# Modelling Regeneration Success and Early Growth of Forest Stands

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# IMITATION MODELLING OF HETEROGENEOUS UNEVEN-AGED STANDS' SPATIAL DYNAMICS TAKING INTO ACCOUNT SILVICULTURAL TREATMENT

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## ABSTRACT

An imitation spatial dynamics model is tested for a mixed uneven-aged forest range. The model is a part of a complex information system (DBMS, GIS, MODEL). The system is intended for the information service of forest management units (FMU) and can promote the organisation of sustainable forest exploitation.

## INTRODUCTION

Forecasting the processes of forest resources changes under the influence of economic activity and decision making aimed at sustainable development of separate forest areas are becoming very urgent. The modern information technologies permit to solve the mentioned problems when including into the complex forest management information system (DBMS+GIS) the modules for forest dynamics forecasting and decision making optimisation.

This paper deals with the problems of combining these modules with the FMU information system. In the forecasting module we used an original simulation model (Chumachenko 1992, East European... 1994), in which two major principles are realised. First, the model uses standard data, obtained by practising forestry. Secondly, the imitation modelling is based on the algorithms, coordinated with known bioecological characteristics of processes to occur in real forest communities.

The main difference of the used model from Gap models (Botkin et al. 1972) is the direct account of real tree spatial stand distribution and non-uniformity of the environmental conditions. Unlike mosaic models (Acevedo et al. 1995) the presented one is based upon account of species biological peculiarities and their interaction. The model realizes the possibility of forecasting the economic activity influence on specific sites of the forest. It allows to hope that using the imitation modelling block within the complex FMU information system will help to solve the problem of forestry management optimisation for the maintenance of sustainable forest exploitation.

## MODEL CONSTRUCTION PRINCIPLES

Space and time scales. Setting the task of stand dynamics modelling for the practical purposes of forest management at particular FMU sites, we have defined, therefore, space and time scales of the object under simulation: the sizes of forest ranges make up up to tens of thousand

hectares (the range of FMU area in the European part of Russia); the step of simulation is 10 years.
The simulation predicts the change in stand inventory characteristics (height, diameter, age, stock etc. - up to several tens of characteristics ) by storeys, the change in species and age structure of each stratum (primary account unit of forest planning and inventory works). The most important feature of the described model is the account of strata position in space and their mutual influence.
As initial information for the mathematical model, one uses the per-stratum data bank and cartographical bank of plans and cartographical materials of the forest planning and inventory works, which for particular FMUs is available in the form of information systems (DBMS or GIS). As a result of the model work, a similar information is obtained.
The first stage of initial spatial data transformation consists in dividing the modelling space by rectangular parallelepipeds with a square base (elements). This process is carried out by means of the used GIS (grid-function). The dimension of a square is determined by the geographical latitude of the district and by the height of the top stand story. So, for example, for Moscow latitude and stand height of 25 m, respective area makes about 270 $m^2$. As a result, the complicated configuration of each stratum in the plan is approximated by a set of elements, featured by properties of the corresponding stratum. Further, the element is divided in vertical direction by cells of 2 - 2.5 m high. The cell (from the point of view of simulation) is indivisible minimum unit of three-dimension space. Such representation of the simulated space permits to take into account both self shadowing, and shadowing from adjacent elements during the solar day movement.

To take into account bioecological processes in real forest communities, a large number of reference data bases is used within the simulation . Below are listed the main ones.

Bioecological characteristics of species development. The information, compiling these data bases, was assembled as a result of literature analysis and a long-term natural research (Smirnova et al. 1990, East European..., 1994, Popaduk et al. 1995). The accumulated experience of mixed uneven-aged stands simulation is taken into account (Popadyuk & Chumachenko 1991, Chumachenko 1992). For the model work reference bases are created for species main bioecological parameters separately for each stage of tree ontogenesis of each species. These reference bases were compiled proceeding from the concept of ontogenesis discrete description (Rabotnov 1978, Gatzuk et al. 1980, Diagnoses and keys... 1989). The application of this concept for the simulation of complicated stands gives more authentic results. These reference bases are listed below:

A. Crown biometrics characteristics.

B. Crown form. The crown form is approximated by a combination of elementary bodies of rotation: cone and cylinder. The model peculiarity consists in taking into account the internal crown space (shadow cone), with no photosynthetic elements (Nosova et al. 1995).

