Impact of recent and future climate change on Estonian forestry and adaptation tools

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ABSTRACT: The possible impact of recent and predicted future climate change on forestry in Estonia was studied. The quickening forest growth, about 15% in the last 4 decades, was verified by statistical analysis of the growth of over 50 000 stands, and quickening forest growth was predicted for the next century by the RipFor model. The risk of forest damage and the uncertainty of forest growth predictions have been increasing and will continue to do so. The genome diversity of the dominant tree species growing in Estonia is sufficient for adaptation to the changing climate conditions. Computer-aided decision support systems built into the forest management information system can improve forest management planning.

KEY WORDS: Climate change · Forest · Estonia · Accelerating growth · Model · Species · Genome · Damage · Decision making · Adaptation

1. INTRODUCTION

Almost half of the land area of Estonia is covered with boreal forests, which play a remarkable role in the country's economy and ecology. There have been drastic changes in Estonian forests and forestry during the 20th century, most of them caused by political, economic, and technological changes. There has been a continuous increase in forest area (about 2.5 times), volume (about 3 times), and the average age of stands (about 1.3 times) in Estonia during the last half of the century (Table 1). During the last 80 yr, the forest area has tripled.

For more than 70 yr, forest management has been fully based on forest management plans. The plans are revised for each forest plot every 10 yr, taking into account new forest inventory. This has been a sliding-scale maximum sustainable yield (MSY) planning process with a yearly step for the younger stands and mostly with a 10 yr step for the older ones. The annual amount of tree-removal has been less than half of the annual increment, estimated to be more than 9 Mm^3 yr^{-1}, or about 5 m^3 ha^{-1} yr^{-1}. The amount of forest area,

growing stock, and increment per capita are roughly 5 times higher than the European average, and tree-removal per capita is 3 times higher. Estonia is a timber-exporting country.

The percentages of stands composed of the dominant tree species are as follows: Scotch pine *Pinus sylvestris* L., 38% of the area and 40% of the growing stock (all percentages rounded to integers); Norway spruce *Picea abies* L. Karst, 24 and 26%; and birch *Betula pendula* Roth and *B. pubescens* Ehrh. together, 30 and 27%. Aspen *Populus tremula* L. dominated stands cover 1.6%; gray alder *Alnus incana* L. Moench, 4.1%; and others, 2.5% of the total of woodlands

Table 1. Area of forest land and volume of growing stock in Estonia in 1940, 1958, 1975 and 1994. Source: Economics and Information Centre of Forestry (1995)

Variable	Year			
	1940	1958	1975	1994
Area of forest land (×10^3 ha)	929	1410	1777	1939
Area of stands (×10^3 ha)	853	1271	1652	1846
Volume of growing stock (m^3 ha^{-1})	127	103	119	154
Average age (yr)	–	41	43	52

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(Estonian Forest Department 1995). Most of the stands on fertile soils are mixed stands, so the volume numbers given are not of pure species but of stands. Estonian forests are remarkable for their diversity of species and site types.

About 224 000 ha (20.3%) of state-owned forests in Estonia are in the category of protected forests with strict restrictions for tree-removal; 115 000 ha (10.4%) are in the category of protected forests with comparatively reduced restrictions for tree-removal and 765 000 ha (69.3%) are in the category of commercial forests (Eltermann 1996). In only about 3% of Estonian forests is no direct human influence allowed at all, and natural processes have a leading role in forest changes there. In the remaining 97% of forests, man-made changes predominate.

Today, the forest species composition is influenced mainly by reforestation and afforestation, thinning, and also by recent draining. Almost half a million hectares ($\frac{1}{4}$ of the present forest area) have been planted and seeded in the 20th century. All the reforestation and afforestation activities have been oriented to increase the role of conifers, and especially of pine. During the last 20 to 30 yr, damage by elk *Alces alces* L. has suppressed the use of pine for forest renewal. Thinning has also been used to expand the area of conifers. The present forest species composition in Estonia is the result of both climate and human influences.

2. METHODOLOGY

Some tendencies of climate change (rise in average temperature, lengthening of the growth period, and so forth) have been evident in Estonia during recent decades (Jaagus 1998) and centuries (Tarand et al. 1998). The same tendencies are also predicted for the next century (Keevallik 1998a,b). With this in mind, an attempt was made to determine the recent changes in forest composition, health, growth, and growth conditions in order to use them as an analogue for future predictions and to predict future changes against the background of the predicted climate change. Stand growth was predicted for the next century using the original RipFor model (Arp & Oja 1997). Using this model, the genome diversity of Norway spruce as a natural self-adaptation tool was analyzed.

