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Computer simulation of fir forest dynamics in the Bieszczady Mountains in response to climate change

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ABSTRACT: Results of investigation of fir forest dynamics in the Bieszczady Mountains using a FORKOME (FORest KOzak MEnshutkin) model in response to climate changes are presented. The model was verified in field trials in 1998–2001 in a fir forest in forest district Procisne in the Bieszczady Mountains (Poland). Prediction of tree biomass and tree number was made for the next 600 years. The simulation demonstrated beech domination when mean annual temperature increases by 2°C while with a decrease in temperature by 2°C fir becomes dominant in the examined area. Both one simulation run and Monte Carlo simulation showed comparable results in statistical analysis. The results of FORKOME model simulations enable to set a thesis that forest succession may be used for evaluating the level of climate-change influence on forest ecosystems. Presented results indicate great usefulness of the model while investigating various subjects, especially concerning climate changes, which may have both theoretical and practical importance.

Keywords: forest; fir; computer model; climate changes, Bieszczady

Climate changes can result in potential fluctuations in temperature and rainfalls. Data presented in literature indicate large differences in mean annual air temperatures during the last two centuries. Along with an increase in temperature (e.g. mean annual temperature in 1799 was 4.6°C and in 1989 was 9.8°C) the vegetation period became longer (KOWALSKI 1993).

The main problem we will face in forthcoming years is the change of climate. If we consider climate warming, it is worth noticing that a majority of the currently used general circulation models show that a global temperature increase of the magnitude of 1°C to 4°C is conceivable with CO_2 doubling (MAXWELL 1992). Global warming is estimated as an increase in the mean annual air temperature (BEDNARZ et al. 1994; OBRĘBSKA et al. 1997) by 2.5°C until the end of the year 2100 (PUHE, ULRICH 2001). The increase in temperature for Central Europe is forecasted for 2–3°C (2–5°C in winter, 1–3°C in summer).

Many crucial parameters concern forecasting the climate influence on forest ecosystem evolution (KRAUCHI 1993). Common demand claims development of tools to be used for prediction of the potential effect of climate change on ecosystems. Many scientists deal with this problem in literature (KRAUCHI 1995; HONG et al. 1999; BRZEZIECKI 1999).

Little is known about possible alterations in fir forests, which often dominate besides beech forests in the Bieszczady Mts. from 500 to 950 m a.s.l. in different climatic conditions. Therefore we carried out investigations into computer simulation of fir forest succession on research plots with various scenarios of climate change using the FORKOME model. The goal of the simulation was to verify possible fir forest changes and the relationship between fir and beech forests in climate change conditions.

MATERIALS AND METHOD

We used data concerning the distribution of fir (*Abies alba* Mill.) forest communities in the Bieszczady Mountains. After having analysed the results concerning fir forest succession presented in literature a site was selected. Research plot is situated on the northern slope of Kosowiec Mountain (forest district Procisne) in the Bieszczady Mountains (Poland). The plot is located on the slope of the mountain (inclination 12°) at the altitude of 650 m a.s.l. Brown soils over the Carpathian flysch are characteristic of the plot. Dominating tree species was fir. The initial conditions of the stand are: average age of the fir stand – 75 years, average diameter – 44.3 cm. On the research area (1/12 ha) there were 22 individuals of fir and 1 individual of beech. There are diameters d.b.h. (cm) of each of 22 fir trees: 50; 44; 46; 56; 48; 61; 56; 37; 35; 53; 7; 15; 52; 44; 67; 45; 56; 43; 72; 32; 36; 47 cm. The diameter of beech was 18 cm.

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Different types of scenarios were simulated:

Control – in the actual conditions: annual temperature 7.5°C, precipitation 800 mm;

Scenario 1 – in conditions of a temperature increase by 2°C;

Scenario 2 – in conditions of a temperature decrease by 2°C.

Description of the FORCOME model was presented in detail in our former articles (MENSHUTKIN, KOZAK 1997; KOZAK, MENSHUTKIN 2000, 2001). Here only new, additional functions, added to the model recently will be illustrated.

The first important feature is a possibility of computing climate changes while simulation runs. Four new parameters concerning temperature fluctuations were added: K_0, K_1, K_2, K_3.

As far as degree-days are concerned (sum of temperatures higher than 5°C), a new formula is proposed:

$$K = K_0(1 + K_1 t) + K_2 \, Sin\left(\frac{2 \cdot 3.14}{K_3} t\right)$$

where: K – sum of effective temperatures (higher than 5°C),
K_0 – constant coefficient,
K_1 – direction of the sum of mean effective temperatures change,
K_2 – alternation amplitude of the sum of mean effective temperatures,
K_3 – alternation period of the sum of mean effective temperatures,
t – time period (years).

