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Prediction of beech forests succession in Bieszczady Mountains using a computer model

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ABSTRACT: This work presents the results of investigation into beech forests succession in Bieszczady Mountains using the FORKOME (FORest KOzak MEnshutkin) model. The model was verified in field trials in 1998–2001 in the forests with dominating beech *(Fagus sylvatica* L.) in Stuposiany Forest District in Poland. For the natural beech forest the model assumes cyclic changes in the number and biomass of beech and fir in a single simulation run and Monte Carlo realizations. The cutting out of trees does not change the general tendency of the dynamics of beech and fir stands. Under the logging management only the time of this dynamics varies.

Keywords: beech; forest; computer model; Bieszczady Mountains

Since the 1970s progressive mathematisation in the field of ecology has developed. As a result different models of forest dynamics were constructed (WAGGONER, STEPHENS 1970; SULLIVAN, CLUTTER 1972; SUZUKI, UNEMURA 1974; MITCHELL, 1975; HORN, 1975; SOLOMON 1977; SHUGART, WEST 1977).

The forest gap model approach has proved to be useful in many respects (SHUGART 1984). The first models (BOTKIN et al. 1972) were rather simple. Subsequent research led to more complicated models. These models included detailed information such as soil processes (PASTOR, POST 1985), phytosociological concepts (KIENAST 1987), explicit modelling of tree crown structure (LEEMANS, PRENTICE 1989), detailed treatment of ecophysiological (FRIEND et al., 1993) and biophysical processes (BONAN, VAN CLEVE 1992; MARTIN 1992) and intraspecific competition (PAWŁOWSKI 1996).

The increasing complexity of forest gap models may have helped to make detailed and presumably more accurate projections of forest succession. Development of an ecological model of forest stand applicable under environmental conditions prevailing in Polish forest stands is presented (BRZEZIECKI 1991; 1999).

The main aim of the present study is to investigate the succession dynamics of beech forest in the Bieszczady in different cutting conditions using the FORKOME model.

MATERIALS AND METHOD

Permanent research plots are situated on the northern slope of Kosowiec mountain at the altitude of 800–900 m a.s l. (Stuposiany Forest District) and with inclination 14–18°. Brown soils over the Carpathian flysch are characteristic of the plots. The average age of beech stands is 92 years.

In our FORKOME model we investigate forest changes on 30 small plots of 30 × 30 m in size (KOZAK, MENSZUTKIN 1999). SHUGART (1984) used 1/12 ha plots. The model was based on the main assumption that the dynamics of the whole forest stand is a sum of processes taking place in small units of the size comparable to canopy gaps. The forest dynamics was simulated in such gaps.

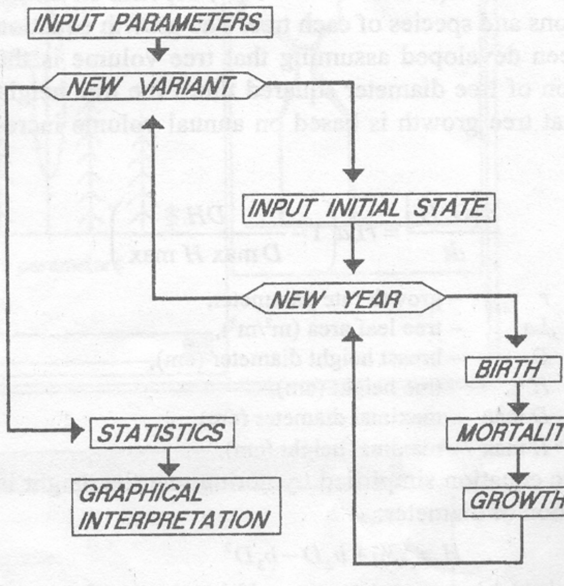

Fig. 1. Diagram of the FORKOME model algorithm

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

Tree species	Hmax (cm)	Dmax (cm)	Age (years)	B2	B3	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

Our FORKOME model was constructed on the basis of FORET model (SHUGART, WEST 1977) with the authors' modifications considering, for example, temperature or other elements.