Forest inventory data recorded for all forest stands at 10 yr intervals provide the most reliable data with regard to Estonian forest history; this data can be used to detect changes in forest growth and composition of species. Ten state forest districts were selected for this study. Two sets of forest inventory data (from 1951 and 1994) for the selected forest districts were used. The most important sub-compartment data—site type with the indicator of ditching, stand origin (cultivated or naturally regenerated), dominant tree species, age, height, diameter, and volume of the first story and sub-compartment area—were copied from the current forest inventory database and entered from the forest inventory record books of 1951. The data sets of both forest inventories (1951 and 1994) were linked through the use of maps. The material prepared for analysis included the inventory data of 20 869 sub-compartments on 26 817.3 ha.

For further invesigations, the forest inventory data of Suure-Jaani Forest Enterprise in central Estonia (stands on 31 589 ha in 1960 and on 32 897 ha in 1990) was used. For comparing the mean values of stand height, diameter at breast height (DBH), and standing volume in 1960 and 1990, the data were grouped by dominant tree species, site type, drainage, and age.

Special complications in forest growth modeling arise in the case of changing growth conditions. The line between the values of stand characteristics (such as average height, DBH, or volume) of groups of similar stands of different ages cannot be assumed as in stable growth conditions to show the real growth. At the same time, the difference between such single-time-measurement-based models and repeated-measurement-based models can be used as an indicator of a quickening or slowing of growth (Nilson & Kiviste 1984, 1986).

A model of stand height depending on stand age and site factors was developed (Kiviste 1997) on the basis of a static set of Estonian state forest inventory data from the period 1984–1993 (511 514 sub-compartments on more than 1 million ha, every stand presenting a single point on the age-height plane). This static model describing the state of stands for the period 1984–1993 was used to calculate 2 estimates of the site index as the average height of a stand at the age of 50, the first of them (SI_{1951}) using input values of the stand's age, height, and other characteristics in 1951 and the second (SI_{1994}) using the same data for 1994.

To analyze which factors the increase of site index ($SI_{1994} - SI_{1951}$) depends upon, the general linear method (GLM) of the SAS statistical program package (SAS 1987) was used. In the GLM procedure, the site index increase from 1951 to 1994 was used as a dependent variable. Pairs of dominant tree species in 1951 and 1994, an indicator of forest generation (the same in 1951 and 1994 or different, that is, cut down and regenerated during the last 40 yr), forest district, drainage (fixed in 1951 and 1994), and stand origin (fixed in 1951 and 1994) were used as classification variables, and stand age (fixed in 1951 and 1994) and the logarithmic transformation of the thickness of organic layer the soil were used as continuous variables.

Forest growth predictions for the next century were obtained using the RipFor model. The original RipFor model was developed based on an earlier model, ForSVA (Oja & Arp 1996, Arp & Oja 1997) and includes an increased number of changing climatic and soil characteristics, such as nutrient availability (N, P, Ca, Mg, K), ion exchange, and replenishment of soil bases (Ca, Mg, K, Na) via soil weathering and atmospheric deposition, radiation, CO_2 concentrations in the atmosphere and in the soil, atmospheric deposition of the nutrients, air temperature, evaporation, and precipitation.

Acceleration of forest growth in the past and predictions for accelerating growth in the future raise the need to estimate its possible consequences for forest management in Estonia. For this, the forest simulation and scenario model MELA (Ojansuu et al. 1991, Siitonen et al. 1995) was used with different changes in forest growth rate.

In the current analysis, the Estonian forest resources were described by a representative sample of 4000 stands. From the sample stand data, sample plots — 1 plot for each sample stand — and sample trees were generated. The sample plots and trees were furnished with site and tree variables according to the Finnish National Forest Inventory rules (Siitonen & Nuutinen 1996). Forest growth and management simulation and optimization software, MELA-JLP, was used for the analysis.

There are many dense and mixed forests and also a wide variety of forest site types in Estonia. For a long time, profitability was not a goal for Estonian forestry, and therefore well-balanced multiple-use forestry with specific management schedules has developed in the country. The optimization algorithm was defined on the basis of maximizing the net present value of timber cutting with a real interest rate of 3%. For the sustainable use of forests, specific constraints were implemented: non-decreasing growing stock of forests, non-decreasing timber cutting, and increasing net present value of forests.