In our model we took into consideration leaf transpiration depending not only on meteorological parameters, as implemented in other gap models (SHUGART 1984; BRZEZIECKI 1999), but also on the tree species. The model includes dependences of various tree species on the groundwater level and dependences of the rate of tree growth on the amount of available water. The core of this block is the following formula concerning water balance:

$$W(t+1) = W(t) + \text{Prec}(t) - \text{Trans}(t) - \text{Evapor}(t)$$

where: $W(t)$ – amount of water in the ground in time t,
Prec(t) – precipitation, rainfall,
Trans(t) – tree transpiration,
Evapor(t) – water evaporation from the ground surface.

Transpiration depends on the biomass and species composition of the forest.

Comparing former articles, more detailed illustration of the algorithm used in the model is presented here (Fig. 1). The algorithm is divided into several blocks. The block PARAMETERS represents the estimation of temperature, precipitation, influence of animals and felling on the research plot. It is possible to simulate forest dynamics in different scenario condition and different initial state.

Since this model is stochastic, the study of its dynamics requires running through many variants (block VARIANT). In the case of investigations and for prediction purposes it may simulate the period of 600 years. These processes are controlled by the block entitled YEAR.

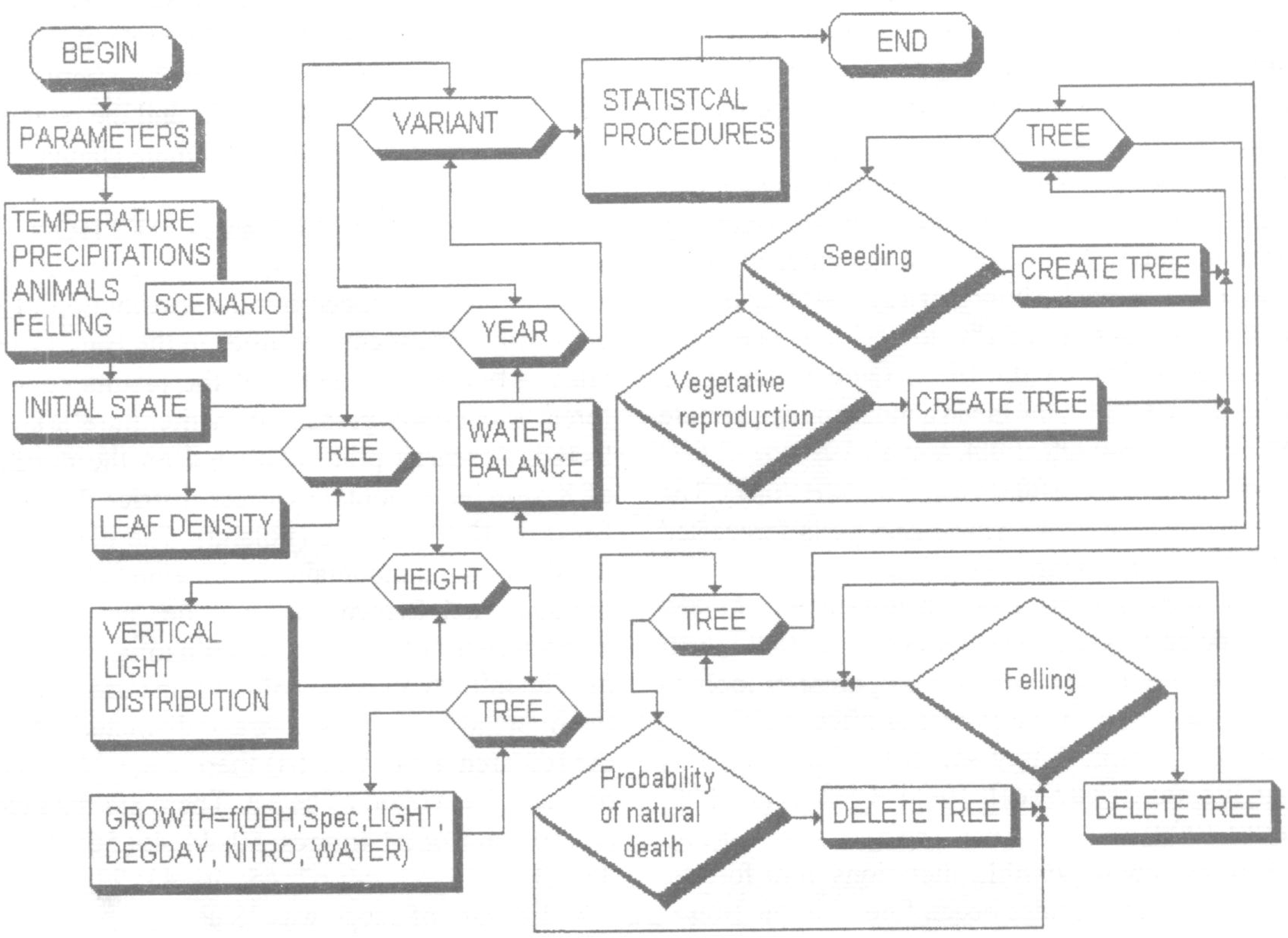

Fig. 1. FORKOME model algorithm

Table 1. Basic parameters of growth for the main tree species in the Bieszczady Mountains used in FORKOME model

