Assessment of CO_2 Fluxes and Effects of Possible Climate Changes on Forests in Estonia

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The present study is the first attempt to carry out an inventory of greenhouse gas (GHG) fluxes in the forests of Estonia. The emission and uptake of CO_2 as a result of forest management, forest conversion and abandonment of cultivated lands in Estonia was estimated. The removal of GHG by Estonian forests in 1990 exceeded the release about 3.3 times. Changes in the species composition and productivity of forest sites under various simulated climate change scenarios have been predicted by using the Forest Gap Model for the central and coastal areas of Estonia. The computational examples showed that the changes in forest community would be essential.

Keywords climate change, forest composition, Forest Gap Model, forestry, greenhouse gases
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1 Introduction

Climate change and a realistic assessment of CO_2 release from and uptake by forests have been considered major environmental problems during the last decades. Although the problem has a global importance, it is particularly essential for countries rich in forests.

The total area of the Republic of Estonia, including areas of inland water, is 4 523 000 hectares, of which land area is 4 310 000 hectares (Statistical Yearbook 1994, Karoles et al. 1994). On 1 January 1994, the area of productive forest land was 2 016 600 ha, of which about 1.9 Mha was actually forested (Forestry… 1995). During the last half-century the area of forest stands has more than doubled and will be increasing in the nearest future. In 1993 the forest cover was 47.7 %. The current total increment of solid wood over bark in forests is estimated at 9.6 Mm^3/yr, corresponding to about 4.8 $m^3/ha/yr$ on productive forest land. The area of forest land has been gradually increasing (Fig. 1) mainly due to abandonment of agricultural lands.

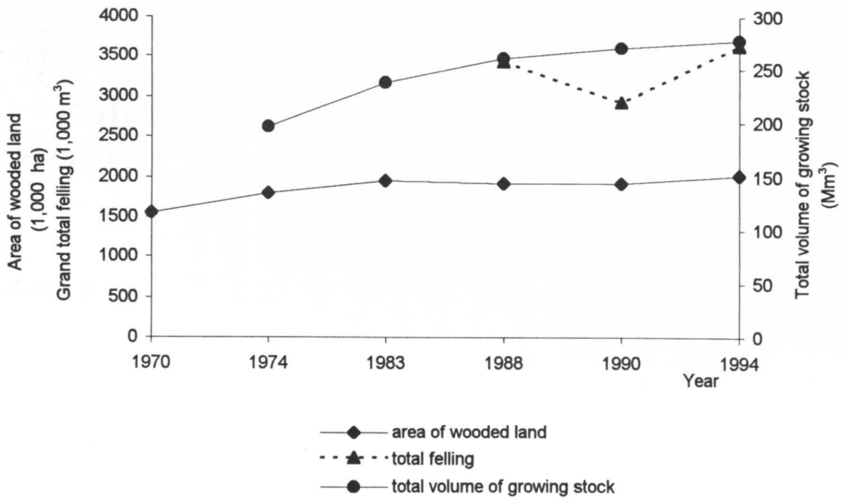

Fig. 1. Changes in wooded land, volume of growing stock and grand total felling (Karoles et al. 1994, Statistical yearbook 1994, Forestry… 1995).

In 1993 the total volume of standing growing stock in closed forests was reported to be 277 Mm^3. Coniferous forests make up 63 % of the total area of the Estonian forests and 66 % of the total forest yield and deciduous forests 37 % and 34 % respectively (Statistical Yearbook 1994) (Fig. 2).

At the present time 87 native and over 500 introduced tree and shrub species have been recorded in Estonia (Karoles et al. 1994). The main coniferous tree species are Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.). Deciduous trees are represented by several species of birches (*Betula pendula* Roth, *B. pubescens* Ehrh.), speckled alder (*Alnus incana* (L.) Moench), aspen (*Populus tremula* L.) and black alder (*Alnus glutinosa* (L.) Gaertn.). Other broad-leaved trees, e.g. oak (*Quercus*), ash (*Fraxinus*), linden (*Tilia*), elm (*Ulmus*) make up only 1 % of the standing volume (Supply, production and costs… 1994) (Fig. 2).

