Volume 26, Number 6
November–December 1999

ISSN: 1062-3590
CODEN: BRASEK

Kozak I. 1999. Recreation-Induced Changes in the Spruce Ecosystem Component. Biology Bulletin. Volume 26, No 6, p. 582-585.

Kozak I., Menshutkin V.V. 1999. Computer simulations of forest Ecosystems Dynamics. Biology Bulletin. Volume 26, No 6, p. 586-592.

275 years
ACADEMY OF SCIENCES

BIOLOGY BULLETIN

Official English Translation of *Izvestiya Rossiiskoi Akademii Nauk – Seriya Biologicheskaya*

Editor-in-Chief
Nikolai G. Khrushchov

http://www.maik.rssi.ru

A Journal of Theoretical and Experimental Research in Various Fields of Biology

IAPC NAUKA

Translated and Published by
МАИК "НАУКА/INTERPERIODICA" PUBLISHING

Distributed worldwide by KLUWER ACADEMIC/PLENUM PUBLISHERS

Biology Bulletin, Vol. 26, No. 6, 1999, pp. 586–592. Translated from Izvestiya Akademii Nauk, Seriya Biologicheskaya, No. 6, 1999, pp. 714–721.

SYMPOSIUM

Computer Simulation of Forest Ecosystem Dynamics

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Received March 1, 1999

Abstract—We used gap simulation of forest communities (Shugart, 1984) to describe dynamics of Carpathian forest ecosystem. The model was verified on the spruce–fir–beech (Piceeto–Abieto–Fagetum) forest in the central part of Ukrainian Carpathians. The simulation prediction of the changes in the trees population and biomass for the 600 years period is presented. The influence of felling on forest ecosystem dynamics was qualitatively assessed.

INTRODUCTION

Gap models receive much attention in the publications describing forest dynamics. Development of such models allowed the prediction of forest ecosystems dynamics for various time periods and climatic zones (Shugart *et al.*, 1973, 1992; Shugart, 1984). The gap models were constantly improving and complemented by new details of forest ecosystems (Krauchi, 1994; Bugman *et al.*, 1996). In addition, JABOA/FORET-type models were compared with the transition Markovian models (Acevedo *et al.*, 1995).

A successful application of gap models was due, on the one hand, to great possibilities of modern computers and, on the other hand, to correspondence between these models methodology and conception of spatiotemporal structure of the forest ecosystems.

Forest ecosystems in the Carpathian region are a good target for simulation. A unique, highly productive forest with variable spatiotemporal structure is conserved in this region and post-war activity is manifested as felling (including clean cutting).

Here, we studied time-related changes in the ecosystem of mixed spruce–fir–beech forest of various age using gap model and predicted the changes using different scenarios: (1) no human intervention; (2) felling after 110 years; and (3) felling after 140 years.

MATERIALS AND METHODS

Investigation of the forest ecosystem dynamics was based on the material obtained in 1984–1987 on the study plot in Gorgany in the central part of Ukrainian Carpathians (Pidlisniv Forestry) at an altitude of 800–815 m above the sea on the south exposition of Borsuchina mountain. The soil is brown mountain–forest on Carpathian flysch.

In 1930 the predominating forest was clean cut and regeneration started. By 1987, there was a 57 year old forest with predominating beech (*Fagus sylvatica* L.) and subdominating fir (*Abies alba* L.) and spruce (*Picea Abies* L.). There was 755 beeches, 170 firs, and 95 spruces per hectare.

The principal pattern of simulating forest ecosystem succession was taken from Shugart (1984) and complemented with certain indices related to beach forest growth in Gorgany.

We used the imitation approach for gap modeling (Botkin *et al.*, 1972; Shugart, 1984; Bugman *et al.*, 1996; Pawlowski, 1996).

The model algorithm includes nine blocks (Fig. 1). The block DATA ENTRY presents an evaluation of each tree and forest community indices. The maximum height and diameter, as well as other indices (Table 1) were taken with an account of specific features of the tree species and climatic indices of the studied area. A maximum biomass of beech communities in the studied region of Ukrainian Carpathians is 600 ton/hectares (Golubets, 1983). The unit NEW VARIANT provides for the dynamical passing of multiple variants, which is related to the stochastic nature of the model. Each variant started from the initial stage (INITIAL STAGE unit): the forest was clean cut in 1930. Later, the model reflected growth of the forest community within 57 years. In the case of verification of each 100 variants by the indices recorded in nature (Kozak, 1990), the model is used to predict forest development for a period of up to 600 years. The NEW YEAR unit controls the simulation process. The time increment of the model is one year. The REPRODUCTION unit stimulates the trees reproduction. This is a stochastic process dependent on the trees germination, relief conditions, temperature in the litter, etc. The MORTALITY unit presents the trees death as a stochastic process dependent on their age and previous year growth conditions. The GROWTH unit defines the growth rate of each tree as a function of its condition, species, thermal, light, and nutritional conditions. The STATISTICS unit carries out statistical data processing. The calculated mean and standard deviation values are used to analyze the changes in the mean

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population and biomass for each tree species and community as a whole. The GRAPHIC PRESENTATION unit plots time-related changes in the forest community structure including the tree population and biomass within the predicted period. We have selected 30 verified variants and used them to predict the trees population and biomass, as well as the mean community age each 10 years up to 100 years age and each 50 years up to 600 years age. We also plotted the changes in the tree population (relative) and biomass (both relative and absolute).