Tree species	*H* max (cm)	*D* max (cm)	*AGE* max (years)	B_2	B_3	G	DGD min	DGD max
Fagus sylvatica L.	4,500	150	300	58.26	0.194	290	4,650	12,700
Abies alba Miller	6,000	150	400	78.26	0.261	200	3,855	12,684
Picea abies (L.) Karsten	5,500	150	400	71.60	0.239	370	882	3,960
Betula pendula Roth	3,200	100	100	61.40	0.307	500	0	3,840
Pinus sylvestris L.	4,500	150	400	58.30	0.194	330	270	2,500

There are tree and forest community parameters such as real diameter (*DBH*) of each tree on the research plot and maximum tree diameter (*DBH* max) at a standard height of 130 cm above the ground level, real height (*H*) and maximum height (*H* max), real age (*AGE*) and maximum age (*AGE* max), minimum and maximum of degree-days (*DEGDAY* min, *DEGDAY* max), light intensity, nitrogen and water contents.

Basic parameters for FORKOME model are listed by the species in Table 1. These are parameters used for the main species in the model. The FORKOME model simulates the dynamics of 5 species that dominate on the investigated plots.

The model regards processes of natural death, seedlings, water balance and growth for any year of the run. The growth rate of each tree depended on its dimensions, tree species, and conditions of light, temperature, and supply of nutrients and water.

After the realization of all variants of the model, the programme carries out a statistical analysis of the obtained results (block STATISTICALS PROCEDURES). Different scenarios were simulated for fir permanent

