A Comparison of Three Modelling Approaches for Large-Scale Forest Scenario Analysis in Finland

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Forests play an important role in the sequestration of carbon dioxide and the storage of carbon. The potential and efficiency of mitigation options in forestry have been studied using large-scale forestry scenario models. In Finland, three models have been applied in attempts to estimate timber production and related carbon budgets. In this study, these models are compared. The oldest, MELA, was designed in the 1970s for the regional and national analysis of timber production. The European Forest Information Scenario Model, EFISCEN, originally a Swedish area matrix model, was developed in the early 1980s. SIMA, a gap-type ecosystem model, was utilised in the 1990s for regional predictions on how the changing climate may affect forest growth and timber yield in Finland. In EFISCEN, only the development of growing stock is endogeneous because the assumptions on growth, and the removal and rules for felling are given exogeneously. In the SIMA model, the rules for felling are exogeneous but the growth is modelled based on individual trees reacting to their environment. In the MELA model, the management of forests is endogeneous, i.e. the growth, felling regimes and the development of growing stock are the results of the analysis. The MELA approach integrated with a process-based ecosystem model seems most applicable in the analyses of effective mitigation measures compatible with sustainable forestry under a changing climate. When using the scenarios for the estimation of carbon budget, the policy makers should check that the analyses cover the whole area of interest, and that the assumptions on growth and management together with the definitions applied correspond with the forestry conditions in question.

Keywords carbon budget, forestry model, scenario modelling, MELA, EFISCEN, SIMA
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1 Introduction

The UN Framework Convention on Climate Change (1992) and the Kyoto Protocol (1997) aim at stabilising greenhouse gas levels in the atmosphere. Forests play an important role in the sequestration of carbon dioxide and the storage of carbon. The protection and enhancement of existing and the establishment of new carbon reservoirs and sinks reduce emissions. Yet, despite mitigation measures climate change is, however, evident. The acclimation of forests to a changing climate may require modification of management practices. In addition to environmental protection, forests are needed for timber production, nature conservation and recreation. Therefore, only those measures which are compatible with the maintenance of sustainable multiple-use forestry should be chosen to mitigate and to adapt to climate change.

The potential, and efficiency, of mitigation options in forestry have been studied using large-scale forestry scenario models such as ATLAS and TAMM (Haynes et al. 1994) or FASOM in the U.S. (Alig et al. 1997) and GAYA-JLP in Norway (Hoen and Solberg 1994). A large-scale forestry scenario model is a computerised model built for making long-term projections of forest resources of a large geographic region (Nabuurs and Päivinen 1996). ATLAS, a timber growth and yield projection system, was used together with a price-endogenous, spatial equilibrium model, TAMM, to study the market impacts of different strategies for increasing carbon sequestration (Haynes et al. 1994). Alternative strategies included reducing National Forest harvest levels and increasing planting on agricultural land. FASOM, a multi-period, price-endogeneous, spatial equilibrium model of product and land markets in the U.S. forest and agricultural sector was used to examine the private forest management, land-use and market implications of carbon sequestration policies (Alig et al. 1997). The GAYA-JLP model is based on the simulation of treatment schedules for homogeneous stands and the solution of inter-temporal forest management planning problems by linear programming. This model was used to study which changes in forest management were the most cost-efficient for increasing net carbon dioxide fixation (Hoen and Solberg 1994). These models did not incorporate impacts of climate change in natural processes. In addition, all the models are only applicable for the conditions they were developed for.

In Finland, policy makers have been offered a variety of forest scenario analyses to estimate timber production possibilities and related carbon budgets but the efficiency of mitigation options has not been analysed. The oldest model, MELA (Siitonen et al. 1996), is a forestry model designed in the 1970s for the regional and national analysis of timber production. Since the 1980s, the MELA model has been applied in three rounds of national-level forestry analyses: the Forest 2000 Programme (1986), the Revised Forest 2000 Programme (Siitonen 1993, Komiteamietintö 1995:5) and Finland's National Forest Programme 2010 (Finlands…1999, Nuutinen and Salminen 1999). The MELA analysis for the Revised Forest 2000 Programme (Siitonen 1993) has been used in the estimation of the carbon balance in the forest sector in Finland (Karjalainen et al. 1995). The MELA model was designed for the analysis of optimal forest management under different requirements for forest production. However, the model does not include the effects of climate change on natural processes.