RESULTS

Let us first describe one of 30 model variants with special attention to relative portion of the trees population and biomass, as well as the absolute biomass (ton/hectare).

The model presents development of the forest community from the succession start in 1930 with precise prediction of the trees populations proportion (Table 2) in 1987 (the trees with trunk diameter above 5 cm were accounted). According to the model, in the period from 1930 to 1935 birch (*Betula verrucosa* L.) predominated at the study plot by both population (Fig. 2) and biomass (Fig. 3). This pioneer species is the first to populate forest-cleared regions in Gorgany. In 1940, its population and biomass decreased to 5 and 0.2%, respectively. Single birch specimen could be found up to 1970, which is also confirmed by previous taxation data. Note that the model predicts birch reappearance several times during a sharp decrease in beech and fir population and biomass.

Coming back to the period with known history of the forest ecosystem development, one can note similar predicted proportion of beech, fir, and spruce population (30–38%) from 1935 to 1970 (Fig. 2) despite insignificant predominance of beech (from 1935 to 1945) or fir and spruce (from 1945 to 1970). However, by biomass beech predominated in both relative (Fig. 3) and absolute (Fig. 4) values from 1935 to 1987. The changes in biomass predicted by the gap model for 600 years are presented by a "saw-toothed curve" (Shugart, 1984). This biomass curve is presented as separate curves of various dominating species.

The model predicts beech domination until 2140 by both population and biomass. Later fir will predominate (with insignificant spruce predominance from 2200 to 2250). The end of the predicted period shows a trend for fir replacement by beech. Fir predomination by biomass is predicted until 2410 (during fir predomination beech does not disappear but grows in the shadow of fir accumulating biomass up to 60 ton/hectare) when replaced by beech. These predictions point to cyclic oscillations of beech and fir predomination.