In our FORKOME model different modules (blocks) are distinguished (Fig. 1). The block "INPUT PARAMETERS" represents the estimation of tree and stand parameters. One of them is maximal tree diameter at standard height of 130 cm above the ground (Dmax). Maximal height (Hmax), maximum age (AGEmax) and minimal and maximal sums of degree-days (DGDmin, DGDmax) are also considered.

Basic growth parameters by the species in the FORKOME model are listed in Table 1. The FORKOME model simulates the dynamics of 5 species that dominate on the 15 investigated plots.

Since this model is stochastic, the study of its dynamics requires running through many variants (block "NEW VARIANT"). These processes are controlled by the block entitled "NEW YEAR". The model includes such variables as mortality, birth, and growth for each year of the run. The mortality of trees is a stochastic process depending on tree age and growth conditions in the previous year. The simulation of tree regeneration (block "BIRTH") is represented in the model as a stochastic process depending on the species of tree seedling, soil surface conditions and average temperature at the litter level. The growth rate (block "GROWTH") depends on the dimensions and species of each tree. The growth equation has been developed assuming that tree volume is the function of tree diameter squared times the tree height and that tree growth is based on annual volume increment:

$$\frac{d[D\,H]}{dt} = rLa\left(1 - \frac{DH}{D\max H\max}\right)$$

where: r – growth rate parameter,
La – tree leaf area (m^2/m^2),
D – breast height diameter (cm),
H – tree height (cm),
$D\max$ – maximal diameter (cm),
$H\max$ – maximal height (cm).

Basic equation simplified by noting that the height is a function of diameter:

$$H = 130 + b_2 D - b_3 D^2$$

where: b_2 and b_3 – parameters quantifying the tree form, and the constant 130 (in cm) is breast height.

If a tree has maximum height when it has maximum diameter ($dH/dD = 0$ and $H = H_{max}$ when $D = D_{max}$), then it is possible to calculate b_2 and b_3 parameters:

$$b_2 = 2\left(\frac{H_{max} - 130}{D_{max}}\right)$$

and

$$b_3 = \left(\frac{H_{max} - 130}{D^2_{max}}\right)$$

The growth rate depends on the most important ecological agents such as light, temperature, and supply of nutrients as well as other elements.

The light that reaches a given tree is calculated by attenuating the incident radiation by the sum of leaf areas taller than the tree:

$$Q(h) = Q_{max} E^{-0.25LA(h)}$$

where: $LA(h)$ – distribution of leaf area as a function of height,
Q_{max} – incident radiation,
$Q(h)$ – radiation at height (h),
– 0.25 – constant.

We used two equations; the first for light demanding trees:

$$r = 1 - e^{-1.136[Q(h) - 0.08]}$$

and the second for shade-tolerant trees:

$$r = 1 - e^{-4.64[Q(h) - 0.05]}$$

The growth rate depends on temperature conditions. We applied the following equation (BOTKIN et al. 1972):

$$T = \frac{4(DGD - DGD_{min})(DGD_{max} - DGD)}{(DGD_{max} - DGD_{min})^2}$$

where: T – growth reduction due to temperature effects,
DGD – base heat sum for a site,
DGD_{min} – minimum degree-day value where the species is known to occur,
DGD_{max} – maximum degree-day value where the species known to occur.

For the block of nutrients we used this polynomial function (WEINSTEIN et al. 1982):

$$GMF = a + b[RNA] + c[RNA]^2$$

where: a, b, c – constants estimated by regression from field data,
RNA – relative nutrient availability,
GMF – growth-modifying factor to modify the growth rate of trees under limited supply of nutrients.

In this case

$$RNA = 1 - \frac{B}{B_{max}}$$

and

$$B = 0.1193 \sum_{i=1} D_i^{2.393}$$

where: B – actual trees biomass,

B_{max} – maximum tree biomass.

The probabilities of tree mortality are calculated. If $D^{t+1} - D^t < 0.1$ cm, then $P_n = 0.368$

or:

$$P_n = 1 - \left(1 - \frac{4.605}{AGE_{max}}\right)^n$$

The equations are open to modifications that take into account the influence of other agents on tree growth.

After the realization of all variants of the model, the programme carries out a statistical analysis of the obtained results (block "STATISTICS"). In the simplest case the analysis consists of the calculation of the mean and standard deviation values, whereas in more complex cases serial- and cross-correlation functions are calculated.

