Prediction of Spruce Forests Dynamics in the Polish Bieszczady and Ukrainian Bieskidy Using the Computer Modelling

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The results of investigation on spruce forest dynamics in the Polish Bieszczady and Ukrainian Beskidy using our FORKOME* models are presented. The model was verified in the field trials in 1998–2001 in the forests with dominating spruce (*Picea abies L.*). The FORKOME model confirmed a short life span of man-made spruce forest in the Polish Bieszczady and Ukrainian Beskidy. The transformation of man-made spruce forest into beech forest followed by the cyclic changes in the biomass and number of trees of the beech forest and the fir forest was simulated. The cycles have been changed more often as for number of trees than in biomass dominance. Those cycles were typical of Polish Bieszczady. In the Ukrainian Beskidy the cycles have been predicted not for the biomass but only for the numbers of trees. The model predicted that regeneration of beech forest on the place of spruce was more intensive in the variant of cutting of all trees in the 1 year of model time, than without cutting.

Key words: spruce forests, dynamits, FORKOME, prediction, cutting, regeneration

Introduction

The Polish Bieszczady and Ukrainian Beskidy are located within the Carpathian arc and occupy the central part of this mountain region in the Ukraine and Poland shifted to the North-East with specific climate and ecological regimes and different management systems.

Since 1945 two different management systems have been introduced to the same type of ecosystem, with identical geological and climatic conditions in Polish Bieszczady and Ukrainian Beskidy (most moderate in Poland and very strong within the Ukraine; Augustyn, Kozak 1997). As a result of different management and land use systems in the Ukrainian part are more man-made spruce ecosystems than in Poland part.

From the 1970s the progressive mathematization of the field of ecology was developed. As a results different models have been constructed: (Sullivan, Clutter 1972; Soloman 1974; Mitchel 1975; Suzuki, Unemura 1974; Horn 1975; Waggoner, Stephens 1970; Shugart, West 1977; Oja 1985; Popadjuk, Czumaczenko 1991).

The forest gap model approach has proven to be useful in many aspects (Shugart 1984). Canopy gaps are essential for forest regeneration in many temperate and tropical forests. The phenomenon of forest regeneration in gaps has received more attention recently. It is important for natural (Popadjuk, Czumaczenko 1991) and managed forests.

The first models (Botkin et al. 1972) were rather simple, but the 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 make detailed and presumably more accurate projections of forest succession.

The main aim of the present study was an investigation of the succession dynamics of spruce forest

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in the Polish Bieszczady and Ukrainian Beskidy under different cutting conditions by using the FORKOME model.

Materials and method

Permanent research plots were situated in the Polish Bieszczady Mountains (Poland) on the slope of Kosowiec (Stuposiany Forest District) in the watershed of Gleboki creek and in the Ukrainian Beskidy (the Ukraine) in the Szandroviec creek (Jablunytsia Forest District). There is just one stand in Poland and one in the Ukraine. The plots were located on the north slopes of the mountain (inclination 7^0 - 10^0) at the altitude of 630-650 m a. s. l. Brown soils are characteristic of the plots. Dominating tree species were spruce at the studied research plots. The area of stands was 1 ha. The average age of the stands was 44 years in the Polish Bieszczady and 46 years in the Ukrainian Beskidy. The average dbh of the stands was 19.1 cm in the Polish Bieszczady and 19.6 cm in the Ukrainian Beskidy.

In our FORKOME model we investigated the forest changes in small plots (Kozak, Menszutkin, 1999) within a GAP (30m x 30m). Shugart (1984) used 1/12 ha. Our model was based upon the main assumption, that the dynamics of the whole forest stand can be considered as a sum of processes taking place within a small unit of the size, comparable with canopy gaps. In such gaps the forest dynamics was simulated.

Our FORKOME model was constructed on the base of the FORET model (Shugart and West, 1977) with authors· modifications considering, for example, temperature. In our FORKOME model different modules (blocks) were distinguished (Fig. 1). Block "INPUT PARAMETERS" represents the estimation of tree and stand parameters such as maximum tree diameter (D max) at a standard height of 130 cm above the ground level. Maximum height (H max), maximum age (AGE max), minimal and maximal sums of degree-days (DGD min, DGD max) were also considered.