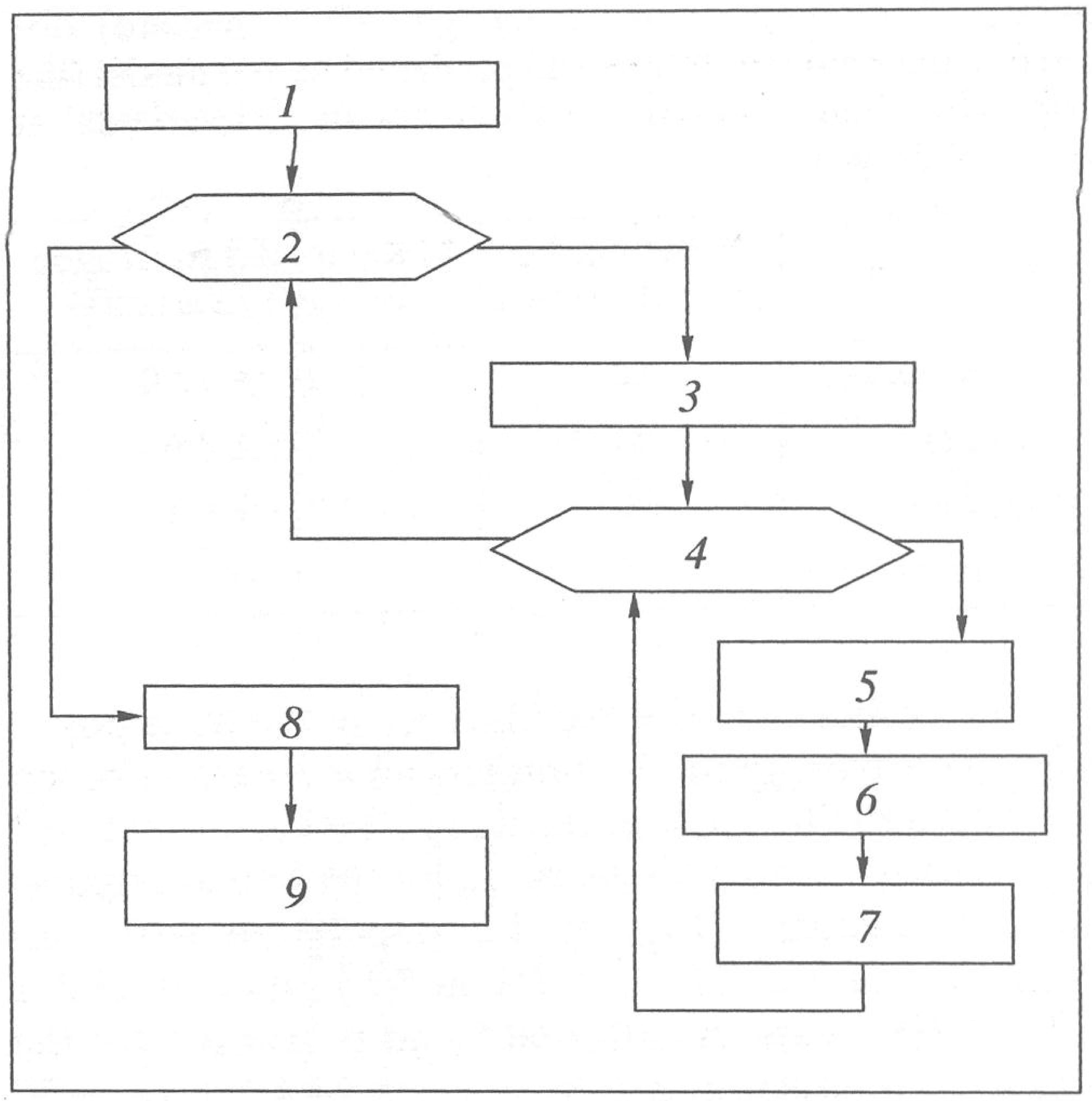

Fig. 1. Diagram of the model algorithm; units: (*1*) data entry; (*2*) new variant; (*3*) initial stage; (*4*) new year; (*5*) reproduction; (*6*) death rate; (*7*) growth; (*8*) statistics; (*9*) graphic presentation.

Let us consider such a cycle in a studied gap model. It starts from the growth of numerous small competing beech, fir, and birch trees. In the course of time large beech trees appear predominating over other trees. The model predicts the death of the dominating beech after 210 years (in 2140, Fig. 4) and a set of trees of more or less even age will start to grow again. This new regeneration wave is a component of a new cycle (Shugart, 1984), but with fir predomination this time. Large fir dominating over other trees will die in 420 years (in 2350), which will initiate the next regeneration wave with beech predomination by biomass.

The data on succession changes in the studied forest ecosystem averaged for the 30 variants are also interest-

Table 1. Maximum height (H_{max}), diameter (D_{max}), age (Age_{max}), as well as minimum (DGD_{min}) and maximum (DGD_{max}) total temperatures taken in the model

Tree species	H_{max}, m	D_{max}, cm	Age $_{max}$, years	DGD_{min}	DGD_{max}
Fagus sylvatica	45	150	300	4650	12705
Abies alba	55	150	400	3855	12684
Picea abies	50	120	350	882	3960
Betula verrucosa	32	35	100	0	3840

Table 2. Trees population in the gap (0.12 hectare) observed in the field conditions and predicted by the model (the mean values and standard deviations for the 30 variants) at the age of 58 years

Tree species	In the nature (Kozak, 1990)	In the model (averaged for the 30 variants)
Fagus sylvatica	64	63 ± 12.9
Abies alba	11	7.5 ± 8.6
Picea abies	7	7.7 ± 6.1
Betula verrucosa	0	0

ing. Let us first consider the changes in the trees population. The average model predicts an increase in beech population to 56 ± 10% at the age of 100 years and will be preserved up to 150 years. Later the beech population will decrease (Fig. 5). Fir population will constantly increase to 34.1 ± 5.2% at 50 years and 37.2 ± 6.3% at 100 years. A different trend is specific for the spruce: its population will increase to 24.4 ± 9.6% at 50 years, decrease to 3.4 ± 0.9% at 150 years, and re-increase to 30.1 ± 12.2% at 250 years.

The model predicts an increase in the absolute biomass of beech to 236.0 ± 117.1 ton/hectare at the age of about 500 years (Fig. 6, the variant without felling). Beach biomass will decrease with age down to 64 ± 50.3 ton/hectare at 350 years and will be nearly constant later. Fir features gradual increase in biomass to 62.0 ± 12.1, 72.1 ± 40.0, and 134 ± 84.1 ton/hectare at 50, 150, and 250 years, respectively (Fig. 6, the variant without felling). In the following, its biomass will remain almost constant.

Spruce biomass is insignificant. It will increase to 27.0 ± 6.3 ton/hectare at 50 years and decrease to 7.0 ± 2.1 ton/hectare at 150 years. Later it will gradually increase to 45.3 ± 19.1 ton/hectare at 300 years and will be preserved at this level with insignificant oscillations (Fig. 6, the variant without felling).

Total distribution of all tree species biomass indicates its increase to 317.0 ton/hectare at 500 years followed by gradual decrease down to 248.1 ton/hectare at 300 years and constant level further (Fig. 6, the variant without felling).