The interface of FORKOME model (Fig. 2) has different pictures for SINGLE SIMULATION RUN: "PARAMETERS", "INITIAL STATE", "SHOW GRAPHICS", "PRINT GRAPHICS". After having pressed the left button of the mice in the position of each tree in the picture, information about age, height and diameter of the tree can be obtained. The right button of the mice allows cutting of the tree.

The statistical processing "MONTE-CARLO REALIZATION" can simulate as much as 200 runs under the same starting and management conditions. It was accepted that 30–40 simulations were sufficient to estimate statistical parameters of the model in each variant.

The position of each tree in the forest is projected along the diagonal of research plots. The year 1999 was taken as the first year of the model time. In this study time is used as the model time.

RESULTS AND DISCUSSION

For a natural beech forest the model predicts cyclic changes between beech and fir biomass in one realization (Fig. 3a). The cutting of beech trees after the first year (Fig. 3b) and after 20 years (Fig. 3c) of model time does not change this cyclic dynamics. Cutting out beech trees after the first year resulted in a long-term dominance of fir.

Cutting all the trees after the first year and after 20 years does not change the dynamics of beech and fir biomass, either. Depending on the cutting conditions only the time of transformation of beech stand into fir stand differed.

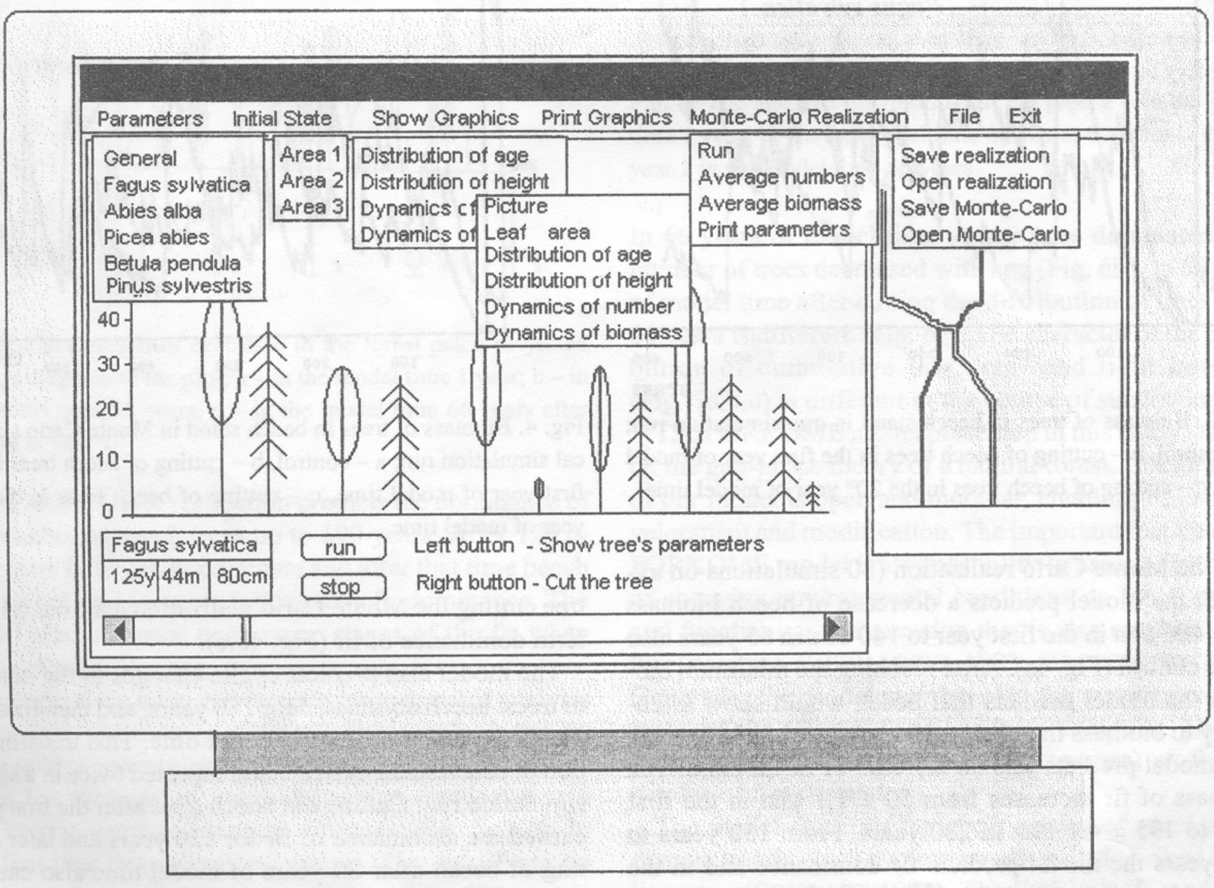

Fig. 2. Interface of FORKOME model

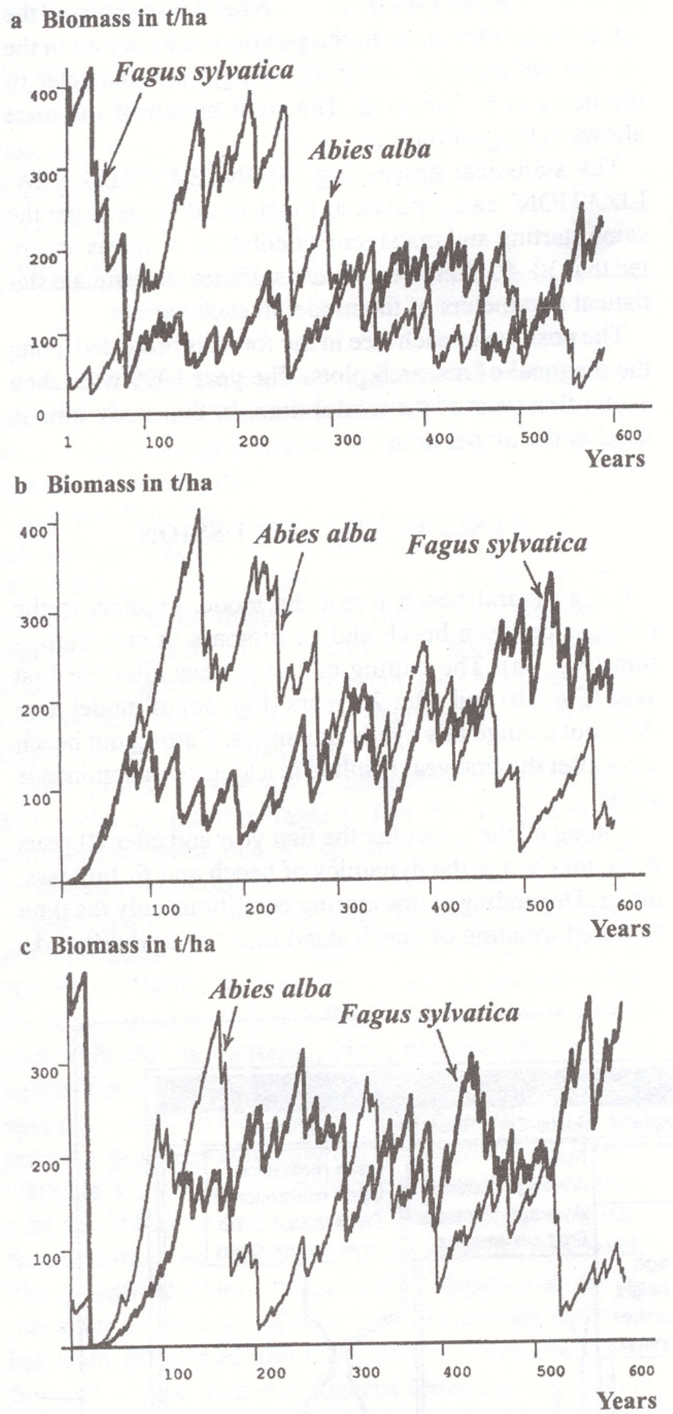

Fig. 3. Biomass of trees in beech stand in one simulation run; a – control, b – cutting of beech trees in the first year of model time, c – cutting of beech trees in the 20th year of model time