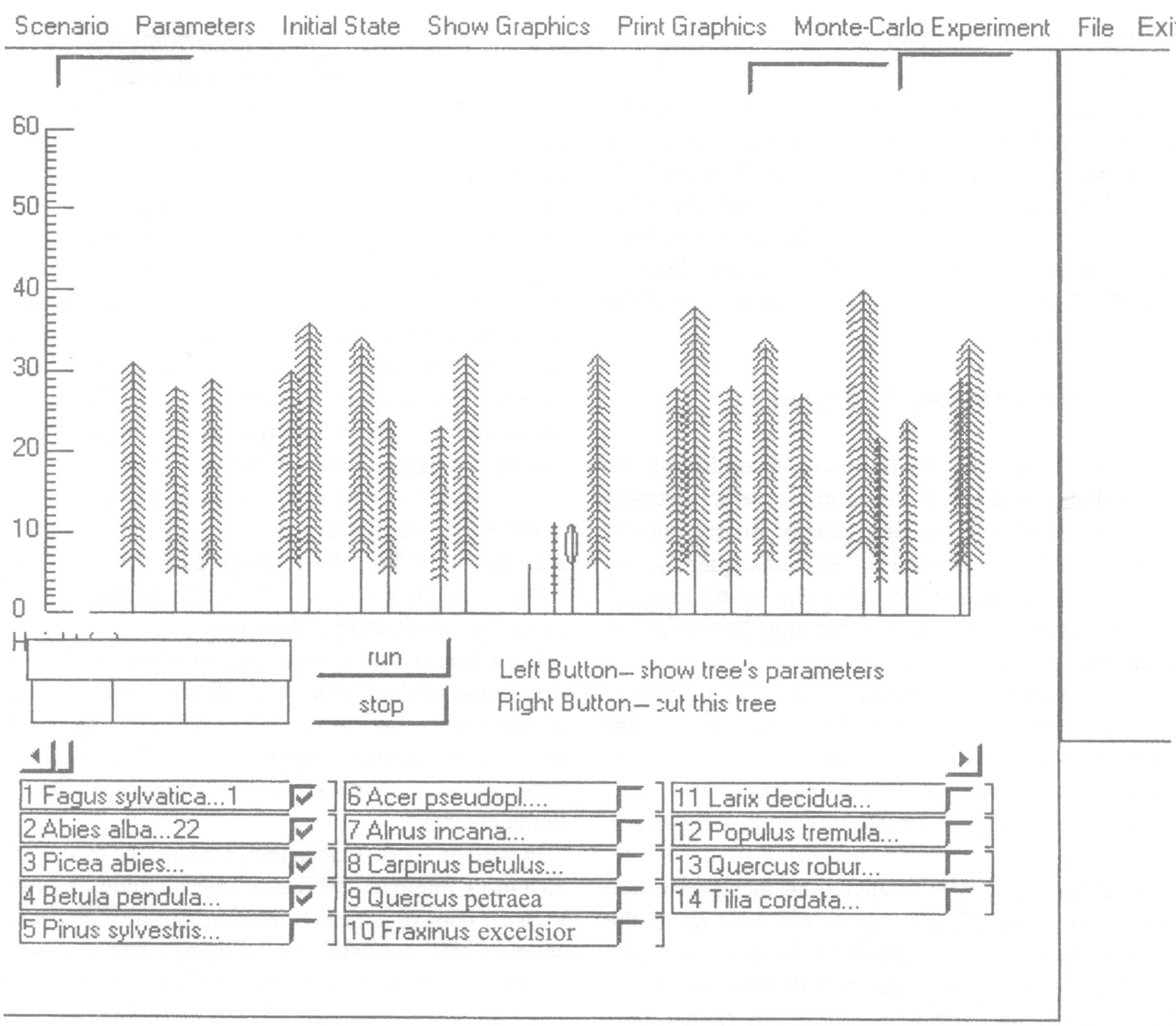

Fig. 2. Interface of FORKOME model

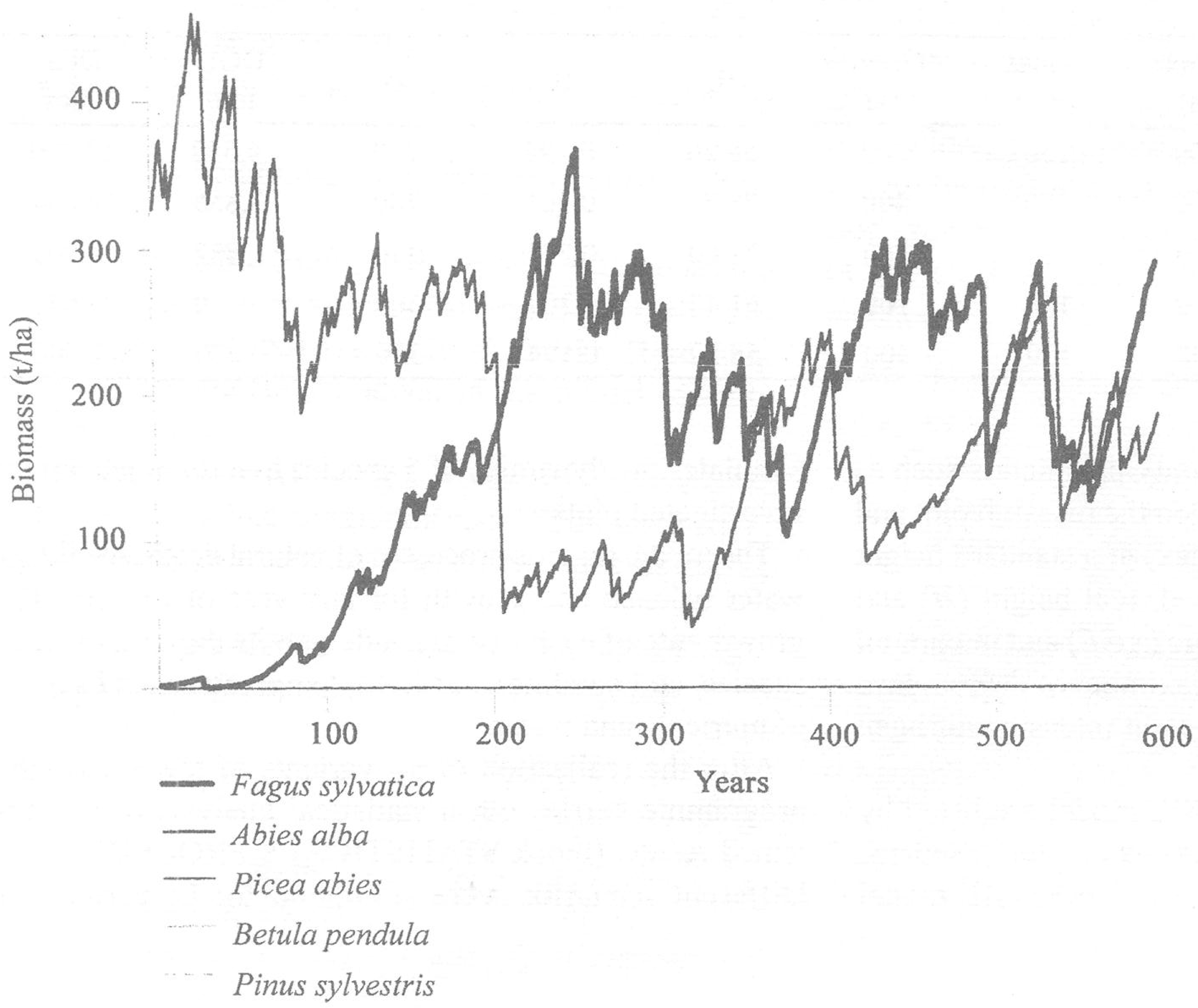

Fig. 3. Biomass of trees (*Fagus sylvatica, Abies alba*) in the fir stand in the control scenario in one simulation run (other species not presented because of its insignificant biomass in the scale of the chart)

