt to build a model of a tree that would be

as realistic and shareable as possible. As it will turn out, it fits in naturally with parallel computers. I shall also deal with some parallel processing technology that will be at our disposal in the near future.

A topological model of a tree

Diagnosing problems of forest health requires an understanding of the physical connections and functioning of the tree's parts and their interactions with the outside environment. For instance, a spruce killed by the bark beetle *Polygraphus* remains green in its top but yellows under the midpole. This is because the bark beetle blocks the downbound material flow in the phloem, but does not harm water transport in the sapwood. However, the ultimate cause of the attack may have been drought that delayed the resinous response of the tree towards the initial attackers.

An expert system that tries to achieve this level of performance must have a model of tree's physical structure and functioning upon which it bases its reasoning. Describing all possible static relationships for each prospective harmful agent with rules would be impractical and leave the knowledge base superficial, not capable for causal reasoning. It would save lots of effort to base reasoning on some existing simulation model of tree dynamics. None of them, however, makes explicit the objects that the diagnostic rules must access; i.e., what is needed is a topology of interconnected objects of various parts of the tree such as leaves, shoots, phloem and bark. The expert system can then reason about the attributes of the parts, such as water pressure and physical damage status.

The most practical way of building such a topology is to grow it from a single initiating seed. This brings us close to L-systems (Lindenmayer 1968, Prusinkiewicz & Hanan 1989). L-systems do provide the foundation for the branching rules used here, but they do not preserve the status of the branching node once it has been drawn. The status is preserved by the object-oriented description of the nodes in the present model. Objects are also ideal for reasoning.

The present model (Saarenmaa 1991) is written in LISP and KEE. It has three top level-classes: TREE, TREE-PARTS and SITE. The various subclasses and instances can be seen in the upper left window, and the slots of all the tree parts in the middle top window of Figure 1. The model is initiated by making an instance of the class SEEDS and sending a message, GERMINATE, to it. This creates a compound instance of some tree species class, say "TREE-1". This compound object has slots that hold the identities of all the TREE-PART instances which are essential for bookkeeping. We are actually dealing here with the PART-OF relation which KEE supports by allowing instances of instances, but this strange feature is not supported by more recent object-oriented tools.

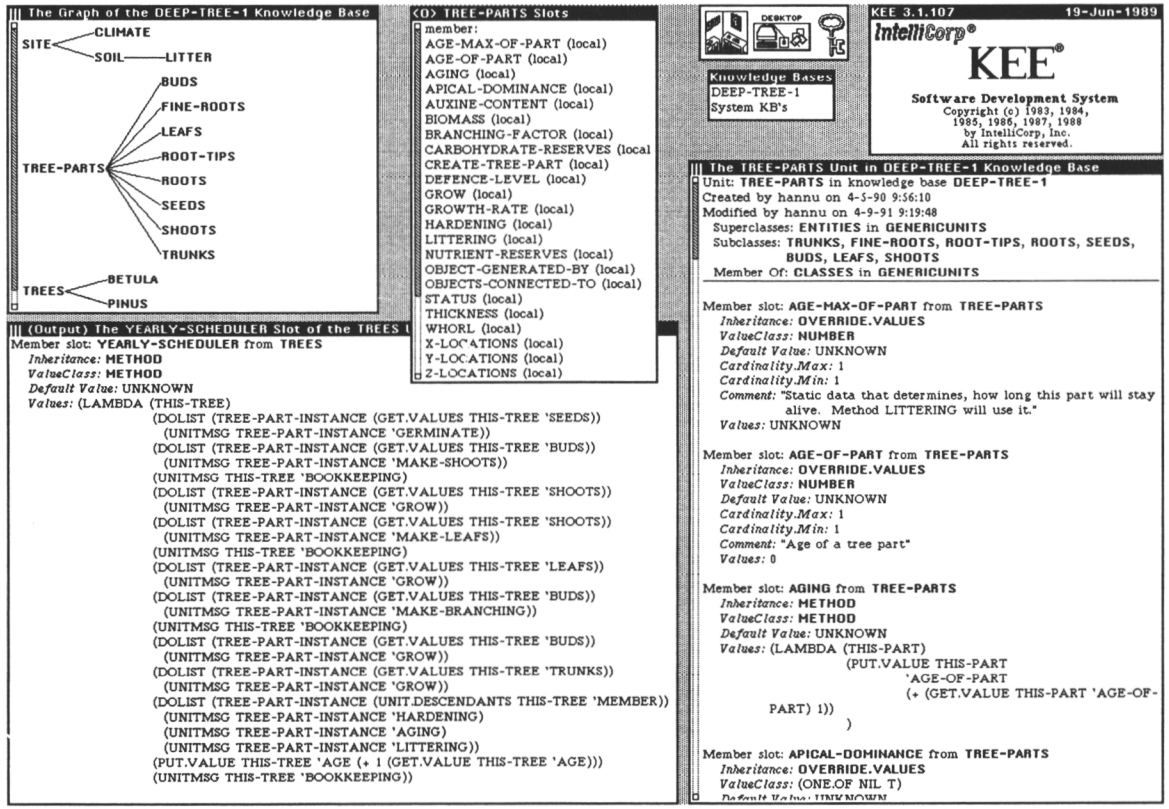

Figure 1. The object class hierarchy of the model DEEP-TREE, the slots of the tree parts, the annual scheduler method, and some examples of the contents of the slots in tree parts.