C. Active growth zone. The comparison of stand development by different stand density has shown that height growth depends on light availability at the active growth zone and not at the top of a tree (Nosova et al. 1995). The active growth zone is a part of the tree crown, where the main share of its green biomass is concentrated. In the reference base this zone is given by the position of the shadow cone in the tree crown;

D. Demand for light (shade tolerance) (Tsel'niker 1978. Evstigneev 1991).
E. Crown transmittance of light.
F. Distance of seeds spread (Udra 1988).
G. Sprouting ability.

Local yield tables. To receive authentic long-term forecast of stand dynamics it is necessary to have exact local yield tables (YT). When there are no such tables, our approach to solve this problem is to develop methods of calculating YT on the basis of local inventory data since such approach permits to take into account most completely particular growing conditions, that, in its turn, provides the correctness of the model work.

The growth of general productivity and stock in pure and two-species mixed stands can be described (Bredikhin 1985 ) by a system of differential equations

$$\frac{dV_i^j}{dt} = \min_i B_i^j\left(A_i^j\left(1-\exp\left(-\left(G_i^1V_i^1+G_i^2V_i^2\right)\right)\right)\frac{G_i^jV_i^j}{G_i^1V_i^1+G_i^2V_i^2} - V_i^j\right)$$

where the upper indices show the number of the species: i - number of the resource $V_i$ - total productivity or volume of one of the species in a pure or mixed stand; $B_i = c_ib_i/g_i$; $A_i = R_i/b_i$; $G_i$ - coefficient for the resource i; $R_i$ - flow of resource i per unit of the stand area; $g_i$ - share of resource i necessary to increase the biomass by a unit; $b_i$ - share of resource i necessary to support the unit viability of already existing biomass; $c_i$ - proportional dimensionless coefficient.

The check of adequacy of this model was conducted by using the available YTs for pure and mixed stands (Kozlowski & Pawlov 1967), and it has shown a good adequacy. In the present imitation model only pure stand YT are used.

For the need of the simulation it was carried out processing of inventory descriptions of 717 strata of pure stands and 74 strata of mixed stands in FMU "Gorky" (Moscow Region). The data were obtained for pure oak, pine and birch stands as to stock, mean height and diameter . The site classes for pine stands are 1a, 1, 2 and 3, for oak stands - 1, 2 and 3, for birch stands - 1a, 1 and 2. The lowest mean relative error for the initial data are for stock - 5.5%, for mean diameter - 9.0%, for mean height - 4.3%. The largest mean relative error for the calculated data for these stands are for stock -3.1%, for mean diameter - 3.3%, for mean height - 1.8%. Also the data were obtained for mixed pine and birch stands of site class 1 for stock, mean diameter and height. Mean relative errors of the initial data are for stock - 10.4 %, for average height - 9.2 %, for average diameter - 6.7 %. The mean relative errors for the calculated data are for stock of pine 2.6 %, for birch 7.5 %, for average height 1.9 and 1.0 %, for average diameter 1.3 and 2.7 %. These results also testify the good adequacy of the model and the possibility of using its results for obtaining local YT.

Solar radiation. Data on solar radiation at a given latitude of district were used. The differentiation of light flow is proceeded by azimuth, by height of the Sun above horizon, by quantitative relation between direct and scattered radiation. Also were used data on average long-term quantity of sunny (cloudy) days in the region during the vegetative period; on condition of clouds and dust in the day time; on general air pollution which weakens natural light factors .

Table of biological site classes. The methods of for stands, typical in various growing conditions, is still developed insufficiently. In the present realization of the model the table of

greatest possible site classes for the prevailing species is built by an expert in interactive mode on the basis of initial inventory data and relief characteristics by taking into account available moisture and soil active nutrients, with the use of the following main assumptions.
The dependence of bioproductive process on habitat conditions may be presented by a bell-form distribution - schematically this dependence can be described by a system of second-power equations of three variables, namely moisture amount in air drainage zone; sum of temperatures; hydrothermic factor that describes the relation between heat and moisture (Pusatchenko 1987). For each kind of plants these functions have approximately the same form, but differ by appropriate species constants.
Under more or less constant climatic conditions as to heat and moisture availability, the regime of humidity at air drainage zone is of primary importance, within a wide spectrum of natural taiga conditions, it is adjusted, generally by the relief of the district. At watershed areas there are observed bands with various degrees of soil humidity, where different conditions for forest growing are allocated. Sites of various potential efficiency can be divided by areas with actively developing processes of swampiness, when they are placed parallel to stream and drainage divide line according to the drainage conditions. The distinctions in drain conditions at particular watersheds are determined by soil filtration at the air drainage zone, and by relief morphometric characteristics. Such picked out bands are referred to maximum site classes to be met in inventory data bases for similar habitat. Further it is assumed to automatize the process of biological quality matrix construction by means of algorithms of relief digital models analysis (Shary 1995).