In this study, the problem of forest growth rate change is redefined for the MELA-JLP system as a growth calibration problem. Dynamic change has been redefined to a static problem with average forest growth rate values. Six different growth rates, 75 to 125% of the actual tree growth rate, were used. The simulation period was chosen to be 60 yr—from 1997 to 2057. The constraints of non-decreasing timber removal and non-decreasing total volume were applied to fulfil the sustainability requirements of forestry. Tree growth rate has a remarkable influence on forest growth rate. The maximum tree growth rate of 125% used in this study corresponds approximately to a 3 m increase in forest site index in 50 yr.

Recent changes in forest damage due to climatic factors were used as analogues for future predictions. The adaptation methods were determined on the basis of general principles of optimum decision-making in a complicated changing stochastic environment.

3. RESULTS AND DISCUSSION

3.1. Recent changes in dominant tree species

Distribution of stands over thicket age (above 20 yr for coniferous and hardwood and 10 yr for deciduous forests) by indicator of forest generation (same stands or different stands), origin, and dominant species in 1951 and in 1994 used in this study is presented in Table 2.

The data reflecting the changes in dominant tree species indicate the drastic human impact on this process. Only in the case of the same generation of trees in 1951 and 1994 can a change be seen from the pioneering deciduous-dominated stands to spruce-dominated stands as a regular succession process. But even there, thinning also has an important role in speeding up this change. The change in dominant species in the case of deforestation and the subsequent planting or natural regeneration is the consequence of silvicultural measures like planting, cleaning, and so forth, or, for example, a result of lack of control over the elk population, which leads to the need to reforest an area previously dominated by pine into an area of spruce. All these

Table 2. Distribution of forest area by dominant species, generation, and origin in 1951 and 1994. 'Other' species in the table are mainly aspen, grey alder and common alder *Alnus glutinosa* L. Gaertn.

Dominant tree species in 1951	Dominant tree species in 1994 (%)				Area (ha)
	Pine	Spruce	Birch	Other	
Same generation					
Pine	**91**	5	4	0	3220
Spruce	6	**77**	11	5	2111
Birch	6	10	**72**	12	4603
Other	1	10	34	**55**	1100
Different generations, plantations					
Pine	**66**	33	1	0	340
Spruce	5	**93**	1	1	901
Birch	1	88	**10**	1	693
Other	1	95	2	**1**	176
Different generations by natural regeneration					
Pine	**27**	19	49	4	934
Spruce	1	**25**	51	23	1415
Birch	0	7	**69**	24	1716
Other	0	3	51	**46**	626
Total area (ha)	3891	4771	6824	2347	17 833

changes can be explained on the basis of the traditional theory of silviculture against the background of an unchanging environment. The possible weak influence of climate change on this process may remain unnoticed. Very similar results were obtained from the data of Suure-Jaani Forest Enterprise.

In the commercial forests planned for harvesting during the 21st century (established mostly in the 20th century), the possible change of species as a result of forest renewal, cleaning, and thinning will also forcefully override the changes caused by climate. In the 3% of all forests where no human activity is allowed, no adaptation problems can arise. The intra-species genome diversity provides additional flexibility to handle the results of a warming climate during the next century (Màtyàs 1997).

3.2. Forest growth has been quickening in Estonia during the recent decades

The authors have previously developed a hypothesis about the quickening growth of forests in Estonia and the neighboring countries (Nilson & Kiviste 1984, 1986), and recently an international program co-ordinated by the European Forest Institute has proved the same for most of the countries involved (EFI 1996a,b, 1997). The current project was designed to check this against the background of the increasing amount of CO_2 in the atmosphere and the probable climatic consequences of this in Estonia during the recent decades.

Data on sub-compartments with the same dominant species in 1951 and 1994—arithmetical means, numbers of observations, and standard errors of average site index increase (SI_{1994} – SI_{1951}) by the main species, drainage, and generations—are presented in Table 3.

According to Table 3, the average increase in site index has been more than 2 m. The site index increase was higher in pine (2.35 m) and birch (2.47 m) stands, while in spruce stands it was about 1 m lower (1.44 m). The average increase of site index in ditched forests was higher than in non-ditched forests (2.43 and 2.09 m respectively). The site index increase in forests of the same generation was higher than in the forests of different generations. Although surprising, this turns out to be one of the best lines of proof that growth acceleration has occurred. The base age—50 yr—is almost in the center of the average rotation age. As shown earlier (Nilson & Kiviste 1984, 1986), in the case of quickening growth, the static model will be distorted, remarkably more for older stands than for the young ones. Although the standard deviation of the site index increase calculated from that data set was 3.30 m, the standard error of the mean increase was only 0.04 m.