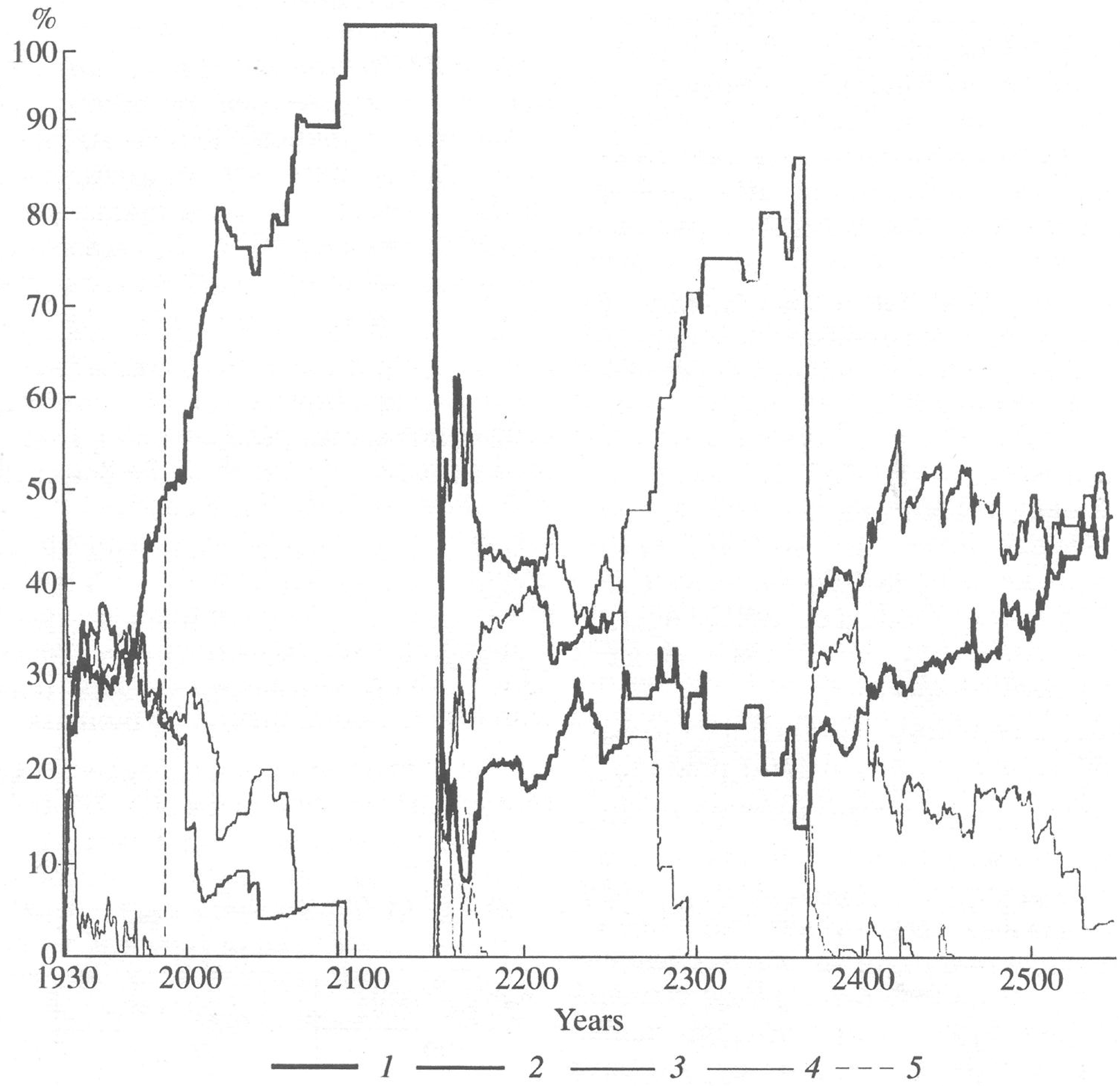

Fig. 2. Time-related changes in the plant communities structure, %: (*1*) beech; (*2*) fir; (*3*) spruce; (*4*) birch; (*5*) the model verification.