Exogenous thinning. The model permits to simulate the effect of various catastrophic factors and forest management influence (final felling, cleaning cutting, forest regeneration measures etc.). The main purpose of cleaning cutting is the increase in valuable species share within stand structure, first of all for long-boled (seedling) oak, spruce, lime. When the stand reaches its maturity age, a final felling is simulated (a total elimination of the stand first story).
Forestry-generated impacts are defined for a stratum on the basis of stratum inventory characteristics, of which the main are stand formula, age and stand density. The reference base "Exogenous thinning" is developed mainly to solve tasks of forestry influence simulation, and it consists of the rules on the basis of which the algorithms of this block are worked out, as well as tables of standard maturity age, optimum stand density, etc. These rules and tables are based on normative documents on cleaning cutting and final felling, accepted by the Federal Forestry Service of Russia.

## MODEL STRUCTURE AND FUNCTIONING

The program complex "Forest range" consists of several target blocks. Block "Light" begins each step of simulation, where it is determined the transparency of each cell by taking into account the species parameters. The integral value of the photosynthetic active radiation (PAR) in the space cell is calculated with account of self-shadowing and light penetrating characteristics of the adjacent cells. Using the data on growth of species to be available in the stand structure, the block "Growth" calculates for each element the current increment of the species by diameter and height, taking into account the element position and its light maintenance. It is accepted in the model, that the main factor, affecting the tree growth under forest canopy, is the light availability, because other considerable factors (such as available moisture and soil fertility) are rather stable integrated (average for 10 year) characteristics of the element and are taken into account when species biological qualities are determined for each stratum.

The block "Thinning" includes two main options of behaviour of the model: endogenic thinning, as a consequence of intra- and interspecific competitive relations and thinning as a result of exogenous factors.

The endogenic thinning is simulated by three consecutive operations. Firstly, the model searches and excludes from the element those species which do not reach the habitus, being typical for a given species at a given age (for the lowest of site classes available). Similarly the model excludes the species, that have reached the utmost age, according to YT data for these ones.

Secondly, because of light being the main limiting factor in the model, for each species in the given stratum element it is calculated a factor of increment loss during one step. The factor in the model is defined as a ratio of the real increment to that from YT. The dying off criterion is the calculated factor being reduced below the given level (in the present realisation of the model - 10 %).

Thirdly, for the maintenance of tree number below critical values (according to biological parameters), the block "Thinning" executes the recalculation of tree number within an element. In each story the zone of best competition for space - a cell with maximum crown plan, and accessible area for crown growth - is determined. The redistribution of area in story is executed at the expense of intercrown clearance and begins with shade-tolerant species. In such way, supersede more intolerant, changing the proportion of areas engaged to each species.

Thinning as a result of exogenic factors includes anthropogenic, technogenic and other external effects on the simulated species. The conditions of additional thinning can be considered at any step, and they are selective ones. After simulation of thinning, each cell light availability is recalculated with simultaneous data changing as to crown height for some species in the element.

In the block "Reproduction" the quantitative valuation of young growth appearing is made. The intensity of germ occurrence depends on the degree of the element remoteness from generative trees of the given species and the light conditions of their development. The opportunity of coppice young growth in the element is also simulated. In view of various speed of growth and ontogenesis duration, different YTs for coppice and seedling stands are calculated separately.

After processing of each step of the model, the element contains characteristics for species and age structure of the stand and its biometric parameters: species, stem quantity, age and age condition, average height of tree and average crown height, average stem diameter, crown canopy and crown form, achieved (calculated) and biological quality of locality. Besides these are calculated stock and stand density. These data are basic for the work of various applied blocks, being external to the main model.