When the model is running, TREE-1 invokes its YEARLY-SCHEDULER method (visible in Figure 2's lower left window). This causes a mushrooming of instances: BUDS generate other BUDS and SHOOTS, SHOOTS make LEAVES, and so on. Aged instances are detached from "TREE-1" and become members of LITTER. Shoots merge to form TRUNK. A complex topology is grown by each instance maintaining the identities of the other instances that it is connected to by its slots, and the identity of the object that generated it. This topology can, to some degree, be examined and debugged with the dynamic slot graphs that KEE provides (Figure 2).

Functioning of all the parts of the tree is modelled only minimally at this point, since most of the research on tree physiology is useless for this modelling approach. Very few papers have report mechanistic miniature-scale interactions between clearly defined objects: "The effect of changes in carbon and nitrogen in needles to carbon and nitrogen in shoots" is the kind of paper that would be useful. Future research should make explicit the objects studied, always identifying the triple OBJECT-ATTRIBUTE-VALUE before presenting any rate functions. However, quantitative information can be substituted for qualitative data in the present model. The large amount of objects makes simulating with just boolean values practical.

Even just above ground, the amount of instances in a tree cumulates rapidly as the following table shows:

Year	Number of instances
0	1
1	9
2	40
3	200
4	900
5	6 000
6	20 000

Although no metabolism is simulated, an 8 megabyte Symbolics 3620 LISP-machine spends all its time at this point swapping and collecting garbage. Were the model written in Common LISP Object System instead of KEE, the inevitable could be delayed by some time steps. There have to be other ways of making the model practical.

If metabolism is being simulated, storing the actually calculated values for each situation and using them for all repeatable situations could reduce the computational burden (Ahonen & Saarenmaa 1991). But this is complex. Another solution is to generate compound objects between the tree instance and all its parts, such as crown, foliage, root system, and make statistics of the instances within them. This approach will probably be used in practical expert systems. But where "virtual trees" are grown, we have to move onto using massively parallel hardware.

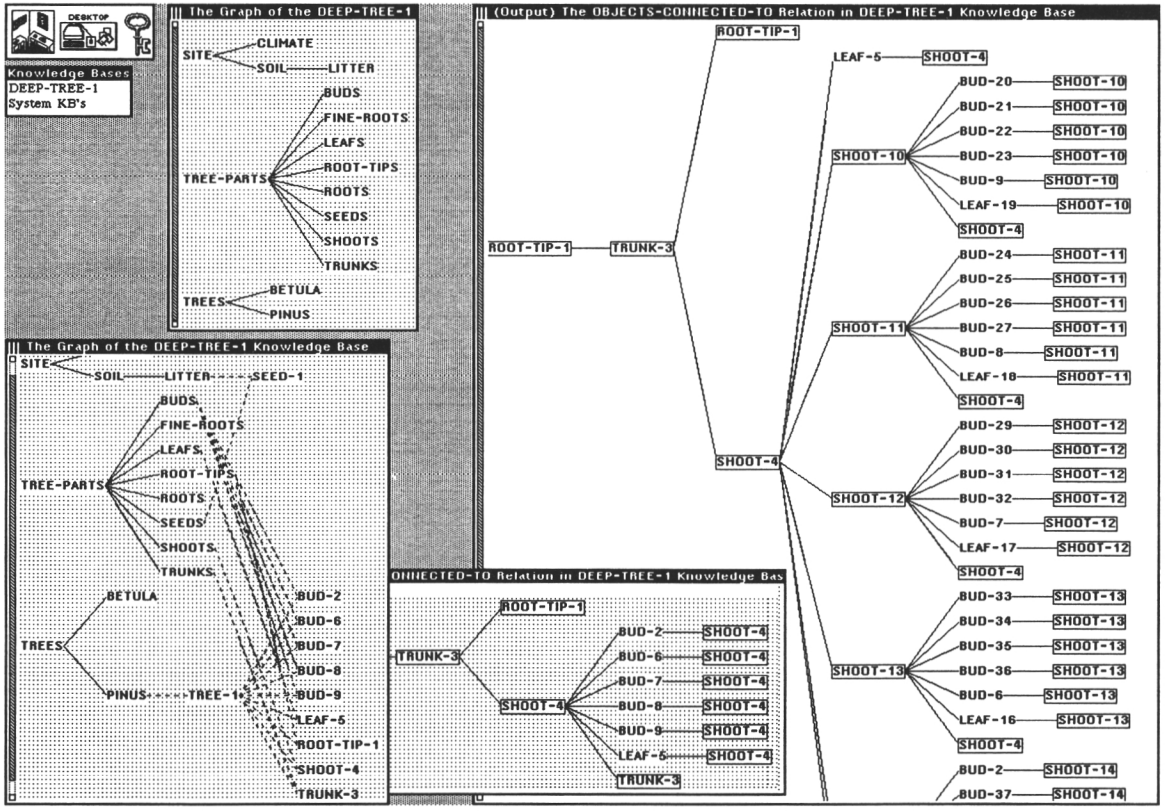

Figure 2. The generation of above-ground objects during the simulation. The class hierarchy windows on the left present years 0 and 1 of the simulation. The slot graphs on the right present years 1 and 2.

