SCIENTIA FORESTALIS
n. 73, p. 73-89, março 2007

The use of simulation model FORRUS-S in the ecological management in forestry: strategic and tactics planning

Uso do modelo de simulação FORRUS-S no manejo florestal ecológico: planejamento estratégico e tático

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Abstract

Computer program package FORRUS-S has been developed for simulation modeling of forest stand ecosystems dynamics. FORRUS-S consists of the model of natural development of multi-species uneven-aged stand, the model of exogenous influence (including silvicultural activities) and a set of accessories. The model utilizes the standard input data that have traditionally been using in forestry of the Russian Federation and available for virtually all Russian territory. An informational technology for forecasting data analysis and decision-making at forest management unit level was implemented by integrating a forest ecosystem model FORRUS-S with an interactive visualization and analysis of spatially and temporally referenced data system CommonGIS. The paper describes the results of computational experiments at different scenarios of forest management (natural development, legal forestry, and illegal forest practice) over 100 years. The paper discusses the results of an analysis of changes in forest biodiversity quantitatively estimated by monitoring a dynamics of various indicators using a sample forest stand located in the Moscow region (Central European Russia). Exploratory analysis of the simulation results demonstrated that (1) natural stand development is the best alternative for forest biodiversity; (2) legal forest management is the best regime for timber production; (3) illegal forest practices lead to a fast decrease in forest productivity and decreasing biodiversity. Interactive and dynamic visualizations with maps and statistical graphics played a crucial role in data cleaning, model validation, and analysis of simulation results. The case study demonstrated the potential of integrating forest ecosystem models with exploratory data visualization for the analysis and expert evaluation of forest biodiversity at the local level. This approach allows to bridge the gap between the researches done on developing the framework for measuring sustainability of forest management and a lack of similar efforts in monitoring and using these indicators as a formal part of the planning system.

Keywords: Simulation modeling, Multi-species uneven-aged stand, Forest biodiversity, Stand-level, Criteria and indicators, Silvicultural strategies, Geovisualization, Exploratory spatial data analysis

Resumo

O pacote do programa computacional FORRUS-S foi desenvolvido para modelagem da dinâmica do ecossistema de povoamentos florestais. FORRUS-S consiste em um modelo de desenvolvimento natural de um povoamento florestal misto e dissentâneo, um modelo de influências exógenas (incluindo tratos silviculturais) e uma série de acessórios. O modelo utiliza entrada de dados padrão que foram tradicionalmente adotados no manejo florestal da Federação Russa e disponível virtualmente para todo o território russo. Uma tecnologia informacional para análise de dados de predição e tomada de decisão no nível da unidade de manejo florestal foi implementada integrando o modelo de ecossistema florestal FORRUS-S com uma visualização interativa e análise referenciada espacial e temporalmente no sistema de dados CommonGIS. O artigo descreve o resultado de experimentos computacionais em diferentes cenários do manejo florestal (desenvolvimento natural, procedimentos legais de manejo florestal e práticas florestais ilegais) ao longo de 100 anos. Também são discutidos os resultados de uma análise de mudanças na biodiversidade florestal, estimada quantitativamente através do monitoramento da dinâmica de vários indicadores utilizando como amostra uma área florestal situada na região de Moscou (Rússia). Análise exploratória dos resultados da simulação demonstrou que: (1) o desenvolvimento natural do povoamento é a melhor alternativa para a biodiversidade florestal; (2) o manejo florestal legal é o melhor regime para a produção de madeira; (3) as práticas florestais ilegais levam a um rápido declínio da produtividade e da biodiversidade florestal. Visualizações interativas e dinâmicas com mapas e gráficos estatísticos tiveram papel crucial na eluci-

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dação dos dados, na validação do modelo e na análise dos resultados da simulação. O estudo de caso demonstrou o potencial de modelos que integram o ecossistema florestal com a visualização exploratória de dados para a análise e avaliação aprimorada da biodiversidade florestal no nível local. Este enfoque permite estabelecer uma ponte entre as pesquisas realizadas sobre o desenvolvimento de parâmetros para medir a sustentabilidade do manejo florestal e a falta de esforços semelhantes no monitoramento e na utilização desses indicadores como parte formal do sistema de planejamento.