Using the GLM procedure, a general linear model of all available factors was created. The model was highly significant; although, according to the coefficient of determination, $R^2 = 0.15$, only 15% of the variation in the site index increase can be described by the listed arguments. Most of the factors, except drainage fixed in 1951, stand origin fixed in 1994, and stand age fixed 1951, were significant (at the level of $\alpha = 0.05$) in the

Table 3. Descriptive statistics of increase in site index (SI_{1994} – SI_{1951}) by main species, by drainage, and by generations on the basis of sub-compartment data with the same dominant species in 1951 and 1994

Main species	Not drained forests			Drained forests			Total
	Same generation	Different generations	Total	Same generation	Different generations	Total	
Average of site index increase (SI_{1994} – SI_{1951})							
Pine	2.03	1.73	1.99	2.93	4.17	3.25	2.35
Spruce	1.49	1.38	1.45	1.38	1.39	1.39	1.44
Birch	3.02	1.50	2.64	2.50	1.46	2.13	2.47
Other	3.23	2.71	3.11	3.46	0.88	2.27	3.00
Total	2.30	1.55	2.09	2.61	2.10	2.43	2.18
Number of stands							
Pine	1382	248	1630	494	172	666	2296
Spruce	1178	852	2030	99	133	232	2262
Birch	1415	467	1882	645	355	1000	2882
Other	338	104	442	35	30	65	507
Total	4313	1671	5984	1273	690	1963	7947
Standard error of site index increase							
Pine	0.09	0.28	0.09	0.14	0.27	0.13	0.07
Spruce	0.07	0.11	0.06	0.25	0.32	0.21	0.06
Birch	0.09	0.19	0.08	0.11	0.18	0.10	0.06
Other	0.17	0.31	0.15	0.38	0.42	0.32	0.14
Total	0.05	0.09	0.04	0.08	0.14	0.07	0.04

general linear model. The increase in the site index proved to be most dependent on the thickness of the organic layer of soil and on the forest district. Here again, the data from Suure-Jaani Forest Enterprise fully confirmed that forest growth in Estonia is quickening.

3.3. Changes in nutrient fluxes will possibly increase forest productivity in the future

To analyze the possible changes in nutrient availability in Estonian forests during the next century, the RipFor nutrient cycling and forest productivity model was used. Generally, an increase in the availability of all major nutrients (N, P, Ca, Mg, K, S) can be expected as a result of the increased circulation of nutrients in the soil-vegetation system. This will be caused by the increasing water fluxes through soil and higher organic matter decomposition rates at increasing temperature. Also, nutrient circulation will additionally increase due to higher growth rates of forest species at increasing atmospheric CO_2 concentration and warmer temperature. Simulated N uptake can also increase with the changing climate scenarios, but, according to our calculations, N leaching will remain more or less the same during the period analyzed, except for some possible increase when the stand becomes old. The higher leaching rates from the older stand can be partly related to the starting degradation of the stand and the lowering of its growth potential. Increased uptake means faster biogeochemical cycling of N in the stand. Similar increase in uptakes can be seen for all nutrients.

The increased availability of nutrients, particularly of N, clearly favors the further increase in forest biomass. Growth rates of wood biomass under 4 different scenarios are presented in Fig. 1 for a Norway spruce stand in Vooremaa (eastern Estonia). Stable growth without tree-removal and natural disasters like diseases or storms was assumed for all calculations. Wood biomass in these calculations also includes branches, stumps, and bigger roots.

Fig. 2 presents the differences between the additional increase of wood biomass under the 4 different climate change scenarios compared with the growth under actual (present day) climatic conditions. The additional wood biomass growth during the 100 yr period is predicted to be from 2.5 to almost 9%. Increase in harvestable timber can be assumed to be similar as it forms a proportional part of the whole woody biomass.

It can be concluded that the present and short-term change in climatic conditions in Estonia is favorable to forest growth conditions and results in increased
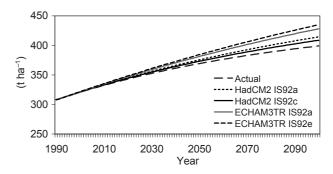

Fig. 1. Wood biomass growth (t ha^{-1}) of a Norway spruce forest in Vooremaa (eastern Estonia) under 4 different climate change scenarios—HadCM2 IS92a, HadCM2 IS92c, ECHAM3TR IS92a and ECHAM3TR IS92e
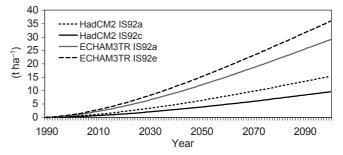

Fig. 2. Additional woody biomass growth (t ha^{-1}) of a Norway spruce stand in Vooremaa under the 4 climate change scenarios as compared to the growth in the case that current climatic conditions continue during the next century

productivity. In the long term, however, a possible decrease in productivity may occur on soils with lower parent material weatherability and base cation content as a result of increased base cation losses. However, the probability of such a tendency is fairly low in Estonia. The theoretically possible deterioration of timber quality—its softening under faster growth and increased N availability—is presumably not going to be a problem as the availability of base cations will also increase and support keeping the nutrient balance in building up the timber.