During the last decade (from 1980 to 1991) the average annual cut reached 3.2–3.4 Mm^3. After that the harvested volume decreased and was estimated at about 2 Mm^3 for 1992 but in 1994 the cut increased again and was estimated at about 3.6 Mm^3 (Fig. 1).

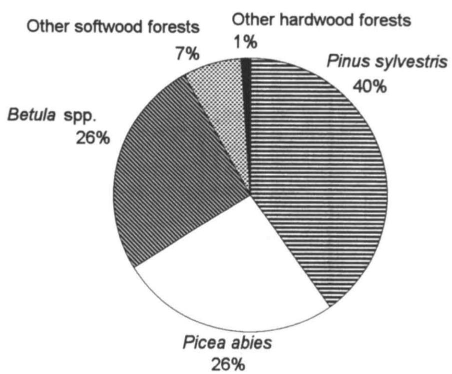

Fig. 2. Distribution of predominant forest tree species according to yield in Estonia.

About 100–200 000 ha has been reported as former agricultural land, abandoned during the last decades and covered mainly with bushes.

The aims of present study were to assess the release and uptake of CO_2 by forests in Estonia at the present time, to evaluate possible changes in the species composition and productivity of

forests under doubled atmospheric CO_2 and climate warming predicted for the future. The study was launched in 1994 as a part of the U.S. Country Studies Program by using the calculation methods and Forest Gap Model recommended by the program (IPCC… 1994, Guidance for… 1994).

2 Assessment of CO_2 Release and Uptake

Principles and Methods

There are notable uncertainties in all the current methods for estimating fluxes of greenhouse gases from forests and land use change. The simplified method for the estimation of CO_2 and other GHG fluxes which has been recommended by the IPCC/OECD Programme on the Development of a Methodology for National Inventories of Net Greenhouse Gas Emissions was used in the present study (IPCC guidelines… 1994).

In the calculations of the CO_2 budget in Estonian forests three main factors were considered:

1. changes in forest and other woody biomass stocks
2. forest conversion
3. abandonment and natural or artificial afforestation of former farm lands.

1990 ± 1 is designated as a base year for the calculation of CO_2 emission and uptake. Since radical changes have been taking place in Estonian economy from 1990, the inventory of CO_2 fluxes was also carried out in 1994 and comparative dynamics of processes was estimated. The data of the Estonian Forest Department, Estonian Forest Survey Centre, Estonian Forest Institute and Faculty of Forestry of the Estonian Agricultural University have been used in the inventory calculations. According to the methodological requirements current emissions of CO_2 from biomass left to decay were estimated over the previous decade (1980–1990). Emissions from soils due to conversions were estimated over previous 25 years (1965–1990). For the immediate release from burning the data of 1990 were used. In 1994 no forest conversion took place and thus no immediate release from burning occurred. To estimate the CO_2 release from abandoned managed lands for a base year the data for 1970–1990 and for 1994 the data for 1974–1990 were used.

In the 1990 inventory the areas converted under ditches with forest roads have been considered as forest conversion because of absence of other conversion types in Estonian land use. In 1994 the situation was completely changed: under the new economic situation the drainage and road building in forests had stopped. This is due to the uncertainties in the fate of forest land because of the continuous process of returning lands to private owners is under way. Forest conversion did not take place during the period of privatization and the ongoing process of restructuring the socio-economic system offers good possibilities for decreasing CO_2 emission.

Due to the changes in forest management the volume of fellings had grown in 1994 in comparison with the base year (1990) mainly because of the increased consumption of fuel wood. Accordingly, the total felling in 1994 was 3626.2 thousand m^3 (Fig. 1), out of which 1414.3 thousand m^3 was used for fuel. Unfortunately the methodology used does not consider the fate of harvested material except of those used as fuel wood. Compared to 1990 the growth in total felling is 24 % and in fuel consumption 33 % (Forestry… 1995).