SIMA (Kellomäki et al. 1992) is a gap-type ecosystem model which was utilised in the 1990s for regional predictions on how the changing climate may affect forest growth and timber yield in Finland (Talkkari and Hypén 1996). The SIMA model incorporates the effects of climate change but has no methods for analysing effective combinations of forest management practices.

The European Forest Information Scenario Model (EFISCEN) was originally a Swedish area matrix model developed in the early 1980s by Sallnäs (1989) and was later used for the IIASA forest study for European forests (Nilsson et al. 1992). The model has been further developed and used, for example, to provide baseline projections for European countries (Nabuurs et al. 1998, Nabuurs et al. 2000). The EFISCEN model, as such, has neither the capability for modelling the effects of climate change on natural processes nor the methods to analyse effective forest management practices, but experiments have been made to incorporate the impacts of climate change on the development of forests (Karjalainen et al. 2000).

The net carbon dioxide sink in Finland is usually calculated by extracting the estimated drain from the estimated increment. The sink has decreased from 1990 to 1998 from 24 CO_2 Tg to 9.7 CO_2 Tg (Metsät…2000). In Finland's National Forest Programme 2010 (1999) it has been estimated that both the drain and the increment will rise to over 75 mill. m^3 yr^{-1} by the year 2010. If the total round wood production will reach for the aimed level, the carbon sink in 2008–2012 (the commitment period in international agreements) can be positive or negative, depending on the amount of increment which in turn is dependent, for example, on the actual cutting profiles and the management of the forests. Scenario modelling applicable in Finnish conditions could assist in the choice of effective mitigation strategies.

The aim of this study is to compare available sets of large-scale forest scenarios in Finland and to analyse reasons for the possible differences and their significance in the issues relevant for decision and policy making, especially in the estimation of forest and carbon balance. In addition, the requirements for the analysis of efficient forest management that may help to meet the multiple needs of society are discussed.

The comparison is based on published reports (Siitonen 1993, Talkkari and Hypén 1996, Nabuurs et al. 2000). All the scenarios start from the base year of 1990, compatible with the agreements of the Conventions of Climate Change and the Kyoto Protocol. The scenarios cover different time periods. The shortest period, from 1990 to 2040, was applied by Siitonen (1993). Differences are also found in the data coverage and definitions applied in scenarios. In the MELA model, the events (felling, growth) happen in the middle of the ten year period. In the EFISCEN and SIMA the felling and increment are presented at the beginning or end of the period. To make the analyses more comparable, the results from all the models are presented for the same years. The results of SIMA and EFISCEN were interpolated from the figures of published reports. The differences are mentioned in the figure captures.

2 EFISCEN

2.1 Material and Methods

EFISCEN uses an area matrix approach to simulate forest development for a period of 50 to 70 years. The model requires data on area, volume and increment per age class by forest types. A forest type can be distinguished according to region, owner-class, site-class and species. A separate matrix – an area distribution over age and volume classes – is set-up for each forest type. (Nabuurs et al. 2000).

In the matrix, growth is expressed as transition probabilities between cells. The growth simulation is based on five year volume increment as a percentage of standing volume. The percentage is predicted as a function of age. The growth functions are estimated from the data based on standing volume, volume increment and age. Each growth function is related to a particular series of standing volume over age. To prevent high stocked cells from growing exponentially fast and to take into account the increase in growth after thinning, explicit corrections are made (Nabuurs et al. 2000).

The user defines the removal from thinnings and final fellings for each species group and afforestation over time at the national level. Thereafter, the model calculates where to harvest according to growth dynamics, age class distributions, and theoretical management regimes. The thinning regimes are incorporated as the range of age classes at which a thinning can be carried out. Final felling regimes for each age class are incorporated as a probability that a final felling can, in principle, be carried out. The model generates projections of growing stock, increment, timber harvest volumes, age class development over time by country, region and species. (Nabuurs et al. 2000).

For this study, two of the published scenarios are selected. The felling at the level of 1990 (55 mill. m^3 per year) was chosen for the "business-as-usual" scenario (EFISCEN1). The proportion of conifers in fellings was set at 77 percent and the proportion of thinnings at 40 percent. In the so called maximum sustainable felling scenario (EFISCEN2), the sustainability was defined as a felling level under non-decreasing average standing volume. The simulation covered the period 1990–2050. (Nabuurs et al. 2000).

The data were based on the 8th Finnish National Forest Inventory (1986–1994) and covered 19.92 mill. hectares of forest land. The land-use class is forest land if the site can produce 1 m^3 ha^{-1} yr^{-1} of stem wood with tree species suitable for the site and with a normal management schedule and a rotation age of 100 years. In the data, two regions, eight site classes – defined by soil type and the vegetation – and four species were distinguished. (Nabuurs et al. 2000).