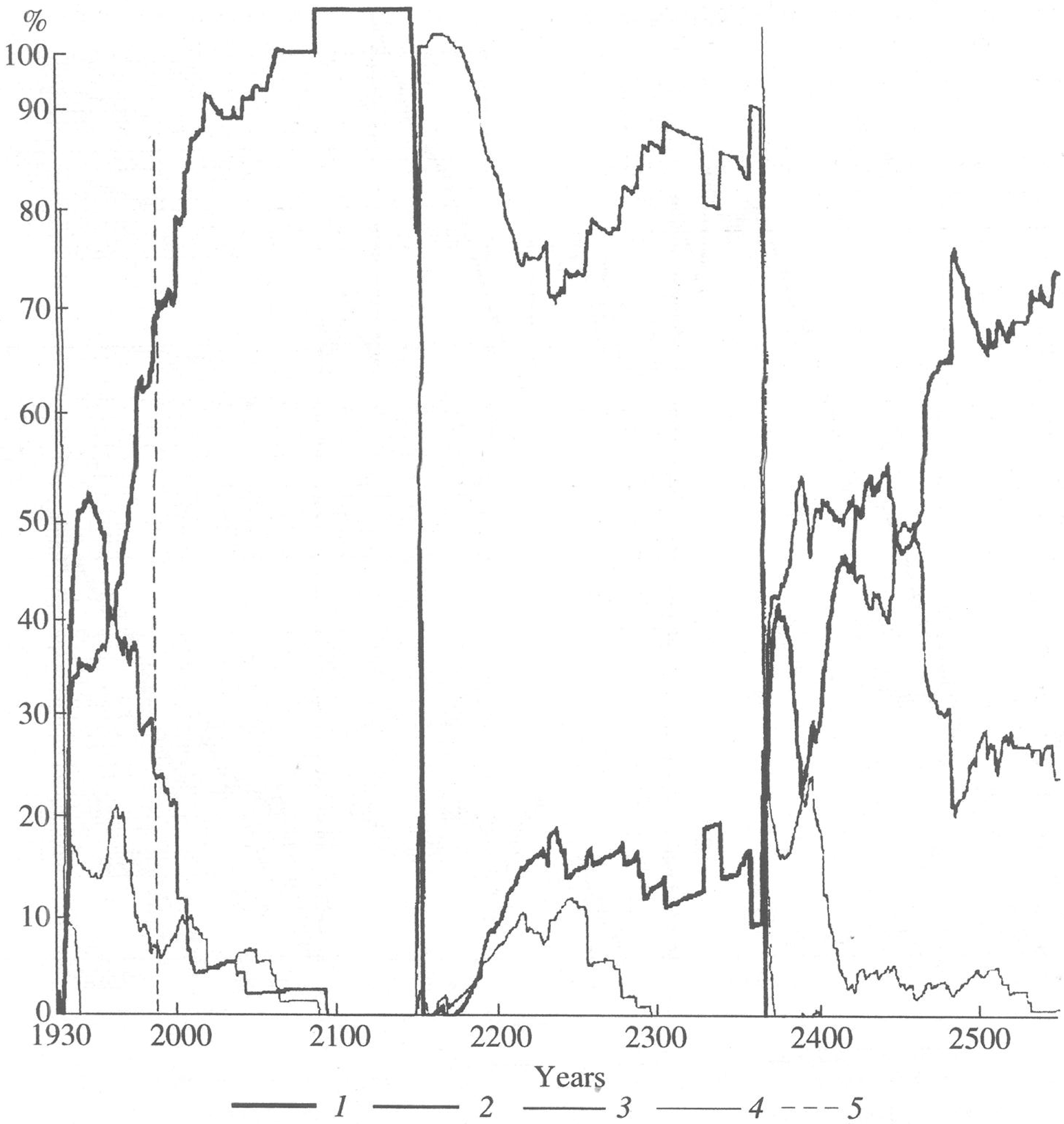

Fig. 3. Time-related changes in the plant communities structure, %: (*1*) beech; (*2*) fir; (*3*) spruce; (*4*) birch; (*5*) the model verification.

Predicted changes in the ecosystem induced by felling at different ages are also interesting. We used clean cutting at 110 and 140 years in the model.

Clean cut was specific for Ukrainian Carpathian forestry after the war. The model predicts the changes in the tree population and biomass within account of felling pattern and time.

Beech biomass at the age of 150 years was 56.3 ± 9.4% in the variant without felling, while after felling at 110 and 140 years it will decrease down to 36.0 ± 8.4 and 34.3 ± 9.2%, respectively. Population of fir and spruce of the same age will increase after felling as compared to the variant without felling (Fig. 5).

In the variant with the later felling at 140 years the model predicts rapid increase in populations of beech, fir, and spruce within a shorter time period (up to 20 years) after the felling.

Biomass of beech at the age of 150 years will decrease from 236.4 ± 117.1 ton/hectare in the variant without felling to 157.1 ± 116.0 and 104.7 ± 70.2 in the variants with felling at 110 and 140 years, respectively (Fig. 6). This trend to decelerating biomass accumulation after felling is also specific for total biomass distribution (317.0, 256.4, and 235.3 ton/hectare, respectively). For fir and spruce the model predicts the reverse trend. At the age of 500 years biomass of fir and, particularly, spruce will be higher in the variants with felling than without it.

Distribution of total biomass indicates that the variants with felling have not only decreased biomass as compared to the variant without felling, but also reach the maximum biomass later (approximately, by 50 years, i.e., at the age of 200 years rather than 150 years specific for the variant without felling).

DISCUSSION

Long-term predomination by population (Fig. 2) and biomass (from 2140 to 2410, Figs. 3–4) confirms the proposed high probability of mixed forest growth with fir domination on the north macroslope of Ukrainian Carpathians. This hypothesis was proposed by Milkina (1985) for description of the core forest and