The calculations used:

1. Annual biomass C uptake (t C/yr):

   $U = AP \times GP \times CP$

   where

   AP = area of managed forests (ha)

   GP = annual biomass growth rate (t dm/ha/yr)

   CP = C fraction for managed forests (t C/t dm) (biomass C fraction = 0.45; default value from IPCC guidelines (1994))

2. Annual biomass C removal (t C/yr):

   $R = ((RW \times EF) + FW + OW - FC) \times C$

   where

   RW = roundwood harvest (m^3/yr)

   EF = biomass conversion/expansion factor (t dm/m^3) (default values for converting volume data to tons are 0.65 t dm/m^3 for deciduous trees and 0.45 t dm/m^3 for conifers (IPCC guidelines 1994); 2/3 of the Estonian forests are coniferous (Statistical Yearbook 1994), hence the conversion ratio = $2/3 \times 0.45 + 1/3 \times 0.65 = 0.5$)

FW = annual fuel wood consumption (t dm/yr)
OW = other wood use (t dm/yr)
FC = wood removed from forest clearing and burned off-site (t dm/yr)
C = C fraction (t C/t dm)

3. Total C released by burning aboveground biomass on- and off-site (t C/yr):
$CO_n = A \times (BB - BA) \times FB_n \times FO_n \times C + A \times (BB - BA) \times FB_f \times FO_f \times C$
where
A = area converted annually (ha/yr)
BB = biomass density before conversion (t dm/ha)
BA = biomass density after conversion (t dm/ha)
FBn = fraction of biomass burned on site
FOn = fraction of biomass oxidized on site (fraction of biomass oxidized during burning both on- and off-site = 0.90; default value from IPCC guidelines (1994))
FBf = fraction of biomass burned off site
FOf = fraction of biomass oxidized off site
C = C fraction (t C/t dm)

4. Total C released by decay of aboveground biomass (t C/yr):
$CD = AA\text{-}10 \times (BB - BA) \times FD \times C$
where
AA-10 = 10-year average annual area converted (ha/yr)
BB = biomass density before conversion (t dm/ha)
BA = biomass density after conversion (t dm/ha)
FD = fraction left to decay
C = C fraction (t C/t dm)

5. Total C released from soil (t C/yr):
$CS = AA\text{-}25 \times SC \times FR$
where
AA-25 = 25-year average annual area converted (ha/yr)
SC = soil C fraction before conversion (t C/ha) (C in soil per unit forest area = 185 t C/ha; although, in Estonian forests the soil carbon content ranges from 44 to 192 t/ha (Kylli 1988) the default value recommended by IPCC guidelines (1994) has been used in calculations)
FR = fraction released over 25 years (fraction C released from soil following forest conversion = 0.5/25 yrs; default value from IPCC guidelines (1994))

6. Annual C uptake in soils, ≤ 20 years (t C/yr):
$CSL = AY \times RS$
where
AY = total area abandoned and regrown during last 20 years (ha)
RS = annual rate of C uptake in soils (t C/ha/yr) (average annual soil C accumulation per unit area regenerating = 1.8 t C/ha/yr; default value from IPCC guidelines / 1994/)

7. Annual C uptake in aboveground biomass, ≤ 20 years (t C/yr):
$CBL = AY \times RB \times C$
where
AY = total area abandoned and regrown during last 20 years (ha)
RB = annual rate of aboveground biomass accumulation (t dm/ha/yr)
C = C fraction of biomass (t C/t dm)

Results

The calculation results showed that CO_2 uptake by Estonian forests in 1990 exceeded 3.3 times its emission.

It became evident that while compared to 1990 the emission of CO_2 has decreased and removal has increased during these four years. CO_2 emission due to commercial harvest and fuel wood consumption had increased by 7 % (Table 1). Taking into account the changes over the four year period, the emission from Estonian forests had increased by 1 %. Annual removal of CO_2 from Estonian forests in 1994 was 11089 Gg. This is 2 % lower than in 1990 (Table 1).