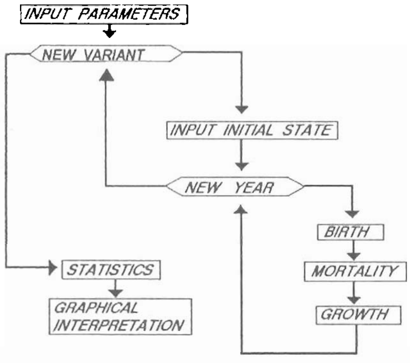

Figure 1. Diagram of the FORKOME model algorithm.

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

Table 1. Basic parameters of the growth for main tree species in Polish Bieszczady and Ukrainian Bieskidy Mountains used in the 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.	4500	150	300	58.26	0.194	290	4650	12700
Abies alba Miller	6000	150	400	78.26	0.261	200	3855	12684
Picea abies (L.) Karsten	5500	150	400	71.60	0.239	370	882	3960
Betula pendula Roth	3200	100	100	61.40	0.307	500	0	3840
Pinus sylvestris L.	4500	150	400	58.3	0.194	330	270	2500

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 depends on tree age and conditions of the growth in the previous year. Block "BIRTH" depends on the species of seedlings, soil surface conditions and average temperature at the litter level. We also analysed if the species requires leaf litter and mineral soil for successful recruitment and take into account if the species recruitment is reduced by hot seasons of the year and if the species is a preferred food of deer, wild boar or small mammals. To basic parameters used for species attributes in FORKOME model added the tolerance class of each species (shade-tolerant, intolerant). The growth rate of each tree (block "GROWTH") depends on the dimensions and species of each tree. The growth equation has been developed by assuming that tree volume is a function of a tree diameter squared times the tree height and that tree growth is based on the annual volume increment:

$$\frac{d\lfloor D\ H \rfloor}{dt} = rLa\left(1 - \frac{DH}{D\max H\max}\right)$$

where:
r - a growth rate parameter,
La - a trees leaf area (m^2/m^2),
D- the diameter at breast height (cm),
H- a 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 the diameter:

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

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

If a tree has the 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 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:

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

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

The following two equations have been applied: the first one for light demanding trees:

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

and the second one for shade-tolerant trees:

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

The growth rate depends on the conditions of temperature. 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 - the growth reduction due to temperature effects, DGD - the base heat sum for a site, DGD_{min} - the minimum degree-day value where the species is known to occur, DGD_{max} - the maximum degree-day value where the species is known to occur.

For block of nutrient we used polynomial function of the form (Weinstein et al. 1982):

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

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

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 mortality of tree 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 next modification. It allows taking into account the influence of next agents at the growth of trees.

The programme carries out a statistical analysis of the obtained results (block "STATISTICS"). In the simplest case the analysis consists of calculation of the mean and standard deviation values, whereas in more complicated 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 pressing the left button of the mice in the position of each tree at the picture it is possible to get information about age, height and diameter of the tree. The right button of the mice allows cutting of the tree.

The statistical elaboration " MONTE-CARLO REALIZATION" can simulate up to 200 runs with the same starting and management conditions. In the investigation process it is accepted that 30-40 simulations are enough for estimation of statistical parameters of the model in each variant.

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

Different variants simulated the scenario for spruce permanent plots in the Polish Bieszczady and in the Ukrainian Besakidy. Variant 1 was taken as a control, variant 2 assumed cutting all trees in the first year of model time.

Results

Our FORKOME model confirmed the short life span of the spruce. The model predicted in the control conditions a decrease in the numbers of spruce trees and of spruce replacement by beech. For example, in the Polish Bieszczady the number of spruce trees decreased from 35 individuals in the 1st year of model time to 2 individuals after 20 years (Fig. 3a). In the following up