plots (TEMPERATURE, PRECIPITATION, ANIMALS, FELLING).

As showed in the interface of FORKOME model (Fig. 2) the position of each tree in the forest is projected along a diagonal of research plot (1/12 ha). The year 2000 was regarded as the first year of the model time. The study time is used as the model time. Each variant begins from the identical initial state corresponding to the situation in forest GAP of 2000 year, when the average age of the forest was 75 years.

RESULTS AND DISCUSSION

In one simulation run for the control conditions the model predicted that the biomass of fir trees increased from 325 ± 5.6 t/ha in the first year of model time to 456 ± 8.1 t/ha in 23 years (Fig. 3). Subsequently, the biomass of fir decreased to 185 ± 4.3 t/ha in 96 years and after that the biomass of fir dominated until 200 years and was at the same level.

The biomass of beech increased from 5 ± 0.1 t/ha in model time 1 year to 180 ± 3.1 t/ha in 200 years. After that the biomass of beech trees dominated until 360 years. Subsequently, the model predicted a short dominance of biomass of fir during 50 years with following beech dominance again.

In the control the model predicted an increase in tree numbers of fir from 21 individuals per 1/12 ha in the first year of model time to 56 individuals in 38 years (Fig. 4). Subsequently, the fir numbers decreased to 26 individuals in 100 years. At that time the beech tree numbers increased. From 100 years to 200 years the number of fir and beech trees was similar. After 200 years the number of beech trees was dominating on the plot.

In the Monte Carlo realization (30 simulations) the model also assumes these changes. The amplitude of these changes is not as high as in a single simulation run. But in the Monte Carlo method it is possible to analyse the tendency of changes in tree biomass and numbers.

The Monte Carlo method also showed a decrease in biomass of fir trees and an increase in biomass of beech trees for the model time from 1 year to 200 years. Subsequently, the model predicted a short dominance of beech biomass, after that dominance of fir until 355 years. Then the model again predicted beech dominance until 560 years and after that fir dominance until 600 years.

The Monte Carlo simulation run showed that the number of beech trees on the 1/12 ha of simulation area increased from 1 tree in the first year to 30 trees in 400 years of model time. In the second part of the succession beech trees were dominating.

In variant 2 (increase in temperature) in the Monte Carlo simulation run the dominance of beech biomass appears sooner – since the 160^{th} year (Fig. 5). Dominance of beech biomass lasted longer – from 160 to 600 years. The dominance of beech stems was more frequent in variant 2 than in the control.

In variant 3 (decrease in temperature) the model predicted a more intensive decrease in beech biomass compared with the control in one realization. It is also evident in the Monte Carlo simulation run (Fig. 6) when fir dominance occurred all time and biomass of beech was only about 100 t/ha. For the number of stems the distribution in the control and in variant 3 was similar.