Net CO_2 uptake by Estonian forests in 1994 was estimated at 7660 Gg, which is 4 % lower than in 1990 (7950 Gg CO_2) (Fig. 3).

Although the net emission of CO_2 in 1994 had not changed in comparison with 1990, great differences in the balance of land use and forestry categories were observed (Table 1). The ratio removal/emission was 3.34 in 1990. In 1994 it was 3.23. The 3 % decrease in the ratio removal/emission indicates a possible growing trend in the CO_2 emission.

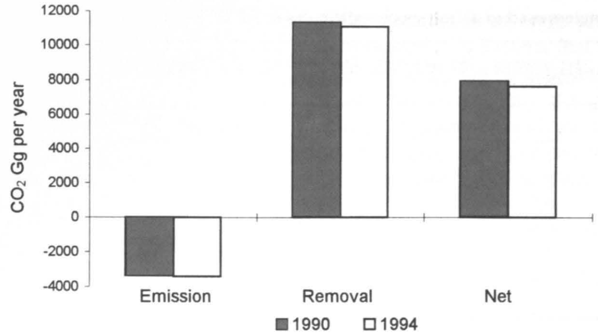

Fig. 3. CO_2 emission and removal.

Table 1. Dynamics of removals/emissions (Gg) of CO_2 due to forestry and land use change from 1990 to 1994.

		1990		1994	
		Removal	Emission	Removal	Emission
Forest management	Biomass growth increment	7438.27	-	8602.47	-
	Harvest	-	2791.01	-	2989.14
Forest conversion	On- and off-site burning	-	62.73	-	0
	Decay	-	33.82	-	19.32
	Soil	-	508.75	-	420.57
Abandoned managed lands	Aboveground biomass	1642.70	-	1045.04	-
	Soil	2265.78	-	1441.44	-
Total		11346.75	3396.31	11088.95	3429.03

3 Prognosis of the Dynamics of Forest Community under Climate Change

Atmospheric CO_2 concentrations are the net result of continuous emissions and sequestration that occur through natural processes and human activity. Models of global climate change suggest a doubling of the present atmospheric CO_2 with a 4 °C mean rise in global temperature within the next 100 years (Manabe and Wetherald 1980).

The importance of climatic factors in the function and structure of the boreal forests is well

Table 2. Basic parameters used to define species attributes in the FGM.

Species	Max. observed diameter, m	Max. observed age, yr	Max. observed height, m	SEDmax	L	minPET ratio
Picea abies	1.5	350	47	50	1	0.94
Pinus sylvestris	1.7	450	40	40	3	1.20
Quercus robur	2.5	999	39	20	2	1.10
Betula pendula	0.7	150	31	100	3	0.98
Betula pubescens	0.6	120	25	100	2	0.97
Populus tremula	1.0	200	34	40	3	1.00
Alnus glutinosa	1.2	200	30	20	2	0.94
Alnus incana	0.5	70	20	40	1	0.98

Max. diameter (Laas 1967, Paal et al. 1989).
Max. age (Laas 1967, Tappo 1982, Paal et al. 1989).
Max. height (Laas 1967, Paal et al. 1989).
SEDmax – maximum yearly seedling establishment scaled to plot (Laas 1967, Holdridge 1967).
L – light response category: 1 – shade tolerant, 2 – intermediate, 3 – shade intolerant (expert estimation).
minPET ratio – potential evapotranspiration (PET) allowing tree growth, as species specific bioclimatic index of drought tolerance. It is the quotient of PET and average annual precipitation (Holdrige 1967).

Table 3. Incremental climate change scenarios for central Estonia and coastal area of Western Estonia.