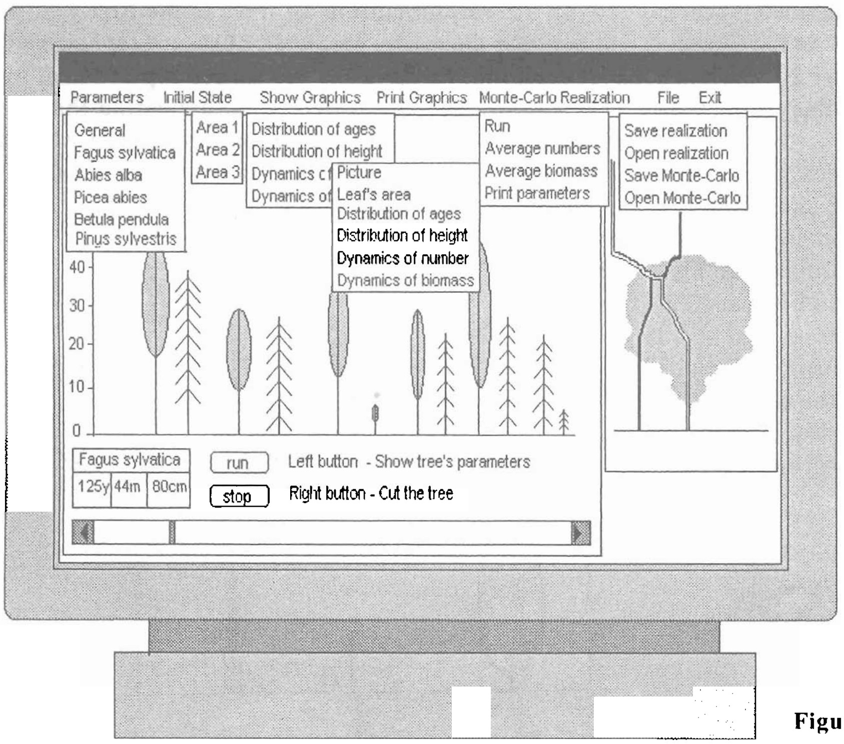

Figure 2. Interface of the FORKOME model

to 600 years the number of spruce trees increased only to 5 individuals and decreased to 1 very often. Such a pattern is typical also of birch trees (*Betula pendula L.*). An increase in spruce and birch percentage was probable in the periods of beech or fir weakening. After 20 years of model time beech dominated up to 60 years and after 60 years up to 260 years fir dominated. In the following up to 550 years dominated beech again and after that dominated fir from 550 to 600 years.

In the Ukrainian Bieskidy the model predicted in the control conditions a decrease in the number of spruce trees and regeneration of beech forest too. The number of spruce trees decreased from 37 individuals in the 1st year of model time to 3 individuals in 20 years (Fig. 3b). In the following the number of spruce and birch trees increased was similar to the Polish Bieszczady. After 20 years of model time beech dominated till 40 years. From 40 to 120 years fir dominated. Domination of species was the following: beech from 120 to 160 years, fir from 160 to 185 years, beech from 185 to 280 years, fir from 280 to 300 years, beech from 300 to 450 years, fir from 450 to 540 years and beech from 540 to 600 years.

In the process of spruce replacement by beech, the biomass of spruce trees was reduced from 82 т ha^{-1} in the first year to 0 after 20 years (Fig. 4a) in the Polish Bieszczady. The model predicted the beech dominance till 100 years. In the subsequent time the cyclical change between beech and fir repeated (from 100 to 250 years