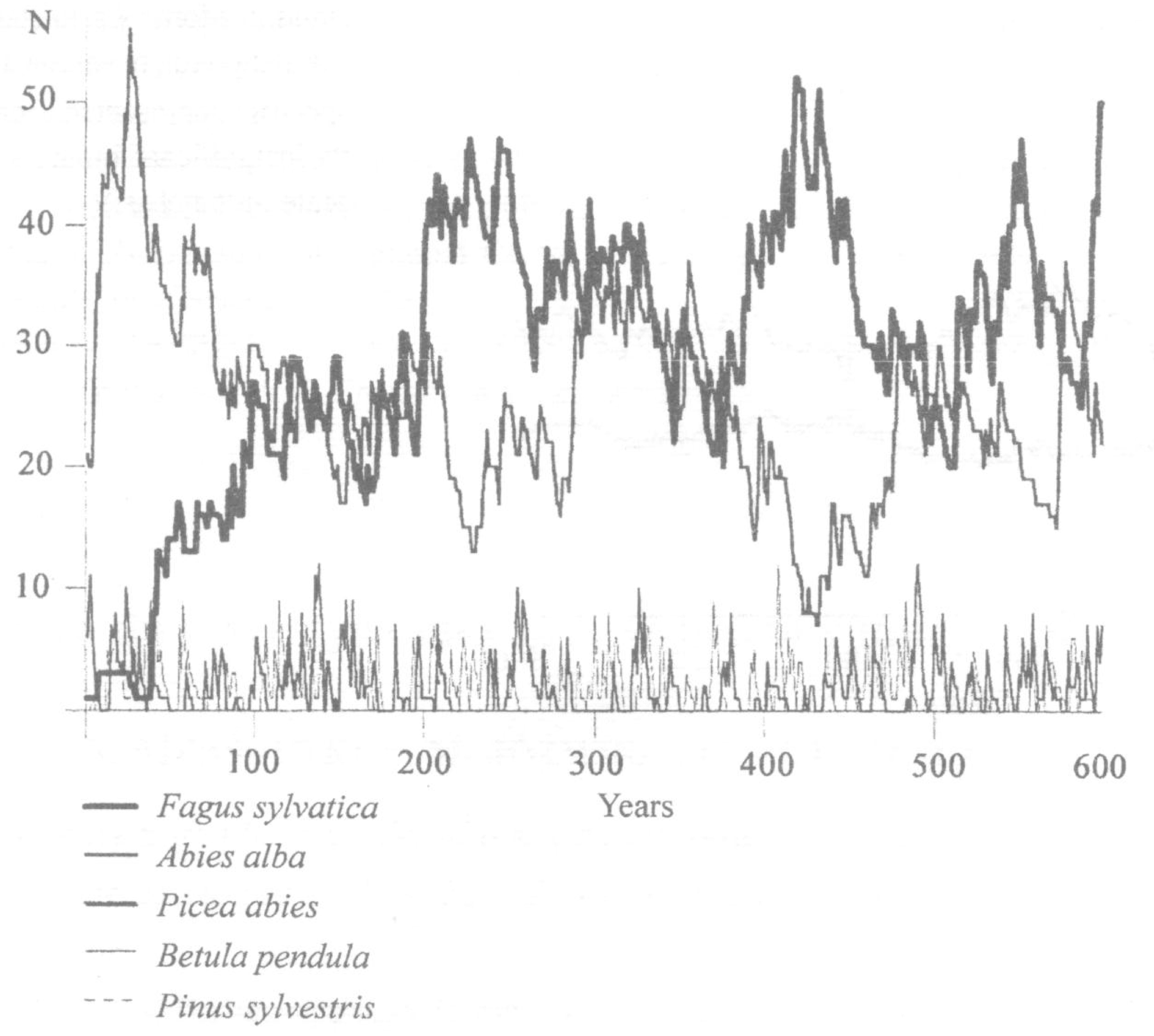

Fig. 4. Numbers of trees in the fir stand in the control in one simulation run

The obtained results suggest that even the smallest climate changes, especially in air temperature and rainfalls, can cause high fluctuations of sequel in succession. It is consistent with data presented in literature (KRAUCHI 1995; HONG et al. 1999; BRZEZIECKI 1999).

For example, on Solling plot in Germany the simulation of FORSUM model was performed with the use of IPCC – 'business-as-usual' climatic scenario (IPCC 1992), which presumes an increase in mean annual temperature by 0.3°C for each decade by the end of 21 century (KRAUCHI 1995). Like our model, the simulation presumed an increase in beech tree number. It was illustrated that *Picea abies* would definitely vanish from Solling area and would be replaced by *Luzulo Fagetum* forest type including *Acer platanoides*, *Quercus petraea* and *Fagus sylvatica* (KRAUCHI 1995). In