Regions, climatic parameters	Location	Scenario 0: present climatic conditions*	Scenario 1: +4 °C	Scenario 2: +4 °C, –10 % AP	Scenario 3: +4 °C, +10 % AP
Tudu	59°12' N 27°00' E				
GDD		2257	3264	3264	3264
PETratio		0.72	0.88	0.98	0.8
AP		670	670	604	737
Virtsu	58°36' N 23°30' E				
GDD		2503.7	3609.9	3609.9	3609.9
PETratio		0.82	1.01	1.12	0.92
AP		620	620	560	682

GDD – annual sum of growing-degree days = yearly sum of daily mean temperatures above 0 °C.
PETratio – potential evapotranspiration ratio, mm/mm.
AP – annual precipitation, mm.
* Data of J. Jaagus from the Institute of Geography, University of Tartu.

known and applied in managing forest resources. The trend of climate warming would greatly affect the plants and plant communities.

Generally the computer simulations have indicated that doubling of the atmospheric CO_2 and climatic warming could increase the productivity of tree stands in the boreal zone (Kellomäki et al. 1988, Kellomäki and Kolström 1992, Solomon and Leeman 1990), although some simulations showed a decrease in total forest biomass (Pastor and Post 1988, Overpeck et al. 1990, Lasch and Lindner 1995). It is logical that the character of forest responses to climate changes depends on the physiological tolerance of tree species and several edaphic factors.

Plant communities could respond to changes in climate and increased CO_2 as a function of changing competitive advantages among species (Solomon and Cramer 1993). Given that long sets on forest timescale dynamics are incomplete

in simulations what yet facilitate the study of forest growth and demography. Using the Forest Gap Model for simulating a range of the dynamics of forest composition and diversity under various exogenous disturbance climatic regimes are found. We examined the sensitivity of forest trees to climate warming and changes which may occur under doubled CO_2.

Model Description and Species-Specific Parameters

In determining the responses of predominant species of Estonian forests to changes in environmental conditions (doubling of CO_2, increase of temperature and annual precipitation) the simple version of the Forest Gap Model (FGM) (Botkin et al. 1972, Shugart 1984), recommended by the U.S. Country Studies Program was used. The Holdridge Life Zones Classification Models mapping in triangular coordinate system (Holdridge 1967) was also used to determine the potential evapotranspiration ratio for forest ecosystem types and species.

The FGM evaluates changes in the species composition and productivity of species in forested sites of areas smaller than 1 ha. FGM simulates the establishment, growth and mortality of individual trees on a forest stand on an annual time step and is capable of simulating stands with mixed-species and mixed-age population.

The potential growth of each tree is estimated from species-specific optimal growth curves, derived from silvicultural data on maximum tree size and longevity (Botkin et al. 1972, Shugart 1984). The environmental conditions on the plot (e.g. light, available moisture, resource depletion, temperature) modify the optimal growth of the tree in a stand. The interaction of responses of yearly diameter increment to the changing environmental conditions is computed through the product of all growth factors.

Main attention was paid to the evaluation of the changes in the species composition and of the tolerance of forest trees under various climate change scenarios in Central Estonia (Tudu) and in the coastal area of Western Estonia (Virtsu), which differ in the present climatic and landscape character.

The parameters of eight predominant forest trees (species) in Estonia that were used in the FGM for modeling biomass and species composition dynamics under the potential climate changes for both regions are given in Table 2. Stand simulations were done with nine plots for each region with yearly time step during 250 years.

Into the modeling framework four climate change scenarios were incorporated (Table 3). According to FGM possibilities the transient climate change was applied before forest growth and the forest development began from bare ground under already changed climate.

Results

In the simulation of long-term forest development (250 years) our analyses showed significant potential changes in forest community structure for two different regions of Estonia under various climatic conditions (Fig. 4). Competition, succession and changes in species composition as a function of time and climate may be predicted by the given version of FGM under the baseline scenario.