2.2 Results

In the first scenario, the annual felling (EFISCEN1 in Fig. 1) was assumed to remain at the level of 55 mill. m^3 until 2050. According to the simulations, the corresponding growing stock exceeds 2700 mill. m^3 in 2040. Average annual increment (Fig. 3) decreases slightly and high average volumes (140 m^3 ha^{-1}) are reached. (Nabuurs et al. 2000).

The second scenario (EFISCEN2 in Fig. 1) shows that the felling at the level of 70 mill. m^3 yr^{-1} would result in only a slight increase in the average growing stock (Fig. 3). In that scenario, the increment decreases more than in EFISCEN1. (Nabuurs et al. 2000).

3 SIMA

3.1 Material and Methods

SIMA (Kellomäki et al. 1992) is a gap-type ecosystem model. In the model, the growth of trees is based on the diameter growth, which is controlled by light conditions, temperature, soil moisture and nitrogen. The same factors control the success of regeneration, which can be based on natural processes or planting. The thinning rules and the length of rotation can vary according to site type, dominant tree species, and location of stand. The thinning limits are defined according to dominant height and basal area. The length of rotation is determined by the mean diameter of trees in the stand, and the limits vary by stand location, site type, and dominant tree species. (Talkkari and Hypén 1996).

The model accepts the ground-true sample plots as input data. The simulations utilised the permanent sample plots of the NFI (measurements carried out in 1990–91) as input, which includes the properties of site (soil texture, amount of soil organic and respective amount of nitrogen) and the tree-specific diameter distribution of trees on the plot representing Scots pine, Norway spruce, and birches (*Betula pendula*, *Betula pubescens*). Only the sample plots on forest land mineral soils were included (Talkkari and Hypén 1996). According to the 8th NFI (Tomppo and Henttonen 1996), the area of forest land mineral soils is ca. 15.2 mill. ha.

In the simulation, the management recommendations of the Forestry Centre Tapio were adopted. In the first scenario (SIMA1), no changes in temperature or precipitation were assumed. In the second scenario (SIMA2), a gradual elevation of temperature at the rate of 0.04 °C yr^{-1} was assumed. The simulation covered the period 1990–2100. (Talkkari and Hypén 1996).

3.2 Results

The growing stock (SIMA1 in Fig. 2) increases from the current (1990) 1535 mill. m^3 to 1900 mill. m^3 by the year 2040, if fellings are based on standwise silvicultural recommendations. In this scenario, annual fellings (SIMA1 in Fig. 1) on mineral soils exceeds 80 mill. m^3 in the period of 1990–2000 and drops, thereafter, close to 24 mill. m^3 – rising up to 40–50 mill. m^3 during the next few decades. The growth increases rapidly during the second ten-year period (2000–2010) after heavy fellings. During the simulation, Norway spruce becomes the major tree species in Southern Finland. (Talkkari and Hypén 1996).

Under the gradual elevation of temperature at the rate of 0.04 °C yr^{-1}, the stocking stabilises close to the level of 2000 mill. m^3 by the year 2040 (SIMA2 in Fig. 2). Later, the dominance of deciduous species increases in southern Finland with a shift in the dominance of coniferous species to northern Finland. After 2040, deciduous species start to replace Scots pine in Northern Finland. (Talkkari and Hypén 1996).

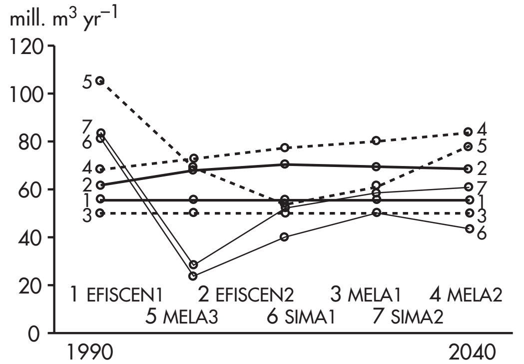

Fig. 1. Felling on forest land (EFISCEN1–2), felling on forest land mineral soils (SIMA1–2), and cutting removal on forest and scrub land (MELA1–3), mill. $m^3 yr^{-1}$ for 1990–2040.