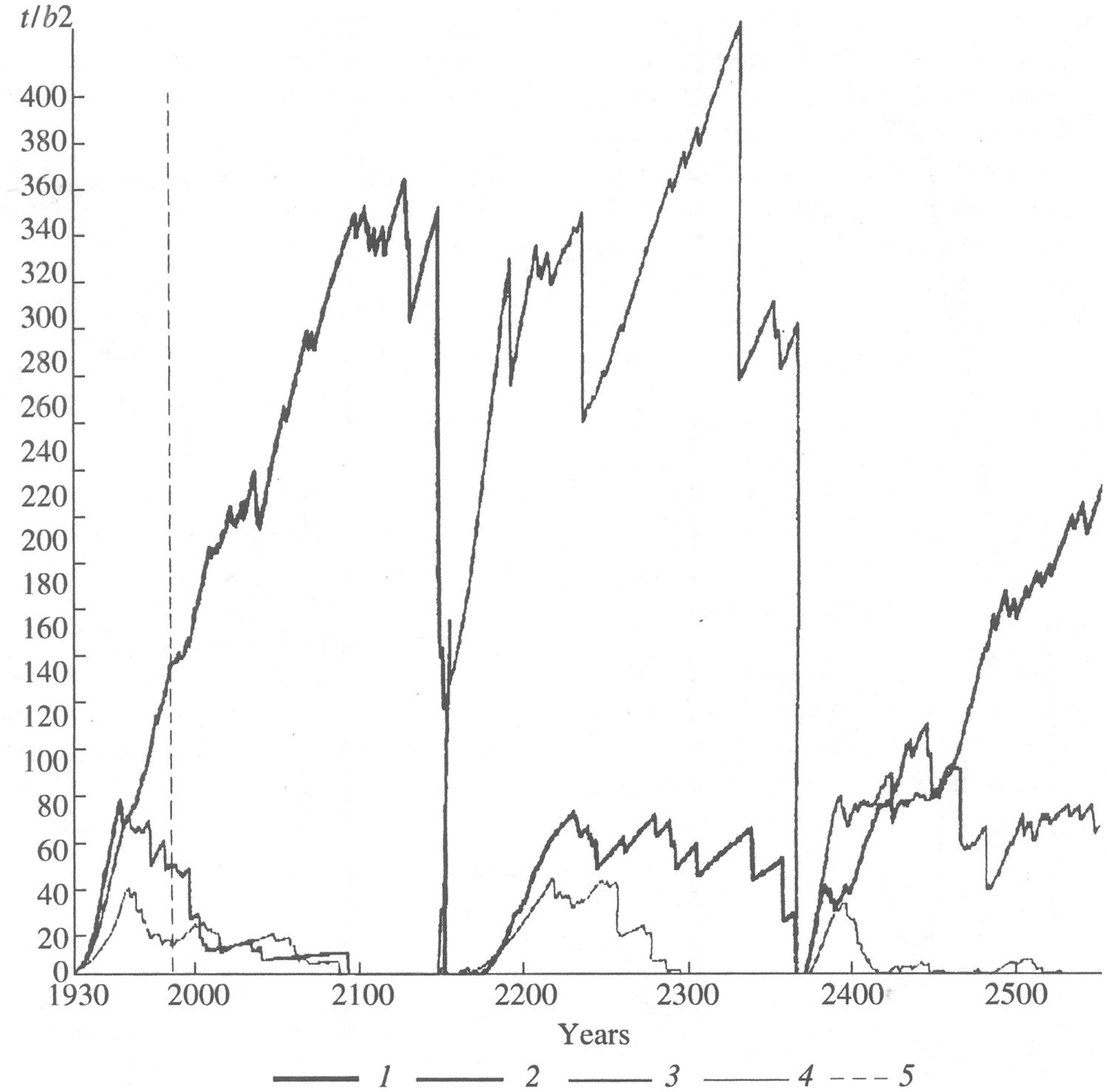

Fig. 4. Time-related changes in the plant communities structure, ton/hectare: (*1*) beech; (*2*) fir; (*3*) spruce; (*4*) birch; (*5*) the model verification.

later confirmed by our investigation in the Prut river basin (Kozak, 1994).

Beech replacement by fir predicted by the model is also confirmed by our territorial investigations. The fir forest at the age of 250–300 years similar to the simulated one was found 1.5 kilometers apart from the simulated area around Mikulichin village.

Favorable ecological conditions for fir rather than beech proposed earlier (Menshutkin and Kozak, 1997) are confirmed by the predicted high fir biomass (up to 420 ton/hectare), its long-term predomination and population (from 2145 to 2520), and constant increase in its population in the average variant (Figs. 5–6).

In the long range, the model predicted cyclic beech replacement by fir (beech domination by biomass until 2140, fir predomination until 2410, and recurrent beech domination after 2410). These cyclic changes in the biomass are related to other periodic oscillations, e.g., light, thermal, and nutritional conditions (Shugart, 1984).

Biomass changes manifested as a saw-toothed curve, as well as other changes in the gap model provide for various aspects of the trees life which we consider as different stages in the gap development. For instance, after the death of the dominating large trees when the biomass and leaves area are insignificant, the regeneration stage predominates. In Fig. 4, this stage averaged for different trees species lasts approximately from 2140 to 2220 and from 2355 to 2380. At the beginning of the succession (from 1930 to 1970), the regeneration stage (which can be considered as the initial one) also takes place. The next stage in the gap development is related to competition in the overstorey of the similar age trees. The starting point of this stage can be conventionally attributed to the moment of forest cover closure; it ends with predomination of one of large trees species. Later the gap enters the initial peak stage (in terms of biomass) affecting the following development.

The model confirms rapid spruce growth up to the age of 50 years. Being a fast grower (Golubets, 1987), it increases the biomass up to 50 years, decreases it up to 150 years, and it gradually increases later (Fig. 6).