3.4. Faster forest growth leads to more diverse decisions

Forest management activities and timber production are dependent on tree growth rate. Table 4 illustrates the prognosis of maximum timber production for Estonian forests as the function of tree growth rate as a result of running the MELA-JLP model. It is assumed that the forest area will remain the same as in 1996.

The relative structure of potential timber production was analyzed. Thinning potential is most affected in

Table 4. Timber production potential of Estonian forests (Mm³ yr⁻¹) depending on tree growth rate as prognosis for the next 60 yr

Tree growth rate (%)	Years						Average for 1997–2057 (Mm³ yr⁻¹/%)
	1997– 2007	2007– 2017	2017– 2027	2027– 2037	2037– 2047	2047– 2057	
125.0	11.28	11.34	11.30	11.39	11.50	11.57	11.40/133.6
112.5	9.84	9.90	9.86	9.91	10.04	10.11	9.94/116.5
100.0	*8.45*	*8.50*	*8.48*	*8.48*	*8.58*	*8.70*	*8.53/100.0*
93.8	7.91	7.95	7.94	7.75	7.80	7.97	7.88/92.4
84.4	6.95	6.99	6.98	6.97	7.01	7.18	7.01/82.2
75.0	6.05	6.07	6.08	6.07	6.09	6.24	6.10/71.5

the case of slower forest growth rate. Regeneration cutting potential and logging residues are most affected in the case of higher forest growth rate. The regeneration cutting area is less influenced, changing from 86.5 to 117.5% when tree growth rate changes from 75 to 125%.

The influence of forest growth rate on forest management can be illustrated by the number of management alternatives in the simulation phase of this study. A higher forest growth rate brought about a greater number of reasonable alternatives. As the study was limited to branching options for alternatives, a quite realistic picture of management options and complexity of decision-making in forest management was obtained. Different optimization algorithms predicted different timber production potentials. A decision complexity index (DCI), describing the number of generated alternatives and variation of possible timber production, was calculated. With tree growth rate at 75% of the current forest growth rate, the DCI was 46%, and, with tree growth rate 125%, the DCI was 195%. Faster forest growth will lead to more complicated and diverse forest management decisions.

3.5. Prediction of forest damage caused by climate warming

Up to this decade, no Estonian forests appear to have been damaged directly by minimum temperatures in winter or other weather conditions. The last serious storm damage occurred at the end of the 1960s and in the early 1970s. Relatively cool weather in the vegetation period and high mortality in winter did not provide favorable reproduction conditions for needle and leaf pests. Trunk pests—bark and pulp beetles and weevils—have mainly a secondary role in damaging the pine and spruce groves. They have only accelerated the death of the trees previously damaged by diseases, human activity, storms, and fires.

Further climate warming will cause some changes; first of all, in the response of dendrofagous insects. The following analysis includes the most important and numerous pest species in Estonia: the pine looper *Bupolus piniarius* L. and the spruce bark beetle *Ips typographus*. The damage caused by the pine looper has been relatively rare in the past, and the average loss has been rather stable. By the beginning of the 1980s, the pine looper was clearly a stenotope species in North Estonia (Mihkelson 1986), and 81.6% of all the damaged stands were of *Cladonia* site type, 14.6% of *Vaccinium* site type, and the remaining 3.6% of other site types. On the contrary, in southeastern Estonia during the period 1991–1993, it was *Vaccinium* site type that suffered most. So there is a shift toward temperately humid sites.

The most numerous and dangerous trunk pest in Estonia has always been the spruce bark beetle. Mortality due to low winter temperatures has regulated its numbers. Lately, however, during the milder winters, this pest has survived better. Weather conditions during its flying period in late April and early May are also important. Even a short period of dry and warm weather is then a good precondition for its successful development.