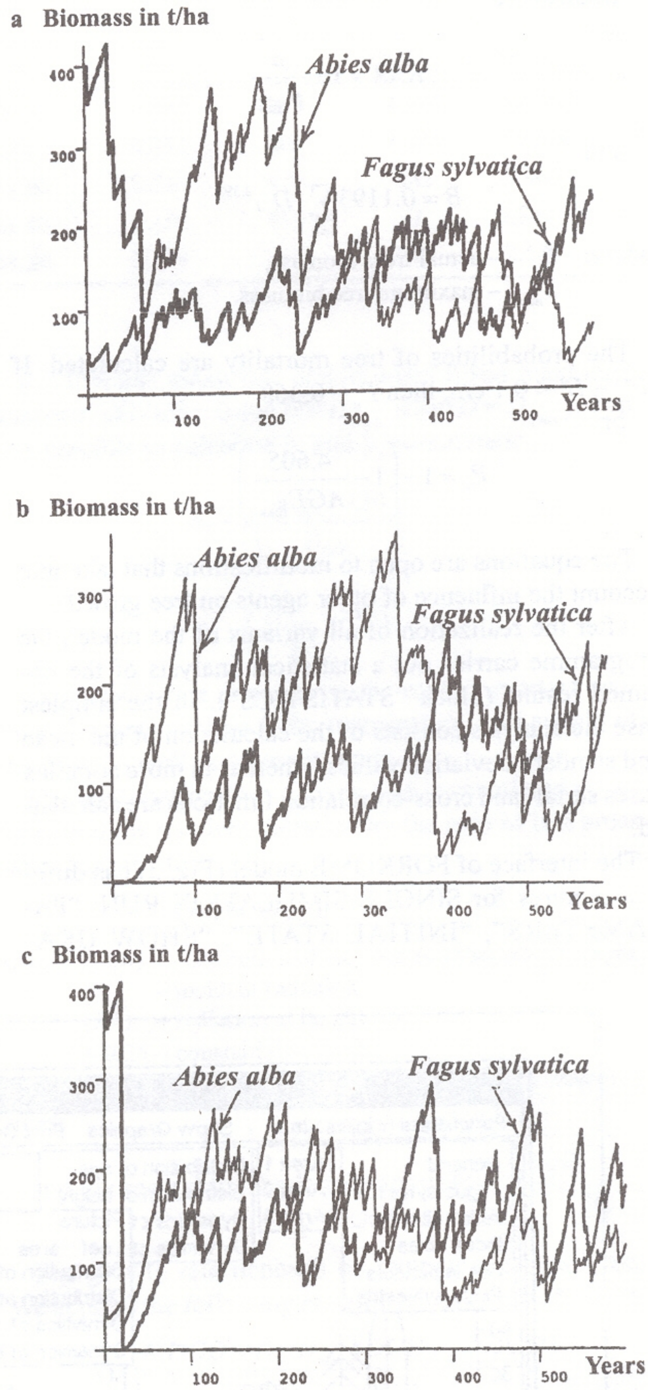

Fig. 4. Biomass of trees in beech stand in Monte Carlo statistical simulation run; a – control, b – cutting of beech trees in the first year of model time, c – cutting of beech trees in the 20th year of model time

In the Monte Carlo realization (30 simulations on average) the model predicts a decrease of beech biomass from 400 t/ha in the first year to 140 t/ha in 65 years also in the control (Fig. 4a). After reaching the minimum biomass the model predicts that beech would show a tendency to biomass increase to 196 ± 7.3 t/ha in 130 years. The model predicts also an increase of fir biomass. The biomass of fir increases from 50 ± 1.1 t/ha in the first year to 195 ± 4.1 t/ha in 280 years. From 150 years to 280 years the model predicts fir dominance and in the following time beech dominance. In different variants of tree cutting the Monte Carlo realization assumes a long-term dominance of fir (Fig. 4b,c).

The model also predicts cyclic changes in the number of trees: beech dominated for 180 years, and then fir dominated for 250 years of the model time. This transformation of beech stand into fir stand repeated twice in a single simulation run. Cutting out beech trees after the first year caused the dominance of fir for 120 years and later cutting of beech after 20 years of model time also caused the dominance of fir for 150 years.