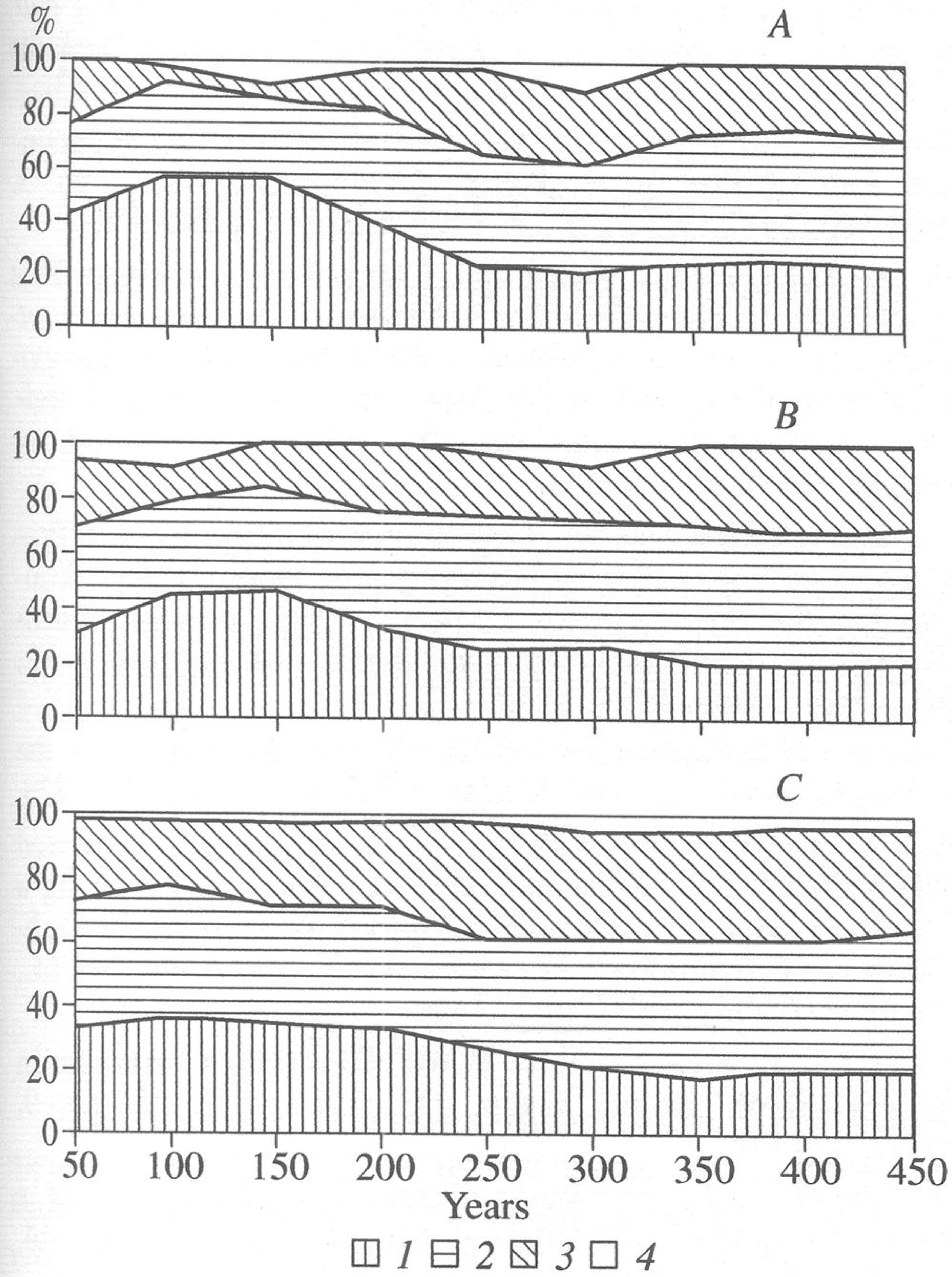

Fig. 5. Changes in the communities structure; ordinate: trees population, %: (*1*) beech; (*2*) fir; (*3*) spruce; (*4*) birch; (*A*) the variant without felling; (*B* and *C*) variants with felling at 110 and 140 years, respectively.