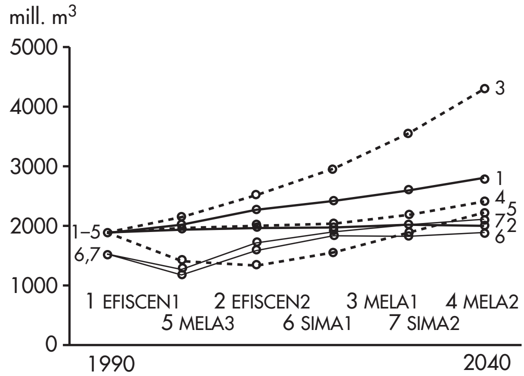

Fig. 2. Volume of growing stock on forest land (EFISCEN1–2), on forest land mineral soils (SIMA1–2), and on forest and scrub land (MELA1–3), mill. m^3 for 1990–2040.

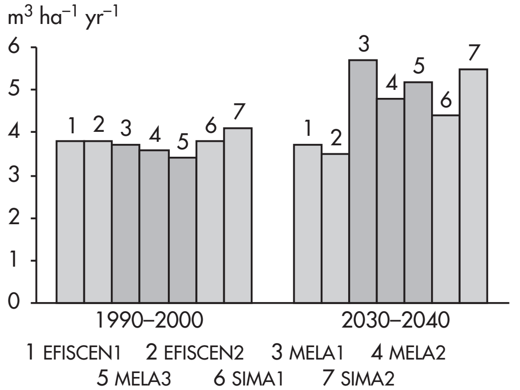

Fig. 3. Average annual increment on forest land (EFISCEN1–2), on forest land mineral soils (SIMA1–2), and on forest and scrub land (MELA1–3), $m^3 ha^{-1} yr^{-1}$ for 1990–2000 and 2030–2040.

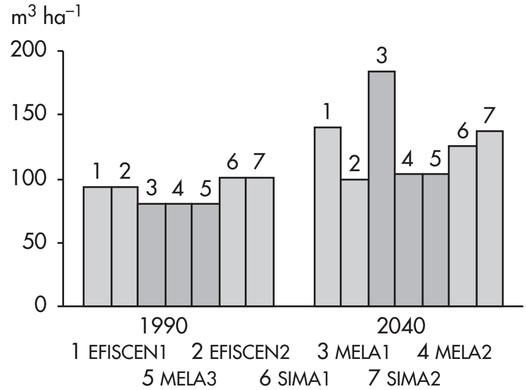

Fig. 4. Average volume of growing stock on forest land (EFISCEN1–2), on forest land mineral soils (SIMA1–2), and on forest and scrub land (MELA1–3), $m^3 ha^{-1}$ in 1990 and 2040.

4 MELA

4.1 Material and Methods

The MELA model (Siitonen et al. 1996) consists of two parts: an automated stand simulator based on individual trees and the optimisation package based on linear programming (Lappi 1992). The simulator automatically generates a finite number of feasible management schedules for management units over a relevant calculation period. Management schedules differ from each other, for example, by management activities and their timing.

The simulation of the management schedules consists of states and events. The events are natural processes (e.g. in-growth, growth and mortality of trees) and management activities (e.g. regeneration, cuttings). The prediction of stand development is based on individual-tree models. The growth of trees over 1.3 m is predicted with distance-independent models for basal-area growth and height growth of trees. Juvenile development of trees, natural regeneration and ingrowth are predicted with regeneration models. Mortality of trees is predicted with the individual-tree survival model. The main simulation variables for trees are the number of stems per ha, tree species, diameter, height and age. (Ojansuu et al. 1991).

Hundreds of variables describing the management schedules are produced. The variables available for the linear programming (LP) problem and the report writer describe the state and the development of the forests, as well as forest production and its economy over the calculation period. The optimiser simultaneously selects the production program for the whole forestry unit and the corresponding management schedules for sample plots. The goal and the restrictions of the LP problem regulate the search of the production program. (Siitonen 1993).

The management units in the MELA input data were based on the NFI sample plots for forest and scrub land (total of 23.3 mill. ha). The land-use class is scrub land if the site can produce 0.1–1.0 m^3 ha^{-1} yr^{-1} of stem wood with tree species suitable for the site and with a normal management schedule and a rotation age of 100 years. A management unit consisted of one or a set of sample plots homogeneous with regard to the present stand characteristics and the expected future management and development. NFI data mainly originated from the 8th and partly from the 7th inventory (on those parts of Finland where NFI8 was not completed). The management unit data were computationally updated based on the cutting statistics up to the base year 1990.