1. *Scenario 0.* In certain points of investigation the present climatic conditions have been used. The results of modeling showed an intensive growth of forest during the first 50–70 years, which is in accordance with the real data on mature and overmature forests in Estonia (Tappo 1982, Yearbook of Forest 1995). A slight decline in the stand and biomass followed after 100 years. In the first period of forest development the pioneer community consisted mainly of birch. After 100 years the predominance of deciduous trees will be replaced by Norway spruce in Central Estonia or by mixed stands in the coastal area.

2. *Scenario 1.* The warming of climate by 4 °C causes essential changes in forest structure. Scots pine seems to the most tolerant to warming of climate and would appear in Central Estonia as a predominant species. During the first one hundred years the high number of birch and aspen could be noticed, but their share decreases with the ageing of forest. In the coastal area the warming of climate favours only the development of

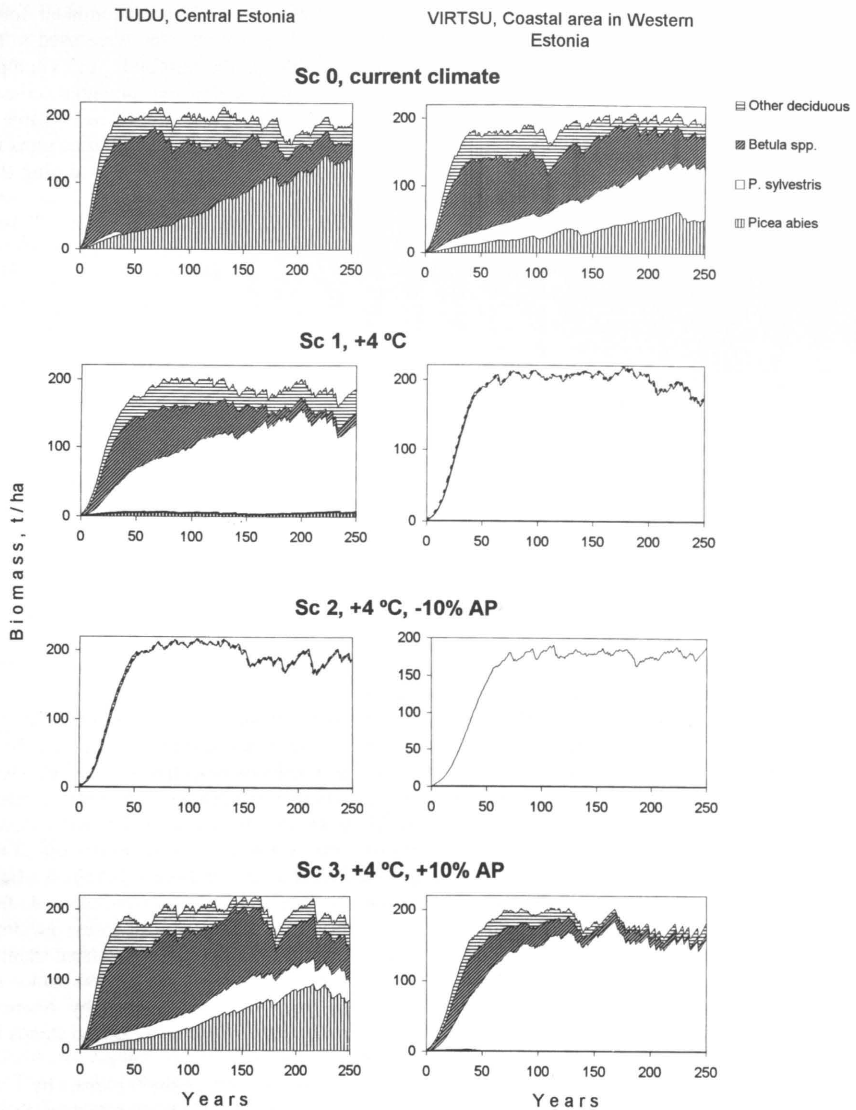

Fig. 4. Possible alterations in the forest community structure under simulated scenarios of climate change in Estonia.