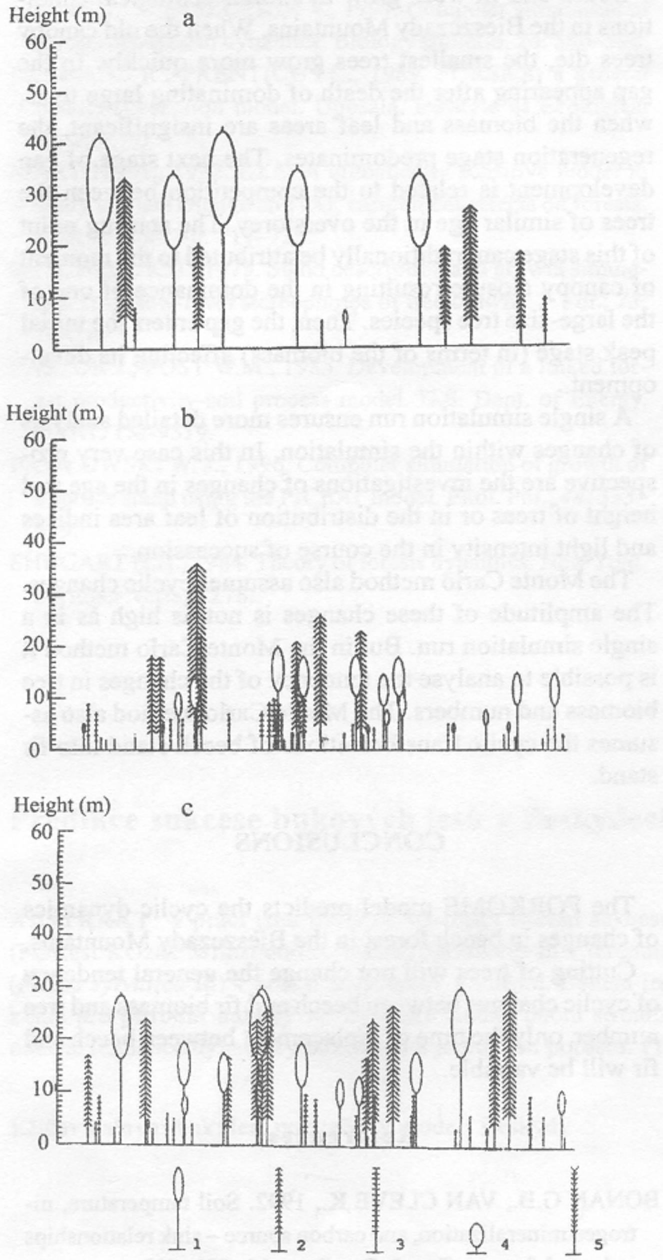

Fig. 5. The position of each tree in the forest patch projected along a diagonal of the plot; a – in the model time 1 year; b – in the model time 66 years; c – in the model time 66 years after cutting in year 1

The Monte Carlo realization predicts the dominance of the number of beech trees up to 190 years. After 190 to 240 years fir began to dominate and after that time beech dominated for 560 years followed by fir dominance. The model predicts more dominance stages of the fir when cutting the beech trees.

A single simulation run ensures more detailed analysis of changes within the simulation. Noteworthy is the investigations concerning the changes in species compositions. For example, in 1 and 66 years of simulation runs the species compositions are different (Fig. 5a,b,c). In the first year there were two groups (Fig. 6a) of age on the research plots (to 20 years and from 50 to 200 years).