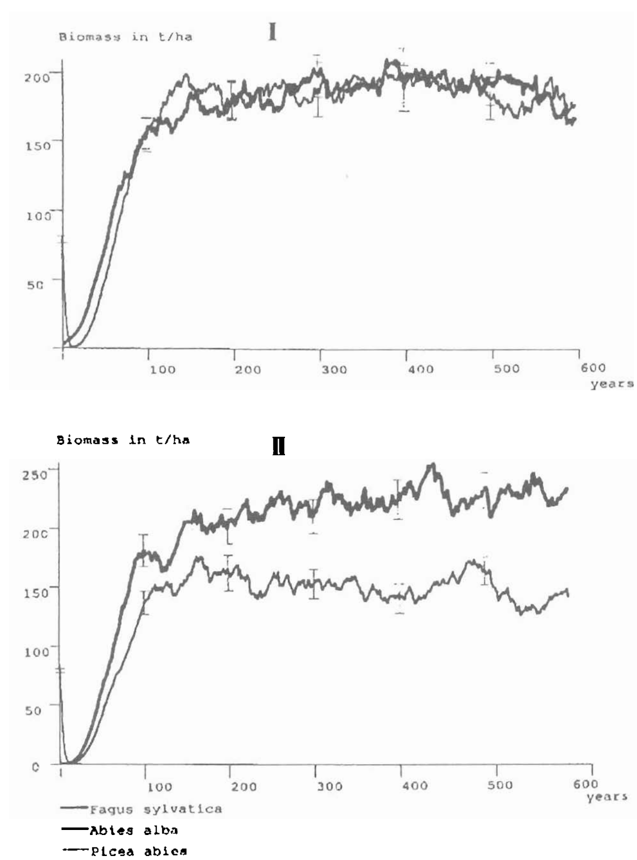

Figure 3. The number of trees in spruce forest stand in the Polish Bieszczady (I) and in the Ukrainian Beskidy (II)

dominated fir, from 250 to 550 years dominated beech and from 550 to 600 years dominated fir). In the Ukrainian Bieszczady the model predicted after 20 years the beech dominance during all modelling time from 20 to 600 years (Fig. 4b).

In the variant 2 -cutting of all trees in the first year of model time, the model predicted similar dominance of beech and fir biomass to 90 years in the Polish Bieszczady and to 50 years in the Ukrainian Beskidy. After that the cyclical change between beech and fir repeated in the Polish Bieszczady only.

Figure 5 illustrates spruce replacement by beech. After the first year of the model time, the spruce plot included 48 spruces, as well as 5 birches, 2 beeches and 1 pine. After 10 years, the spruce number decreased to 4 individuals and the beech number increased to 6 individuals. After 20 and 40 years, the number of beeches and firs increased.

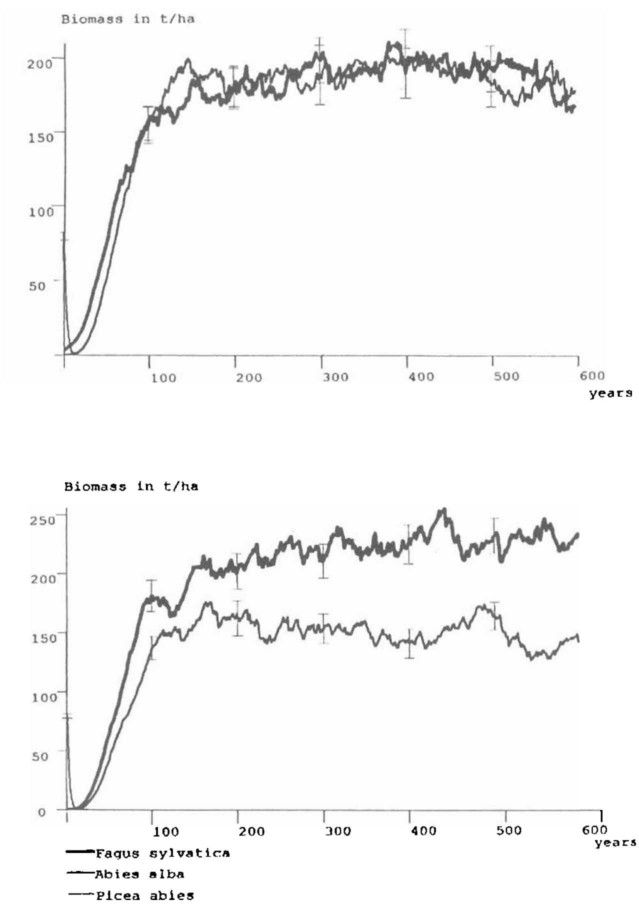

Figure 4. Biomass of trees in the spruce forest stand in the Polish Bieszczady (I) and in the Ukrainian Beskidy (II)

This process led to the change in cumulative leaf area and light intensity after 1, 10, 20 and 40 years of the model time (Fig. 6).

In the variant cutting all trees in the first year of model time the model predicted of spruce replacement by beech too. In this case the spruce replacement by beech would be accelerated. It is interesting that the distribution of the cumulative leaf area in the variant without cutting out spruce trees was less compact than in variant 2 with tree cutting.