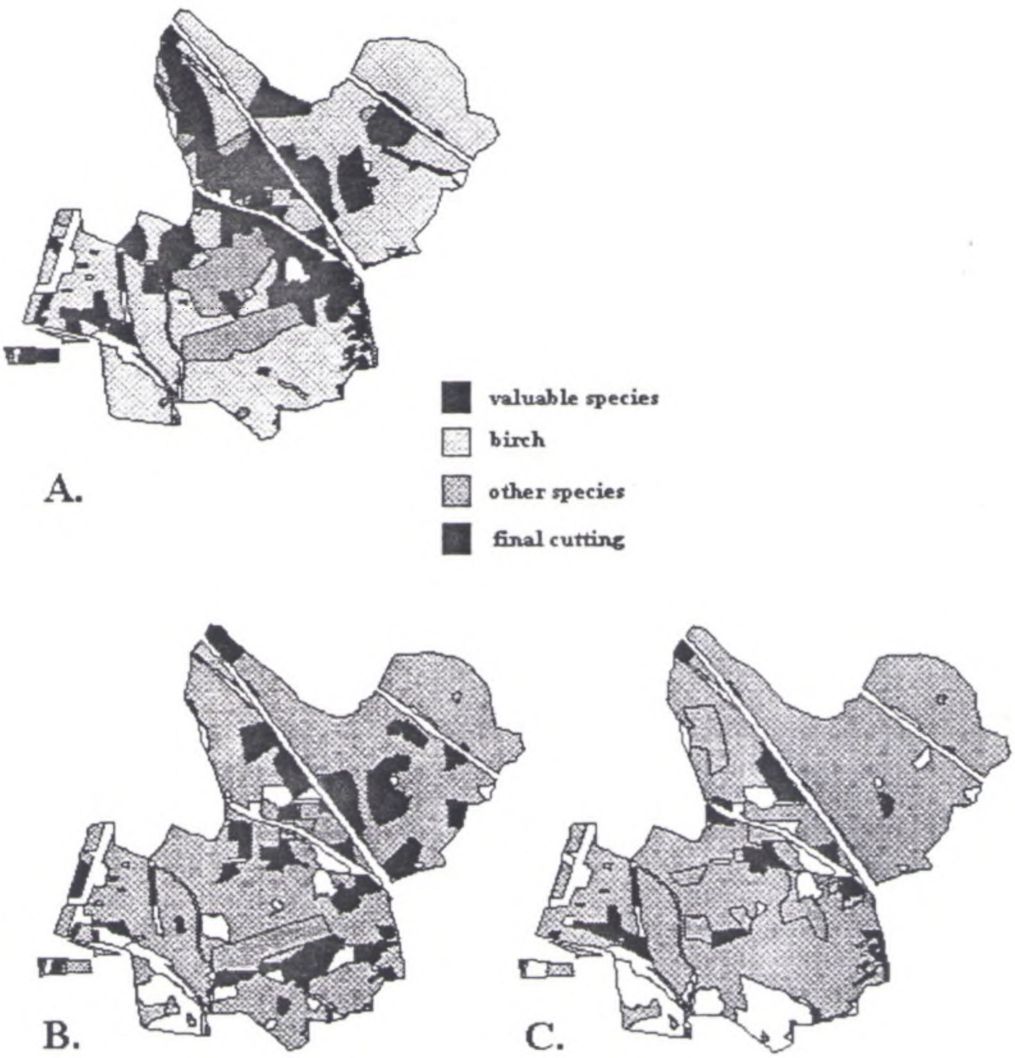
By means of the rules given in the model, the block "Stand" carries out samples, performs statistical processing, executes the assembly of elements into inventory strata and prepares the information for representation to DBMS and GIS.

**Target blocks**

The submitted simulation model is an open one, i.e. it permits to add various target blocks. Such blocks can be attached at any step of the model work. So, under realization of the present project two blocks "Forest management effects" and "Forestry management optimization" were attached.

The block "Forest management effects" is introduced to the model as a scenario variant of external effects. At each step of simulation, a stratum selection is made for forestry operations to be fulfilled (different kinds of cleaning cutting and main felling), volumes of harvested wood by species and cuttings methods are calculated, updating of the data base inventory parameters (stand formula, density, stock) of the first storyis performed, according to the effects, simulated in the model.

**Fig. 1. Distribution in space of different species stands**




## SIMULATION RESULTS WITH IMITATION OF VARIOUS FORESTRY EFFECTS

As a sample object at the present stage of the project development, it was chosen the forest range of Korobovsky forest district in FMU "Gorky". The territory is located in the south of Moscow Region within the limits of spruce-broadleaved forest zone. The growing conditions for the whole forest range are practically homogeneous. Cover loam soils on a carbonate moraine are acting as soil forming rocks. The sample object area makes about 600 hectares. The forests, typical for the middle part of European Russia are growing there. The central part of the forest range (30 % of its area ) is covered by broadleaved forests with prevalence of lime and oak of 70-100 years old, to have appeared at durable forest lands as a result of repeated felling. At the periphery of the forest range, there are birch forests of 60-80 years old (50 % of the area), arisen at arable land (Fig. 1A).