In recent decades, the area of spruce stands damaged by spruce bark beetles has been increasing. In the 1970s and the 1980s, the damaged area in Estonia was 200 to 250 ha. After the 1992 drought, the damaged area has increased 7 to 8 times, making up 1863 ha. This change has been directly caused by warm and dry weather and indirectly by drought stress on trees.

Damage by spruce bark beetles occurs mainly in eastern Estonia. Spruce stands grow there in site types, where soil humidity depends directly on the amount of precipitation. In western Estonia, spruce roots have good capillary contact with groundwater, and thus the negative influence of drought on trees is smoothed.

The most numerous cervines in Estonia are the row deer *Capreolus capreolus* L., the elk *Alces alces* L. and the red deer *Cervus elaphus* L. The first two have been the main inhabitants of the country's forests. The red deer was introduced into Estonia at the end of the 19th century. During the last decades, there have been drastic outbreaks of game damage to young pine stands and middle-aged spruce stands. Therefore the normal reforestation by pine, spruce, and broadleaved trees has been hindered. In many forest districts, one cannot find any undamaged broad-leaved reforested areas. Aspen improvement has completely terminated. All this has a drastic role in species change

in Estonian forests. Continuous weather warming, especially in winter months, obviously has an important influence on increasing the population of row deer and red deer. So there will be increasing damage by cervines, mainly in young stands, if their population is not regulated by hunting.

Root rot *Heterobasidion annosum* with its cosmopolitan distribution can be regarded as the most dangerous fungal disease also in Estonian forests. Nearly $\frac{1}{5}$ of clear cuttings between 1989 and 1994 were urgent cuttings of stands damaged by root rot. The data indicate the increasing role of this disease (Table 5). Up to the middle of this century, the disease affected mainly spruce groves, although some cases of infection in pine, juniper, and some broad-leaved trees have also been recorded. Spruce stands are currently even more damaged (Table 5), but pine stands are also suffering. Intensive death of pine trees due to root rot infection was registered in the late 1950s and early 1960s, mainly in southeastern Estonia. The global weather warming will make environmental conditions for root rot spreading more favorable. More damaged areas and hence heavier economic loss are proposed to occur in coniferous stands.

As Estonia's climate is rather cool and mostly has enough precipitation, the amount of land area damaged by forest fires has remained relatively stable. The damaged stands have been cleaned in time, and so the possible multiplication of forest pests after fire has been avoided. The danger of forest fires will increase with increasing droughts, and there has been a remarkable increase of them during recent years. There was a serious drought in 1992, and a rapid expansion of fire-damaged areas as well. There was a more than 10-fold increase compared with the average for the period 1971–1991. In 1993, 1994, and 1996, the area damaged by forest fires was also more than twice that of the maximum for the period 1971–1991. As 60% of forest fires happen in May and June, the increasing spring-summer droughts will obviously increase the danger of forest fires.

The total area of damaged coniferous stands has been increasing more rapidly in eastern Estonia (Fig. 3).

Table 5. Dynamics of urgent clear cutting areas as a consequence of damage by root rot (ha/%)

Year	Spruce stands	Pine stands	Total
1989	32.8/91.1	4.0/ 8.9	36.8/100.0
1990	17.1/59.6	11.6/40.4	28.7/100.0
1991	14.1/88.7	1.8/11.3	15.9/100.0
1992	20.9/77.7	6.0/22.3	29.6/100.0
1993	162.1/95.0	8.5/5.0	170.6/100.0
1994	383.1/91.2	37.1/8.8	420.2/100.0

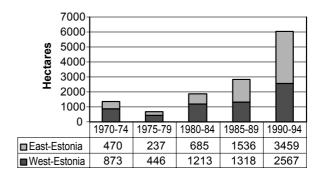|	1970-74	1975-79	1980-84	1985-89	1990-94
East-Estonia	470	237	685	1536	3459
West-Estonia	873	446	1213	1318	2567

Fig. 3. Dynamics of all biological damage in Estonian forests (ha yr^{-1})

With further climate warming, essential changes in the dynamics of forest pests and damage caused by them are possible in Estonia:

(1) Great reproduction outbreaks of pests of coniferous and broad-leaved trees will occur more often. The ecological valence of forest pests will change. Some stenotope pest species may occur as oligotopes, as it has been observed with the pine looper. The preconditions for the immigration of southern dendrofagous insects will improve. The resistance of trees to trunk pests will decrease due to droughts, especially in the best spruce sites—*Oxalis* and *Hepatica* site types. There will be displacements in forest insects' phenology. Trunk pests, which usually have had 1 generation a year, may have 2 generations per year. The recent increase in damaged forest area will continue.