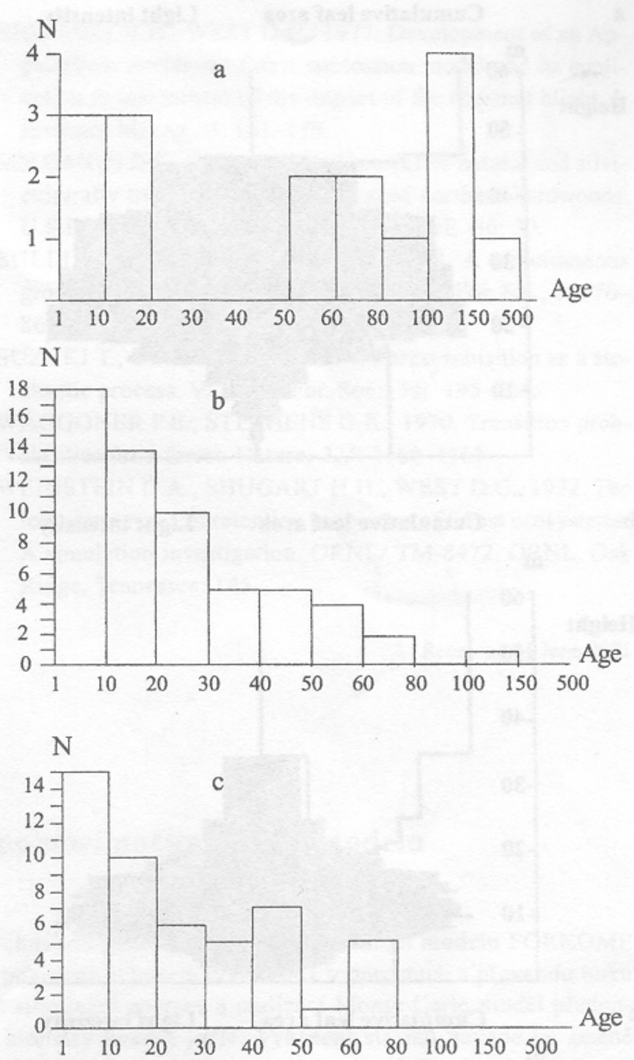

Fig. 6. The age tree distribution on the plot; a – in the model time 1 year; b – in the model time 66 years; c – after cutting in year 1 in the model time 66 years

In 66 years of model time young trees dominated. The number of trees decreased with age (Fig. 6b). In 66 years of model time after cutting the distribution of trees up to 80 years is different (Fig. 6c). The character of the distribution of cumulative leaf area and light intensity (Fig. 7a,b,c) is different in the course of succession.

The FORKOME model presented in this study is based on the gap-phase theory of a natural forest. The structure of our model is open and modular, enabling its easy development and modification. The important feature of the FORKOME model is its possibility to assess the impact of changing environmental conditions on forest growth and functioning, the question that is also emphasised in the literature (BERNADZKI 1993; BRZEZIECKI 1999). Generally, the model may be used for quantitative estimates of the effects of various factors (cutting, climatic changes, introductions of new tree species) on the dynamics of forest stand.

The model confirms the cyclic nature of stand development trends. Such cycles were already described in the literature (SHUGART 1984). The FORKOME model as-