Three different scenarios were defined. The first scenario (MELA1) was designed to analyse consequences if timber production remained at the level of the late 1980s. The second scenario (MELA2) was the allowable cut calculated by maximising the net present value of the future revenues subject to a non-declining flow of timber, saw logs and a net income over a 50-year period, 1990–2040. The third scenario (MELA3) illustrated the immediate cutting potential if sustainability is not taken into account. (Siitonen 1993).

4.2 Results

In the first scenario, the annual cutting removal (MELA1 in Fig. 1) was assumed to remain at the level of 50 mill. m^3 until 2040. According to the simulations, the corresponding growing stock on forest and scrub land (Fig. 2) exceeds 4000 mill. m^3 in 2040. Average annual increment (Fig. 3) increases drastically and high average volumes (Fig. 4) were reached. (Siitonen 1993).

The second scenario was an estimate of maximum regionally sustained cutting removal (MELA2 in Fig. 1). The annual removal is 68 mill. m^3 and rises to over 80 mill. m^3 by 2040. The stocking on forest and scrub land remains stable. The total annual increment increases from 79 mill. m^3 in 1990 to 112 mill. m^3 for the period 2030–2040. (Siitonen 1993).

The proportion of conifers of cutting removal is on an average over 80 percent in 1990–2040. The proportion of thinnings of cutting removal increases gradually from 16 percent in 1990–2000 to 40 percent in 2030–2040. Nearly 90 percent of cutting removal in 1990–2000 is from mineral soils. (Siitonen 1993).

In the third scenario, annual removal (MELA3 in Fig. 1) exceeds 105 mill. m^3 for the period 1990–2000 and drops thereafter up to 55 mill. m^3 – rising later close to 80 mill. m^3. (Siitonen 1993).

5 Discussion

5.1 Comparison of Models

The ability of a model to address specific problems and questions depends on the modelling approach, the data model, assumptions and definitions applied (Table 1).

Both in the SIMA and MELA models the prediction of stand development is based on individual tree-models for regeneration, growth and mortality. The EFISCEN model is based on net annual increment (NAI) calculated as a percentage of standing volume. The predictions based on empirical estimates of NAI are applicable only if natural mortality is small and management of forests does not change. Natural mortality

Table 1. Comparison of models and analyses.

	EFISCEN	SIMA	MELA
MODEL			
Modelling approach	An area matrix model with transition probabilities	A gap-type ecosystem model	Standwise simulation and area optimisation
Scenario method	Iterative simulation	Simulation	Linear programming
Growth model	A percentage of standing volume	Tree-level models	Tree-level models
Exogeneous/ assumptions	Growth and felling	Growth model and felling rules	Growth model
Endogenous/results	The volume of growing stock	Felling, increment, the volume of growing stock	Removal and its allocation, increment, the volume of growing stock
Data unit	A matrix cell	A sample plot	A sample plot/ A management unit
ANALYSES			
Data source	NFI8 (1986–1994)	NFI permanent sample plots (1990–1991)	NFI7 and NFI8 sample plots computationally updated to year 1990
Data coverage	19.92 mill. ha, forest land	15.2 mill. ha, mineral soils	23.3 mill. ha, forest and scrub land
Business as usual	EFISCEN1 based on the amount of felling	–	MELA1 based on the total amount of removal by timber assortments
Maximum sustainable	EFISCEN2 defined by non-decreasing average volume	–	MELA2 defined by the flow of timber, saw logs and net income
Cutting potential	–	SIMA1 and SIMA2 where a management schedule per stand was simulated according to silvicultural instructions	MELA3 where the management schedule corresponding cutting potential was chosen for each stand

may increase, for example, due to an increasing density of stands.

In the EFISCEN model, only the development of growing stock is endogeneous because the assumptions on growth, and the amount and rules for felling are given exogeneously. The exogeneously set fellings prevent the analysis of effective management. For example, the amount of thinnings may be set exogeneously at a high level (at 40 percent of fellings) to prevent overstocking of stands. As a result, thinnings may be simulated for stands where they would be, in practice, economically unprofitable.

In the SIMA model, the rules for felling are exogenous but the growth is modelled based on individual trees reacting to their environment. The growth, the development of growing stock and the corresponding amount of fellings are the results of the simulation. In the MELA model, the management of forests is endogeneous, i.e. the decision when and how to cut an individual management unit is based on the forestry of the whole region and the LP problem. The growth, felling regimes and the development of growing stock are the results of the analysis.

Both the SIMA and MELA models, utilise original sample plot and tree measurements as input data. The EFISCEN model uses cells of a matrix. Due to the small number of calculation units and variables available, the EFISCEN model may not capture all variation within the area of interest.