Scots pine with an inconsiderable share of oak.

3. *Scenario 2.* At the increase of temperature and decrease of annual amount of precipitation the growth of the most drought tolerant species should be possible – Scots pine and oak in Central Estonia, Scots pine in the coastal area.

4. *Scenario 3.* Increase in both temperature and the amount of precipitation favours an intensive growth of deciduous trees during the first 120–170 years. In Central Estonia during the later development of the forest ecosystem deciduous trees will be replaced by Norway spruce. Here is an analogy with scenario 0. In the coastal area the predominant trees in the forest site are Scots pine and deciduous trees to some extent.

It can be seen in the simulations of climate changes that the effect may be considerable on forest species composition. Scots pine, oak and birch seem to be rather tolerant to the increase of temperature and changes in the amount of precipitation level.

4 Discussion

The calculation results showed that CO_2 uptake by Estonian forests exceeds its emission at the present time. The prognosticated doubling of the CO_2 concentration and the accompanying climate change raise the question of the capability of forests of counteracting the increased amounts of CO_2 and surviving under the changed climatic conditions. A number of models and scenarios have been compiled to forecast possible changes in forests.

The used FGM summarizes the results with respect to the ecology of tree species. In our modeling framework only predominant native species occurring in Estonia were used. Exotic and rare native ones were avoided.

Our results suggest that *Pinus sylvestris*, having a broad ecological area of distribution, showed the highest tolerance to climate warming and decreasing amount of precipitation (Scenarios 1, 2). An increase of the mean temperature by 4 °C and of precipitation by 10 % may result also in an increase of the biomass of several deciduous tree species (*Betula* spp., *Quercus robur, Populus tremula*) (Scenario 3), although the total biomass of sites may decrease in all modelled scenarios. Decreasing of forest biomass by climate changes may lead to disturbances of the balance of CO_2 emission and removal. Changes in forest structural composition and possible inhibition of forest biomass formation raised problem of sequestration facilities of enhanced CO_2 by forests in the future.

Although the results of modeling by FGM show some inhibition of forest biomass and serious changes in species composition, we are afraid that projections presented in this paper should not be interpreted as realistic predictions of future forest dynamics.

A logical consequence of such a situation would be the replacement of the present species in forest ecosystems by those of more southern distribution. If the mean annual temperature increased by 4 °C and the mean annual precipitation by 10 %, which is generally predicted, the climate in the region of Estonia could resemble that of southern Poland or central Germany. The replacement of contemporary species may take place and the area of hardwood forests may thus become wider in Estonia. The possible immigrants to Estonian forests community may be *Fagus silvatica, Carpinus betulus, Quercus petraea* and *Ulmus carpinifolia*. The forest communities in Estonia will probably change towards the *Fagion, Carpinion* or *Quercion* types and the total biomass of forest may increase.

Although gap models have been used and modified by several authors (Botkin et al. 1972, Shugart 1984, Urban et al. 1991, Urban and Shugart 1992), some shortcomings in the simulation of forest dynamics by FGM may lead to unsatisfactory results. Lasch and Lindner (1995) conclude from a comparison and modification of two gap models that with currently available models realistic forest dynamics within different climatic zones cannot be simulated without quite substantial model modifications. In Estonia, the heterogeneity of the landscape, particularly the distribution of various soils, will become an important factor determining forest responses to climate change. The incorporation of some vital parameters such as characteristics of landscape, soil and other nutritional factors controlling forest productivity into the model could help overcome these shortcomings. As the applied FGM simulates the growth and mortality of individual tree species in sites, the seasonal timing of morpho-physiological processes, physiological tolerance of species to frost in boreal zones might be suitable to improve the forest succession simulations.

Our calculations reflected a strong response of forests to climate warming, revealed in both the composition and age structure of forest stands. The simulation of possible impacts of climate change for Estonian forests is only preliminary and prior to taking any preventive measures it is advisable to continue with improved climate scenarios and further model development.

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