At this sample plot a stand dynamics was simulated two kinds of external forestry effects: final felling only (when the stand reaches its maturity age) and combined cleaning cutting and final felling. As a result of the model work, per-stratum data bases are obtained of the sample forest range for 8 steps of simulation (80 years) according to the two options of external effects.
In the first case of simulation (simulation of clear final felling), the dynamics of standing crop changes is closely connected with the dynamics of birch stands timber volume (Fig. 2A). The observed sharp fall of birch stock which happens at the third step is connected with the clear felling of the birch stands that reach their maturity age. Besides that, a fall of birch stock is marked on the eighths step, that is also connected with clear cutting of mature birch stands. The share of valuable species (spruce and seedling oak) by such mode of management is very low (Fig. 1C).

**Fig. 2A. Modelling of cleaning cutting**

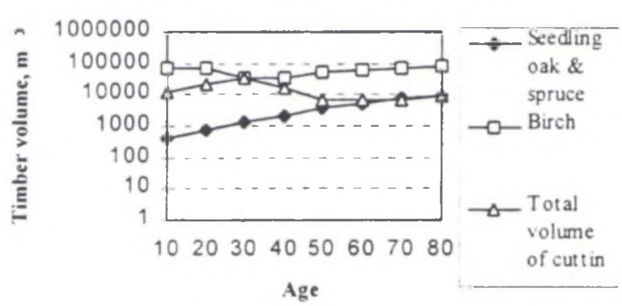
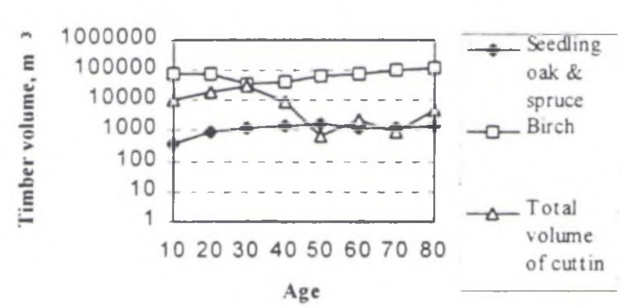



**Fig. 2B. Modelling of clear cutting**




The second way of simulation is different, because in the scenario the simulation of cleaning cutting is added (Fig. 2B). The main difference of this variant from the previous one is the smooth increase of valuable species share (spruce and seedling oak) in stand structure beginning from the third step. It should be noted, that when executing cleaning cutting the birch stocks are on lower level, than in the first case. Besides that, the regular execution of cleaning cutting permits to ensure the constant volume of cut wood of not less than 50 thousand cubic m for each step of the simulation (Fig. 1B).

## RESULTS OF FORESTRY WORK OPTIMIZATION

As a result of simulation by means of “Forest range model” we have obtained stratum inventory parameters for each 10 year step, as well as forestry operations, whose volumes are defined according to forestry requirements. On the basis of these data, we have obtained for each 10 year step by means of optimization models (Bredikhin 1982 ) in succession of years and seasons the volumes of forestry work, defined with taking into account the restrictions of labour and material resources. As a sample, we take the initial period of Korobovsky forest district . For the period 1992-1999 for first clearing are designated 2 cubic metres, for early cleaning - 7 cub. m, for isolation- 440 cub. m, for thinning - 812 cub. m, for forming felling - 1395 cub. m and for sanitation cutting - 1057 cub. m.
As a result of step by step optimization we obtained the following amount of work with distribution within the above-mentioned period (table).

Table 1
The distribution of forestry work volumes within periods, cub. m

| Name of work | 1992 winter | 1992 summer | 1993 winter |
|---|---|---|---|
| First cleaning | 2 | | |
| Early cleaning | | 7 | |
| Isolation | | 440 | |
| Thinning | 812 | | |
| Forming felling | 400 | 400 | 595 |
| Sanitation cutting | 787 | 270 | |

Thus the application of optimization models enables the most rational distribution of forestry work volumes within periods of time taking into account the present technical, financial and labour resources.

## CONCLUSION

The submitted results of model work have shown the adequate reflection of stand growth and development under different scenarios of forestry effects. So, execution final felling only causes an absolute birch domination in the forest range. It corresponds to the biology peculiarities of this pioneer species and reactive behaviour strategy. The model reacts on change of the scenario of forestry effects. When executing a total cycle of forestry work (cleaning cutting and final felling), it will take place an increase of valuable species share in the forest range.
The application of optimization models enables to distribute the execution of forestry work more reasonably within the periods, taking into account available financial and labour resources. The possibility to add target blocks permits considerably to expand the opportunities of the model. So, changing at any step the biological quality of locality plan, it is possible to simulate the influence of environment pollution, swamping, soil infringement, drainage reclamation influence etc.

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