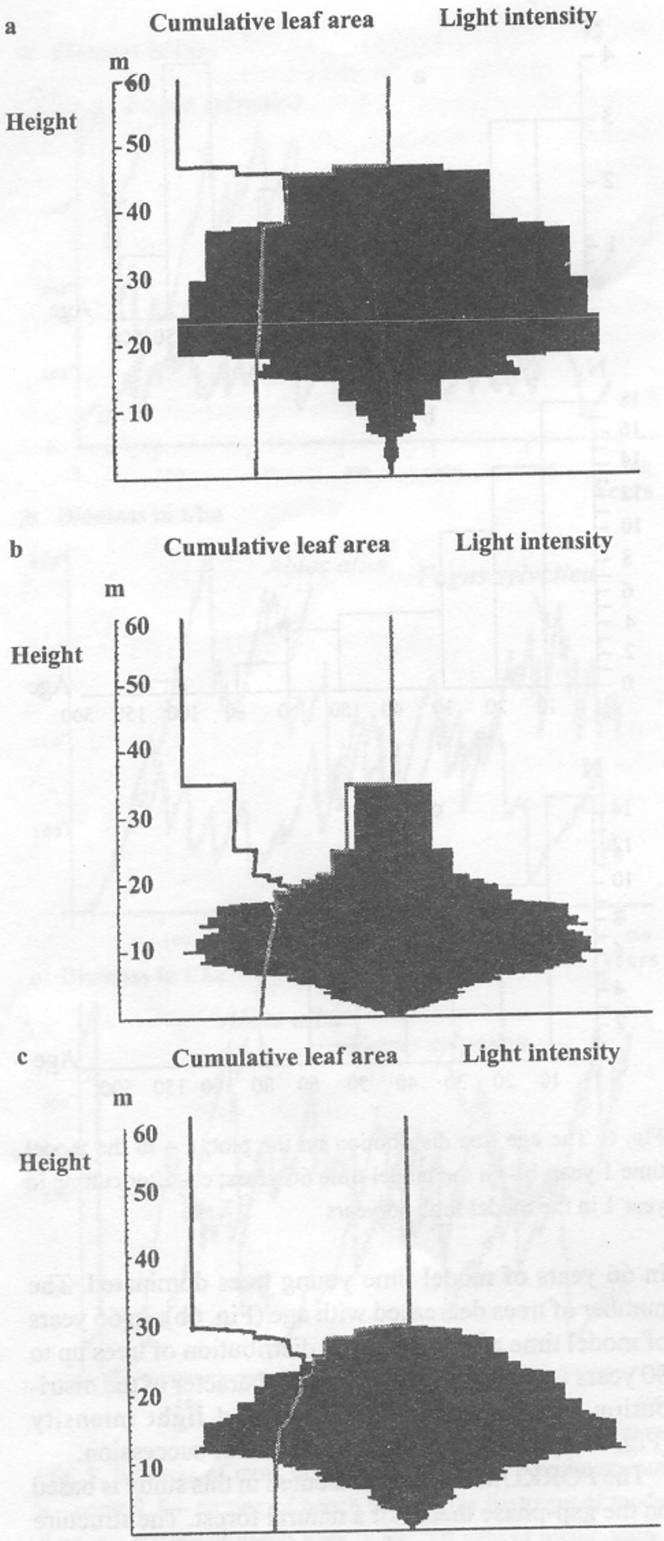

Fig. 7. The distribution of leaf area indices and light intensity in the succession; a – in the model time 1 year; b – in the model time 66 years; c – in the model time 66 years after cutting in year 1

sumes the cyclic dynamics of tree numbers and biomass. In variants with cutting the beech trees only and cutting all trees in the first and in the 20th year of simulation, this tendency of cyclic changes is confirmed too. The cycles were more frequent for the number of trees than the biomass. Under the cutting conditions only the time of this dynamics varies.

Beech and fir trees grow in similar ecological conditions in the Bieszczady Mountains. When the old canopy trees die, the smallest trees grow more quickly. In the gap appearing after the death of dominating large trees, when the biomass and leaf areas are insignificant, the regeneration stage predominates. The next stage of gap development is related to the competition between the trees of similar age in the overstorey. The starting point of this stage can traditionally be attributed to the moment of canopy closure resulting in the dominance of one of the large-size tree species. Then, the gap enters the initial peak stage (in terms of the biomass) affecting its development.

A single simulation run ensures more detailed analysis of changes within the simulation. In this case very prospective are the investigations of changes in the age and height of trees or in the distribution of leaf area indices and light intensity in the course of succession.

The Monte Carlo method also assumes cyclic 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 the changes in tree biomass and numbers. The Monte Carlo method also assumes the cyclic transformations of beech stand into fir stand.

CONCLUSIONS

The FORKOME model predicts the cyclic dynamics of changes in beech forest in the Bieszczady Mountains.

Cutting of trees will not change the general tendency of cyclic changes between beech and fir biomass and tree number, only the time of replacement between beech and fir will be variable.

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Predikce sukcese bukových lesů v Beskydech pomocí počítačového modelu

ABSTRAKT: V práci jsou uvedeny výsledky šetření sukcese bukových porostů v Beskydech pomocí modelu FORKOME (FORest KOzak MEnshutkin). Model byl ověřován v terénních pokusech v letech 1998–2001 v porostech s převahou buku (*Fagus sylvatica* L.) v polesí Stuposiany v Polsku. Během jedné simulační operace a realizací Monte Carlo model předpokládá pro přírodní bukový les cyklické změny počtu stromů a biomasy buku a jedle. Vykácení stromů nevede ke změně obecné tendence dynamiky bukových a jedlových porostů. Při použití těžeb se mění pouze časový průběh této dynamiky.

Klíčová slova: buk; les; počítačový model; Beskydy

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