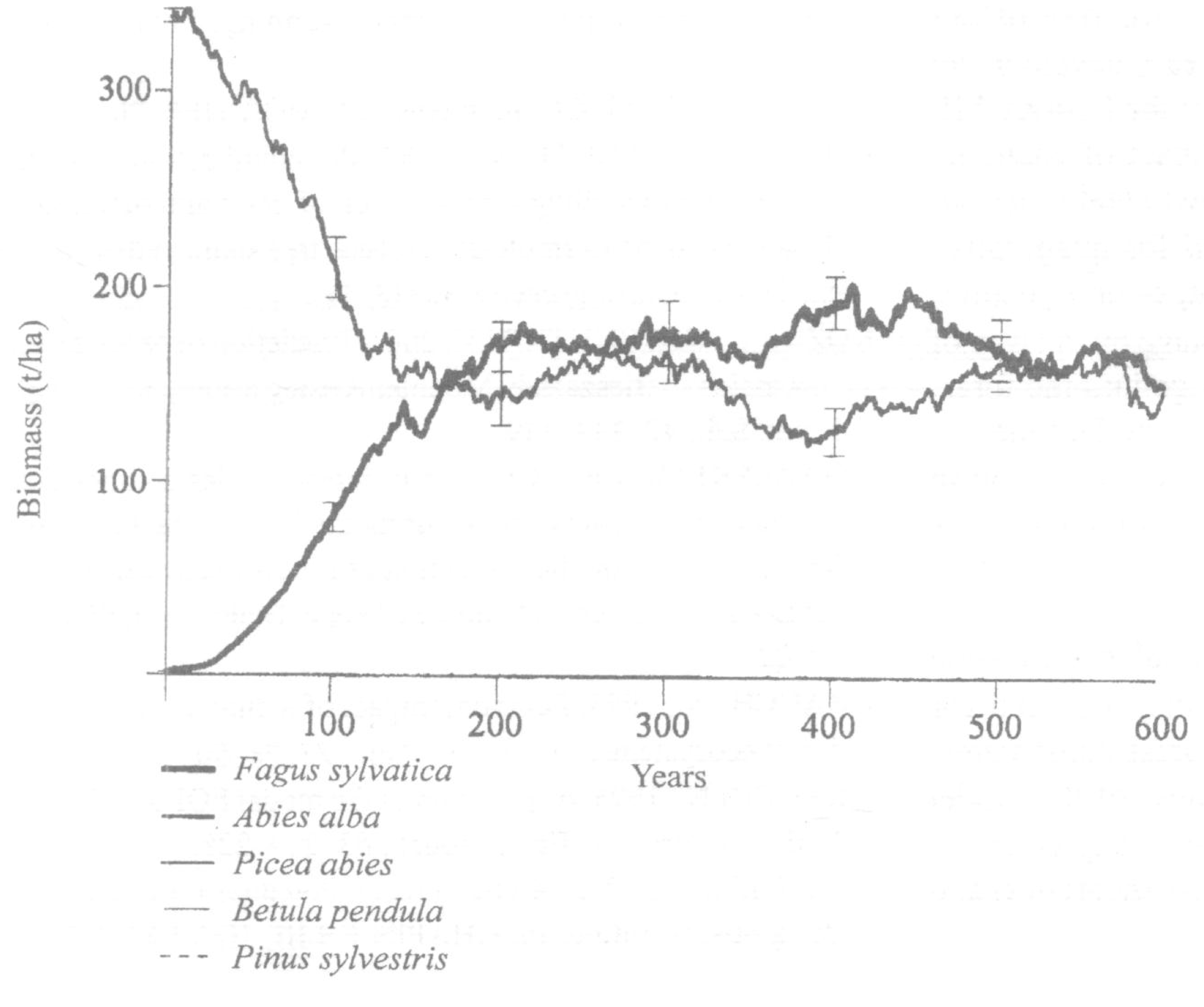

Fig. 5. Biomass of trees (*Fagus sylvatica, Abies alba*) in the fir stand in Monte Carlo statistical simulation run in variant 2 (other species not presented because of its insignificant biomass in the scale of the chart)