(2) The number of row deer and red deer will increase. Thus the danger of artiodactyls to forest, especially to young stands, will increase.

(3) The pathogenesis of the fungus *Heterobasidion annosum*, which causes root rot, will rise and thus the damaged area will enlarge.

4. ADAPTATION TOOLS IN FORESTRY

There are at least 2 aspects of adaptation: adaptation via the biological process itself as described in the case of the spruce, and adaptation of man's activity in changing conditions.

The variability of forest site types, stands, and their functions in Estonia makes it useless to give classic recommendations for adaptation like definite choice of tree species, rotation period, cutting methods, and so forth. These tasks are part of continuous forest management planning on stand level, and general recommendations will draw upon the stand-level decisions made in accordance with the most important criteria and variables.

The quickening forest growth, the increase in the diversity of acceptable forestry solutions in the case of

increasing growth rate, and the growing risks of forest damage by game, insects, diseases, fire, and, sometimes, heavy pollution will lead to an increase in the diversity, promptness, and effectiveness of decision-making in forestry. In the future there is a possibility that negative changes in forest growth rate may occur, especially due to damage in the premature stage. Then the growth curve will be distorted, and the optimum cutting age (OCA) of the stand can be reached much earlier, but, vice versa, the quickening growth without damage will prolong the optimum rotation length. Vagueness in long-term predictions of the OCA will increase, and more attention has to be paid to continuous monitoring of the stands' health and growth in the future.

Diversity and changes are the key words for decision-making in Estonian forestry. The 2 words can be combined into 'changing diversity'. The management decision depends upon at least tens or often more than a hundred changing variables per stand recorded in the forest management database. And there are a number of essential characteristics not yet recorded in the database. Most of the variables are measurable directly or indirectly with continuous values in their origin. It is very important to follow this continuity in the models used in a computer-aided decision support system (CADSS) to handle all the variety without pointless pressure on biodiversity and to avoid the losses caused by quantifying continuous variables (Nilson 1994).

More modern tools and methods are needed in operational forest planning, and it has to become continuous, both in time and in the abstract space of variables. CADSS will be able to handle all the changing diversity of combinations of about 1 million stands, different technologies, needs, and local and global environment, including the climate and environment to minimize the losses caused by poor adaptation. Design of a management information system (MIS) including the elements of a CADSS is now under way for Estonian state-owned forests.

Sliding-scale planning is inevitable in forestry because of unpredictable changes in natural and human-caused conditions during the long forest rotation. The actual result of forest work often differs from the one planned, or the result can turn out less favorable because of changed conditions. Accordingly, plans have to be corrected repeatedly on the stand level as well as on the national forestry level during forest rotation. This kind of planning is demonstrated in Fig. 4. The optimum result in its strictest sense can never be achieved. Some kind of sub-optimality can be the only realistic hope.

In unstable forests with rapid growth changes and a high risk of damage, traditional long-term forecasts
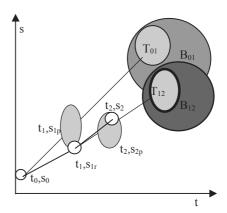

Fig. 4. The basic scheme of step-by-step adaptive decision-making. At the moment t_0, the state of the system is s_0. There is the future background B_{01} and the target T_{01} on it. To achieve it, we plan the state s_{1p} for the time t_1, but we achieve state s_{1r} instead. From the point t_1, s_{1r} the new predictions B_{12} and T_{12} are made for short time decision for the time interval $t_1 \ldots t_2$. This process will be repeated. The ellipses indicate the estimated confidence area on the time-state plane

can fail. So more attention has to be paid to continuous monitoring of the growth and health of every single forest stand for corrections in the long-term objective, and in tactical and operational decision-making. This decision-making, overlapping in time, has to be repeated again and again.

The knowledge put into the forestry MIS will include some elements derived from the analysis of climate change and its consequences for forestry. The most important lessons will result in: (1) improved continuous monitoring and systematic recording of data about actual forest health and growth in the MIS database; (2) formation of archives of records for later analysis; (3) use of sliding-scale plans for the short, medium, and long term, taking into account the errors of predictions; (4) orientation to sustainable rotation with maximum average price or profit increment without discounting as suggested by Price (1993) leading to slightly prolonged rotation, to an increase in the amount of carbon stored in stands, and to a decrease in its sink in commercial forests (see Eq. 2); (5) use of a flexible CADSS for planning of thinning, final cut, and forest renewal.