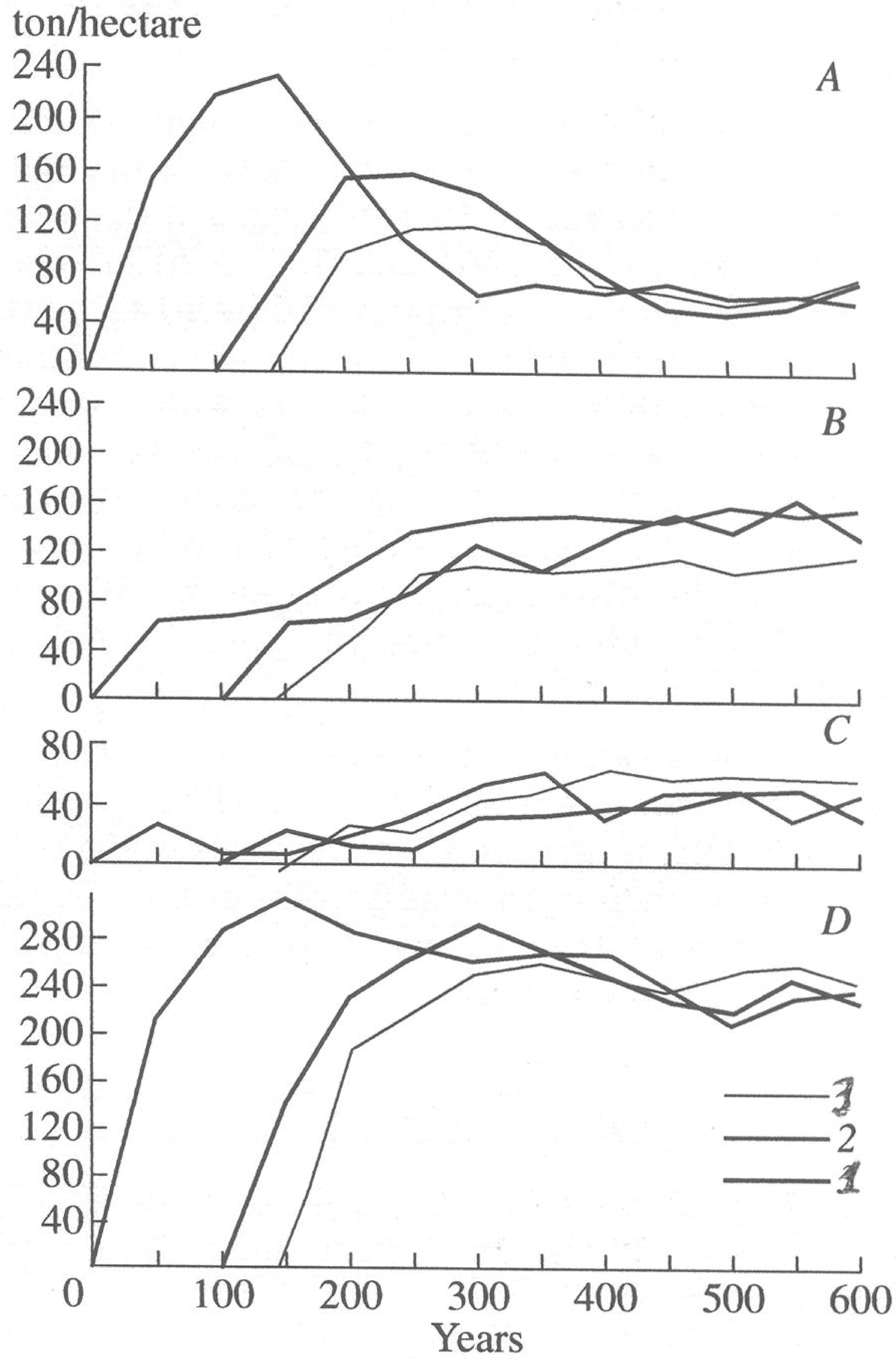

Fig. 6. Changes in the communities structure; ordinate: trees population, ton/hectare; (*1*) the variant without felling; (*2* and *3*) variants with felling at 110 and 140 years, respectively; (*A*) beech; (*B*) fir; (*C*) spruce; (*D*) total biomass of beech, fir, spruce, and birch.

According to the model prediction, an increase in beech, as well as total biomass are observed up to the age of 150 years suggesting to raise the age of forest felling. In the Ukrainian Carpathians, forest was usually cut at the age of 90–100 years. Considering the active accumulation of biomass by the beech forest at this age also confirmed by published data (Golubets *et al.*, 1983; Kozak and Golubets, 1997) we propose to raise the felling age to 110 years and more.

In general, decreased beech population and increased fir and spruce populations were observed at the age of 150 years in the felling variants. In the variant with the later felling sharp increase in population of all trees species was observed 20 years after the felling.

The variants with felling feature lower maximum biomass of beech at the age of 150 years as compared to the variant without felling. The increased age of felling decreases the beech and total biomass (Fig. 6). This confirms depletion of forest ecosystems after clean cut eliminating chemical elements with wood forever from the forest ecosystem.

CONCLUSIONS

The application of gap-simulation (Shugart, 1984) to describe the dynamics of a mixed beech forest in Ukrainian Carpathians, as well as its verification by observation and stationary investigation data (Kozak, 1990) carried out in 1984–1987 proved to be quite efficient.

The realized model confirmed interesting moments in the studied forest ecosystem succession. For instance, it confirms high probability of mixed forest communities with fir domination and the ecological conditions at the study plot favorable for fir rather than beech.

In the long range, the model predicted cyclic beech replacement by fir. The predicted biomass changes as a saw-toothed curve and the corresponding changes in the gap model describe the three recognized developmental stages.

The model confirmed rapid growth of spruce biomass up to 50 years of age. At the same time, the model predicted an increase in beech, as well as total biomass up to the age of 150 years. We propose to raise the felling age in Ukrainian Carpathians.

A simulation of a clean cut at various ages indicates the following decrease in beech biomass (at the age of 150 years from 236.4 ± 117.1 ton/hectare in the variant without felling to 157.1 ± 116.0 and 104.7 ± 70.2 ton/hectare in the variants with felling at 110 and 140 years), as well as the total biomass of the studied community. The decreased biomass in the variants with felling as compared to the variant without it confirms the concept of forest ecosystems depletion in the mountain region of Carpathians. Note later reaching of top biomass in the variants with felling (on the average by 50 years, i.e., at the age of 200 rather than 150 years specific for the variant without felling).

The presented simulation of time-related changes in the forest community has both theoretical and practical significance. The model can be used to assess the influence of various factors (not only felling, but also climatic changes and introduction of new trees species) on the forest ecosystem dynamics.

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