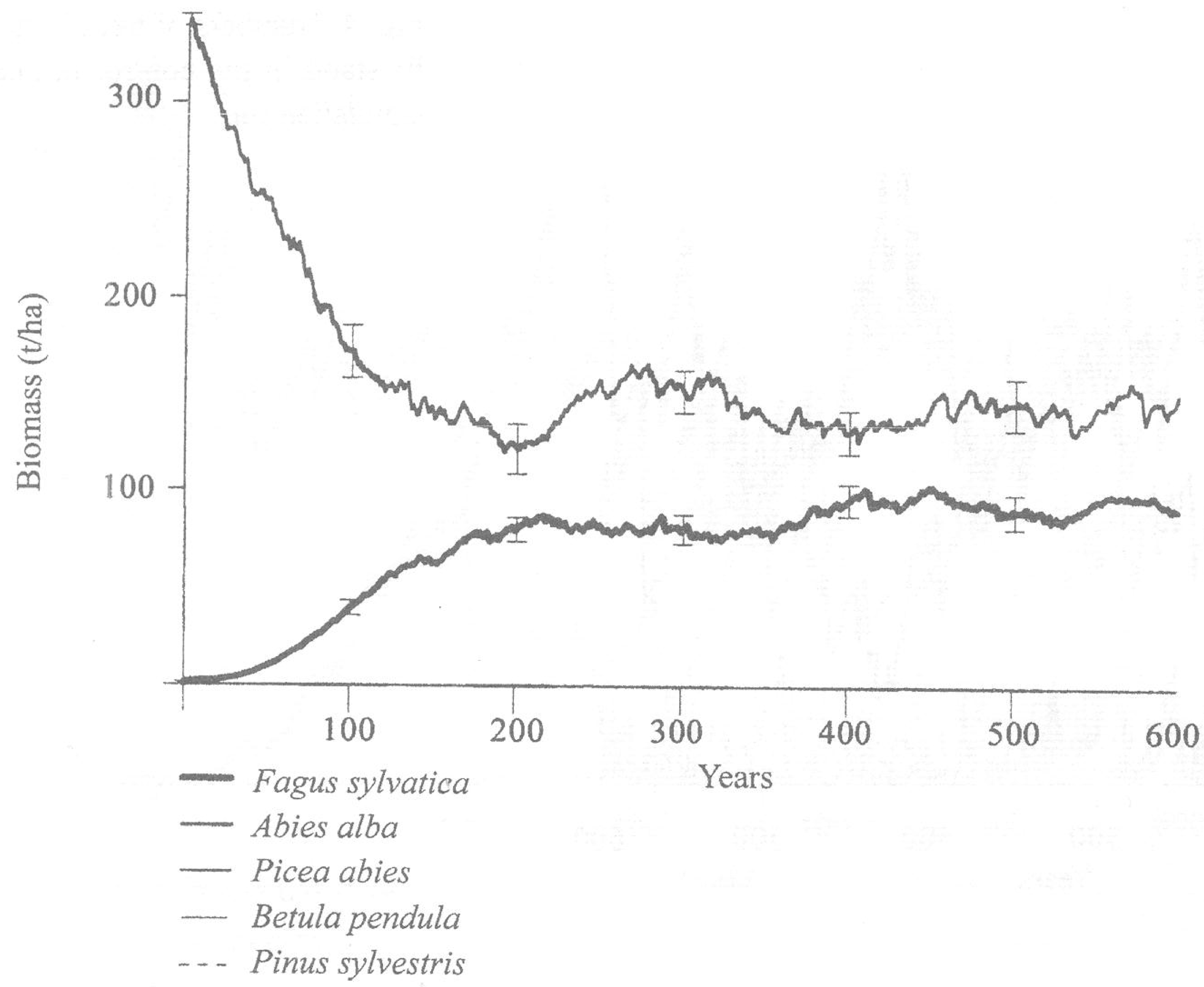

Fig. 6. Biomass of trees (*Fagus sylvatica, Abies alba*) in the fir stand in Monte Carlo statistical simulation run in variant 3 (other species not presented because of its insignificant biomass in the scale of the chart)

view of the simulation it was noticed that a decrease in the number of *Picea abies* trees was caused by decreasing competitiveness. At the end of the century various species can afford an "attack" and successful settling in Solling area. Along with new species such as *Sorbus aucuparia*, *Salix alba* and *Betula pendula*, European beech establishes easily.

CONCLUSIONS

The presented FORKOME model is based on the gap-phase theory of forest dynamics. The structure of our model is open and modular, enabling its easy development and modification. The important thing of the FORKOME model is a possibility to assess the impact of changing environmental conditions on forest growth and functioning. Generally, our model can be used for quantitative estimates of the effects of climate changes on dynamics of forest community. The fir forest is a stage on the way of beech forest regeneration and will change into the forest with beech dominance after 100 years of model time.

The FORKOME model predicts beech domination in the fir forest area in the Bieszczady Mts. while mean annual air temperature increases by 2°C and fir domination while temperature decreases by 2°C.

The results of FORKOME model simulations enable to set a thesis that forest succession may be used for evaluating the level of influence on forest ecosystems. Presented results indicate great usefulness of the model while investigating various subjects, especially concerning climate changes, which may have both theoretical and practical importance.

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Počítačová simulace dynamiky jedlového lesa v Beskydech v reakci na změnu klimatu

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ABSTRAKT: Předkládáme výsledky šetření dynamiky jedlového lesa v Beskydech v reakci na klimatické změny, které se uskutečnilo pomocí modelu FORKOME (FORest KOzak MEnshutkin). Model jsme ověřovali v terénních pokusech v letech 1998–2001 v jedlovém lese v polesí Procisne v Beskydech (Polsko). Prováděli jsme predikci stromové biomasy a počtu stromů pro příštích 600 let. Simulace prokázala dominanci buku, když se průměrná roční teplota zvýší o 2 °C, zatímco při poklesu teploty o 2 °C se dominantní ve zkoumané oblasti stane jedle. Při statistické analýze přinesl srovnatelné výsledky jak výpočet s jednou simulací, tak simulace podle metody Monte Carlo. Výsledky simulací pomocí modelu FORKOME umožňují vyslovit tezi, že pro hodnocení úrovně vlivu změny klimatu na lesní ekosystémy lze použít sukcesi lesa. Předložené výsledky naznačují značnou užitečnost modelu při zkoumání různých objektů, zejména pokud se jedná o změny klimatu, což může mít teoretický i praktický význam.

Klíčová slova: les; jedle; počítačový model; změny klimatu; Beskydy

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