There are 2 critical values in forest management planning: the OCA for every stand, and the amount of allowable cut (AAC) for the whole forest. The AAC depends on the distribution of the stand's age and on the OCA. The error of the estimate of the OCA of the stand increases with the time lag to its OCA. Consequently, the weight of the maturing curve in AAC calculations has to decrease with increase of this time lag.

Our method for planning forest cutting (Nilson 1980, 1996) is a flexible combination of sliding-scale short- and long-term planning oriented to maximum sustain-

able yield (MSY). This leads to an age distribution in a commercial forest that guarantees MSY in the long run and avoids pressure on biodiversity. This distribution is a uniform distribution of normalized age A_n of stands between 0 and 1:

$$A_n \sim U(0,1) \tag{1}$$

where: $A_n = A/\text{OCA}$, A = age of the stand, and OCA = optimum cutting age (rotation length) of the stand.

We present a new flexible formula for computing the yearly area of AAC, which after some time leads to the distribution given by Eq. (1) in the voluntary calculation set of stands, smoothly adapting to changes of age and of OCA distribution in the set:

$$AAC = \sum_{i=1}^{n} Area_i \cdot q^{T_i} \cdot (1-q)/(1-q^{OCA_i}) \tag{2}$$

where n = total number of stands in the calculation set, i = order number of the stand in the set, Area = stand area, q = relative decrease in the 'weight' of the stand in the calculation or increase in the error of maturity estimates with increase of T, T = time left up to maturity (OCA minus age of the stand) in years, and OCA = optimum cutting age.

Most often we used a value of q between 0.93 and 0.97. Both values T and OCA have to be used with step 1 yr.

One can analyze the best strategy in boreal forestry from the aspect of climate change in more general terms. Brown (1997) points at the future decrease in the role of boreal forests as a sink of carbon with age. An elegant and simple tool to handle this problem is the differential growth function by Weber (Kiviste 1988), valid soon after the culmination of increment and before achieving the really maximum amount of biomass (less than B_{max}):

$$\Delta B_t = c \cdot (B_{max} - B_t) \tag{3}$$

where ΔB_t = increment of biomass at age t, c = relative amount of growth factors used to keep a unit of biomass alive instead of growing one additional unit, B_{max} = limit (theoretical maximum) value of biomass, and B_t = biomass at age t

The zero sink of carbon in over-mature stands is the obvious deduction from the existence of B_{max}. They only hold the stored carbon. The value of coefficient c for stem volume in Scotch pine stands is usually between $\frac{1}{50}$ and $\frac{1}{40}$. Storing timber in the form of buildings, furniture, or books with a lifetime of more than 40 to 50 yr leads to an increase in both the carbon sink and the store in timber. This kind of approach is topical for decisions regarding greenhouse gas (GHG) emissions in forestry (Marland & Schlamadinger 1997), and the Weber function can be used for GHG decisions.

Adaptation should not be viewed simply as humans' direct answer to changes. The other aspect is the adaptability of the forest itself. The adaptability of the stand is based on the growth potential of a sufficient number of trees in it. The more growth resources are available for the growth of the tree, the bigger its adaptation potential. The same is true for the stand as a whole. The Weber function can be used here too. Pine and spruce defoliation data from Sweden, based on hundreds of thousands of samples in the Swedish National Forest Inventory (National Board of Forestry 1992, p 100–101; 1995, p 78–85), provide indisputable proof of this. There is an almost linear increase in the defoliation index in correlation with the age of the trees for the years 1987 to 1994. The older the stand, the higher the risk is of fungal, insect, or wind damage. Accordingly, the adaptability of the commercial forest as a set of stands can be increased by avoiding the over-maturing of stands. Orientation to the age distribution by Eq. (1) and to MSY in boreal commercial forests is the best compromise solution in general.

Natural adaptability of more diverse stands (mixed, random spacing of trees, micro-variation of site conditions, large variation of tree size, and so forth) is high, since diversity guarantees smooth and well-timed self-thinning of the stand and enough growth factors for the remaining trees. The genetic diversity of tree species is an additional factor supporting natural adaptation. Most often this has been ignored in model predictions. Planted pure stands have reduced diversity and reduced adaptability. In such cases, well-timed moderate thinning has to be planned, using a CADSS to avoid over-stocking and lack of free resources for growth and adaptation. The last approach, viewing the system of forest and humans together instead of forest only, is closer to the principle of MSY in the case of smooth changes. Exaggerated attention to diversity and natural adaptability as an absolute provision in commercial forests is the result of restricted and non-systemic understanding of forestry. The goal is an optimum combination of natural and regulatory adaptability.

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