5.2 Comparison of Analyses

All three analyses are based on different data sets (Table 1). The different data source and age of data may result in different initial states for simulations. Due to the differences in the data coverage different types of forests in respect to productivity are covered in different analyses. For example, the SIMA analyses include only forests growing on mineral soils whereas the MELA and EFISCEN analyses also include peatlands.

In the EFISCEN2 scenario, sustainability was defined as non-decreasing average growing stock. This definition is based on the assumption that the growing stock of Finnish forests is already on a sustainable level. In the maximum sustained cutting removal scenario of MELA (MELA2), sustainability is based on the flow of timber, saw logs and net income. The dynamic definition makes the LP search for the amount and structure of the growing stock that maintains the timber production at maximum sustainable level.

The cutting removal of 50 mill. m^3 in the scenario MELA1 corresponds to the total drain of 55 mill. m^3 in 1985–89, i.e. quite close to simulated felling in the EFISCEN, which does not include natural mortality of trees. However, the development of growing stock in the scenarios MELA1 (Siitonen 1993) and EFISCEN1 (Nabuurs et al. 2000) differ. The most obvious reasons for the difference are the growth assumptions. In addition, in the MELA1 scenario the amount of felling is small compared to the amount of mature forests and, therefore, the amount of overstocked and fast growing stands increases. The recent modification of EFISCEN (Nabuurs et al. 2000) has decreased the difference between the two scenarios. The difference between the two models is expected to decrease further if the new version of the MELA model (Siitonen et al. 1999) with a new stand-level self-thinning model (Hynynen et al. 2000) will be used.

The SIMA model predicts rapid growth increase after heavy fellings, and success of deciduous species – especially in Northern Finland – due to climate change. The success of deciduous species may partly be due to the combination of the cutting profile and regeneration model.

6 Conclusions

Due to its simple structure and data model the EFISCEN model makes it possible to use a harmonised methodology for different countries with differing amounts of input data or yield information available. The built-in explicit control of growth estimates guarantees forecasts compatible with the empirical data. The built-in control based on the theory of fully stocked forests may be applicable in some parts of Europe. In most parts of Finland, however, the average growing stock and resulting absolute increment are still increasing. Thus, there is a risk that EFISCEN will underestimate the increment in Finnish conditions.

In the estimation of a future carbon budget, a scenario matching with the National Forest Programme should be used. According to EFISCEN scenarios (Nabuurs et al. 2000), the annual increment in Finland would stay under 75 mill. m^3 yr^{-1}. As a result, the estimate of a forest balance would become negative if the total drain exceeds 75 mill. m^3 yr^{-1} as proposed in the National Forest Programme 2010. If the forest balance is anticipated to become negative, the risk avoiding decision makers may cease the increase in fellings. If the negative balance is, however, not real but only the result of underestimated growth, this reaction may cause utility losses. These losses may become even larger if the extensive management leads to dense and overstocked stands where natural mortality and yield losses increase. A natural mortality model which takes into account the overstocking of stands will be essential (Schelhaas et al. 2000) for EFISCEN.

Surprisingly, the SIMA forecasts for the Finn-

Table 2. Evaluation of the applicability of the models and scenarios for the analysis of effective forest management.

	EFISCEN	SIMA	MELA
Models for the effects of climate change on natural processes	No	Yes	No
Models for the effects of changes in forest management on natural processes	No	Yes	Yes
Models to solve forest management endogeneously	No	No	Yes
Models to take into account the multiple needs of society	–	–	Thousands of variables

ish mineral soils are at the same level with the MELA and EFISCEN forecasts, including both mineral soils and peatlands (Fig. 2–5). The SIMA forecasts should be carefully validated. Because the role of peatland is becoming more significant in the future when peatlands forests mature (Nuutinen et al. 2000), the ecosystem model should also cover the peatland forests.

An ecosystem model such as SIMA is especially suitable to predict the impact of environmental changes on growth rates and succession (Table 2). Such changes can be incorporated in the EFISCEN model in an indirect way by fitting new growth functions stepwise during the simulation (Karjalainen et al. 2000). However, in EFISCEN the analysis of the effects of changing forest management on natural processes or the search for effective forest management is not possible.

In the analysis of effective mitigation measures compatible with sustainable forestry, the MELA approach seems most applicable because the tree level models make it possible to take into account the interaction between growth and forest management. In the future, appropriate variables for transferring the estimates of climate change impacts from process-based ecosystem models to tree-level empirical models should be studied.

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