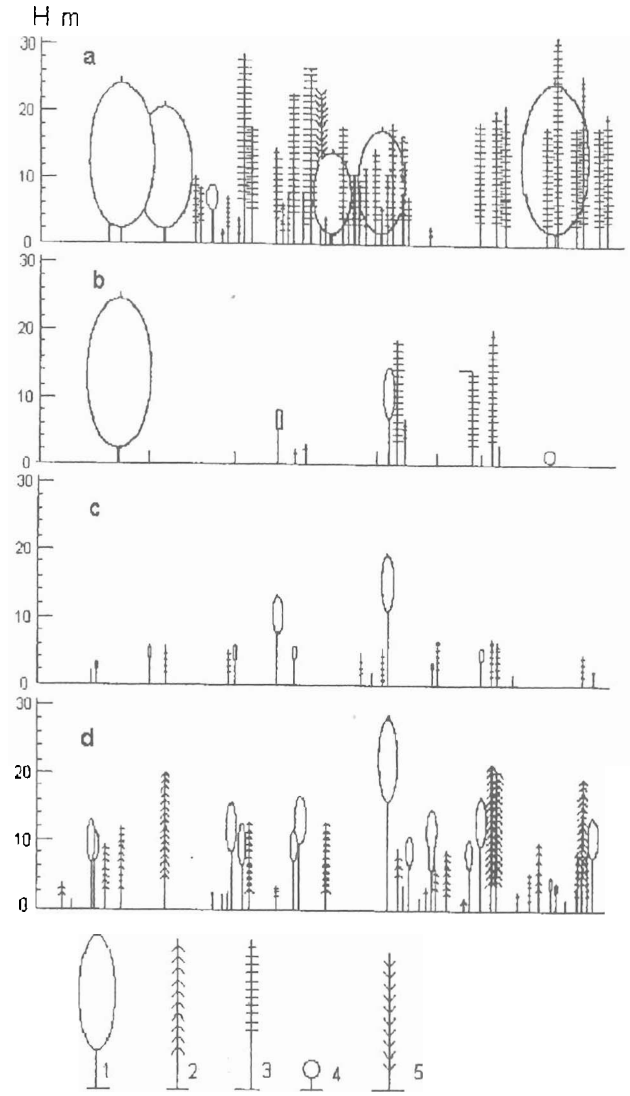

Figure 5. Spruce replacement by beech in the Polish Bieszczady
A-in the 1st year, B- in the 10th year, C- in the 20th year, D- in the 40th year of model time

Discussion and conclusions

Our FORKOME model also confirmed short life span of spruce in the studied Polish Bieszczady and Ukrainian Beskidy parts of the Eastern Carpathians. The model predicted a decrease in the numbers of spruce and in the biomass of trees over 20 years of

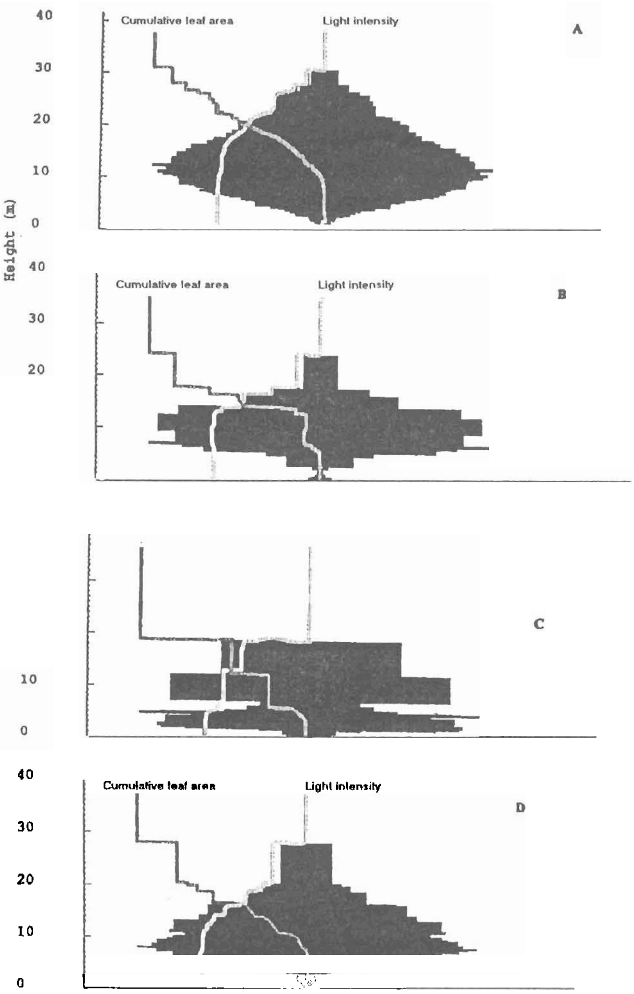

Figure 6. The distribution of cumulative leaf area and light intensity in the process of spruce replacement by beech in the Polish Bieszczady
A-in the 1st year, B- in the 10th year, C- in the 20th year, D- in the 40th year of model time

model time (64-66 years of absolute age of stands) and restoration of natural beech forest.