Parallel processing

The early decision to build serial rather than parallel computers was made because memory was cheaper than processors. While the processor is busy, most of the memory is on idle. Today, both processors and memory are made of the same material, but silicon wafer is wasted at $1 million / m^2 (Hillis 1987).

Parallelism in computers means having more than one processing element working at the same time. In present computers, the number of processors ranges up to 65 536 (Table 1). Massive parallelism begins at about 200 processors where individual processors can no longer be manipulated directly, but require a switching mechanism in the computer's bus architecture; i.e., the bus becomes programmable as well as the processors. Parallelism is not to be confused with vector processing which only allows processing of qualifying arrays in parallel.

Parallel computer architectures can be divided into MIMD and SIMD. The latter, Single Instruction Multiple Data, is easier to implement. In SIMD machines, multiple data elements, such as pixels of an image or spatial information, are broadcast into each processor's memory and the same program is executed at each processor. If there are local connections between neighbouring processing elements, communication is fast. The most successful parallel supercomputer, the Connection Machine, can crank away such problems at 2500 MIPS and 1.4 GFLOPS. The switching architecture, n-cube, in a Connection Machine ensures that each processing element is no more than 12 nodes away from each other. When 65 536 is not enough, the operating system generates up to millions of transparently virtual processors.

Parallel supercomputers are being used for applications in structural analysis, fluid dynamics, and image processing. They complement effectively with Cray's by being more effective and cheaper for data intensive applications. The disk arrays in Connection Machine and Maspar that consist of large amounts of inexpensive standard hard disks make them applicable also for fast data retrieval.

Programming a Connection Machine is done using either *LISP, *C, or *FORTRAN. These languages (prefix is "asterisk") have the extensions necessary for broadcasting data and program into the processors. The programmer does not need to know the processors and memory locations. The basic processing element is a xector that defines pairs of objects and values. The xectors can process themselves; e.g., printed, bound to variables, added, and so on (Hillis 1985). Many of the parallelizing features of *FORTRAN will be implemented in standard FORTRAN-90, where the programmer can process an entire array of numbers without constructing the loops and subscripts.

Programming tools other than languages are still few in number for parallel computers (Kitano et al. 1991). Most of the existing programs run in the Connection Machine, and are for engineering and physics. A frame-based language called PARKA (Evett et al. 1990) is available for AI research.

No true object-oriented tools exist. An emulator for *LISP is available. It is possible to develop code on a serial machine and later execute it on the real thing.

Table 1. Some parallel, vector, and serial computers and their performance (Digital 1991, Moniverkkotekniikka 1991).

Name	N of processors	Peak 32-bit MIPS	Peak MFLOPS
Connection Machine CM-2	4 096...65 536	2 500	14 000
Intel iPSC/860	32...128	6 000	5 000
Maspar/DECmpp 12000 16B	16 384	26 000	580
Convex C3840	4	1 000	500
Cray Y-MP /832	8	1 000	2 667
DEC VAX-9000 440 VP	4	30	500
Sun Sparcstation 2	1	28	3

Conclusions

The use of a parallel computing platform for the present topological tree model is obvious: assign a processor for each tree part. Because there are only local connections (all mechanistic systems have only local connections), the processing would be very fast. A mature tree would require a few millions of parts and the use of virtual memory. In the absence of real object-oriented languages, it would be possible to use just *LISP for programming.

A graphical interface to the present model will be built in future. That picture will at first be a mere branching diagram that can be rotated and debugged, but it can also be rendered for realistic appearance. The final step is "virtual reality", a realistic tree that can simulate symptoms of damage and graphically animate its life and death as in a movie.

Parallel processing can also be used for larger-scale forest simulations. Raster elements from satellite imagery, stands, and trees without detail can be simulated in parallel. The interactions of treatments of adjacent stands can easily be accounted for. Animating the blowing over of a stand in a storm might be useful prior to operations that expose stands to winds.

If parallel computing seems strange at first, after some serious consideration it will look more natural than the way forest scientists do their computing at the present.

The Centre for Scientific Computing at the State Computing Centre will get its first parallel supercomputer soon. While forest scientists have made no use of the Cray or smaller supercomputers so far, a parallel supercomputer

will obviously be more useful. Since their prices begin at $2 million FIM and drop fast, they are not out of reach even for the FFRI. Now is the time to go abroad to learn how to use them.

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