In the literature there are many data on short life span growth and unsatisfactory health condition of secondary spruce forests in the Carpathians. According to the data from the Ukrainian Carpathians (Golubets 1978, Kozak 1990) secondary spruce forests growth quickly to 35-40 years. In the following they have unsatisfactory health conditions and decline. The same situation is in the Polish Bieszczady (Jaworski 1996) and in the Slowakia Carpathians (Klimo 1998, Kodric 1998).

The model confirms that the spruce stands decline. An increase in spruce and birch participation was probable in the periods of beech or fir weakening.

The model confirmed the cycle of community development trends. Such cycles were already described in the literature (Shugart 1984). Our model predicted the cyclical dynamics of species succession between beech and fir after decline spruce forest. The tendency of beech tree number dominance after destroyed spruce forest and later on fir dominance was visible too. The cycles have been changed more often as for number of trees than in biomass dominance. Those cycles were typical of Polish Bieszczady. In the Ukrainian Bieskidy the cycles have been showed only for numbers of trees not for biomass. The FORKOME model simulates the beech dominance in the Ukrainian Beskidy from 20 to 600 years of model time.

One realization allowed a more detailed analysis of change insight the simulation. In this case prospective were investigations of changes in age and height of trees or the distribution of leaf area indices and light in the course of succession.

Statistical Monte Carlo realization showed that the amplitude of these changes was not so high as for one realisation. But in the Monte Carlo realization it is possible to analyse the tendency of changes in the biomass and tree numbers during succession.

The cutting of trees will not change a general tendency of changes between beech and fir biomass and tree numbers. In the cutting conditions only the time of this replacement would be variable.

The cutting of trees in the 1rst year of model time will not allow the dominance of spruce forest. The cutting of all trees in the first year of model time would accelerate the regeneration of natural beech forest.

The structure of our FORKOME model is open and modular, enabling its easy development and modification. The important feature of the FORKOME model is a possibility to assess the impact of changing environmental conditions on forest growth and functioning. The necessity of which is also emphasized in the literature (Brzeziecki 1991).

Processes simulated by the model can be classified into two major categories: processes external to the stand (temperature conditions, moisture regime, light and soil conditions), and demographic processes (natural regeneration, growth and mortality).

The proper parameterization of tree species is of key importance for the high model performance. The tree parameters include a set of biological, ecophysiological and ecological features. Totally, they define for each tree species, its unique life-history strategy, and, particularly, its succession status and a role in the natural forest dynamics. In the FORKOME model, practically all important forest tree species, occurring naturally under conditions of the Central Europe, are taken into account. This makes possible to apply the model under a broad scope of soil and climate conditions.

Generally, our model may be used for quantitative estimates of the effects of various factors (cutting, climate changes, introductions of new tree species) on the dynamics of forest community.

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ПРОГНОЗИРОВАНИЕ ДИНАМИКИ ЕЛЬНИКОВ В ПОЛЬСКИХ БЕЩАДАХ И УКРАИНЬСКИХ БЕСКИДАХ С ИСПОЛЬЗОВАНИЕМ КОМПЮТЕРНОГО МОДЕЛИРОВАНИЯ

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Резюме

В статье представлены результаты прогнозирования динамики ельников в Польских Бещадах и Украиньских Бескидах с использованием компютерного моделирования а именно модели FORKOME. Модель подтвердила кратковременное произрастание производных ельников созданных на месте коренных буковых лесов. После распада производных ельников модель прогнозирует возобновление на их месте буковых древостоев и дальнейшую циклическую взаимосмену между буком и пихтой.

Ключевые слова: ельники, динамика, FORKOME, прогноз, рубка, возобновление