Palavras-chave: Modelo de simulação, Povoamento dissentâneo, Biodiversidade, Planejamento estratégico, Manejo florestal, Rússia, Análise exploratória de dados

INTRODUCTION

Multiple criteria and indicators for sustainable forest management (C&I for SFM) have currently being developed. Documents of Montreal and Helsinki processes for development of C&I for SFM are actively created, conferences and seminars are organized, a number of research projects are running (FINLAND, 2004; MONTREAL PROCESS, 1995; ARICFR, 1998; BEAR, 1998; MONTREAL PROCESS, 2003; ARISMF, 2003). C&I for SFM should serve a number of purposes by providing (1) a set of key terms that can be used in future international discussions on forests; (2) a framework against which countries can evaluate their forest policies; (3) a mechanism for rationalizing and evaluating international aid and technical cooperation programs, and (4) a means of resolving difficulties in international discussions on trade in products from sustainable managed forest (BRAND, 1997). Development of national level criteria and indicators must be supplemented by their elaboration for use at smaller scale such as the forest management unit (FMU), forest district, nature reserves or national parks. Some indicators designed for use at national scale that may not be applicable at an FMU scale. These C&I are related to global carbon sink contribution, land-reservations for protected areas or sectoral socio-economic contributions of forestry, etc. The list of C&I should be extended taking into account the structure of information on forest resources available at local scale.

With development of computer techniques during the last decade mathematical modeling in ecology has substantially improved. Many forest ecosystem models have been developed (CHERTOV *et al.*, 1999); PORTÈ and BARTELINK, 2002) with description of peculiarities and advantages of simulation models. The possibility appeared of direct simulation computer modeling of complex spatial discrete ecosystems. Ecophysiological explanatory models can be realized at different levels of biological system organization, from computation of changes in parameters of individual trees up to forecasting of succession on some territory. Specific models and supporting those programming tools are needed for sustainable forest management. Models aimed to not only simulation of natural forest dynamics but also silvicultural measures should be able to take into account heterogeneity of the modeled space, e.g. different relief, ecological conditions of the stands, difference in the height of the adjacent stands, various configurations of cutover patches, etc.

Possibilities of widely used Gap-models to solve these tasks are limited by the concept of Gap-modeling itself: forest object is considered as an assemblage of independent gaps (BOTKIN, 1993; BOTKIN *et al.*, 1972; LEEMANS and PRENTICE, 1989; PACALA *et al.*, 1995; SHUGART, 1984; SHUGART, 1992; URBAN *et al.*, 1991). Gap-models ignore such processes as: (1) natural regeneration of species lacking in a given gap but present in the adjacent ones; (2) the influence of the adjacent gaps onto light conditions of trees; (3) heterogeneity of growing conditions. The alternative Grid-based approach to modeling allows to partly solving these tasks (BERGER and HILDENBRANDT, 2000). However, description of space in Gap-models and Grid-models does not allow taking into account light conditions in complex multi-storey unevenaged stands.

It was developed a three-dimensional (3-D) model that is intermediate between Gap- and Grid-modeling approaches and uses the technique of ecophysiological (explanatory) modeling. The modeling is based on repeated calculations of the current growth increment (by diameter and height) and thinning out in terms of 3-D crown structure. The calculations are performed for each cohort (a group of individuals of same species and age) in a multispecies unevenaged stand. Growth increment values are calculated based on the influence of the local light environment on a tree crown with implications for properties as degree of closeness, species interactions and availability of basic resources (soil water and nitrogen). A number of external modules simulating silvicultural measures can be enabled or disabled at any modeling step. Modeling area can be up to several thousands of hectares. Thereby FORRUS-S is able to serve as a tool for evaluation of C&I dynamics at different silvicultural strategies or as a system for forest decision-making.

The importance of geographical information systems (GIS) and remote sensing technology as a component of decision support system (DSSs) in forestry has been highlighted by Covington *et al.* (1988) and Arvanitis (2000). A combination of multi-criteria optimization with elements of spatial analysis is now being developed for ecologically based silviculture at the landscape level (DAVIS and MARTELL, 1993; KANGAS *et al.*, 2000). A formal optimization methodology for DSSs in SFM has been proposed (VARMA *et al.*, 2000). A significant contribution to contemporary stand- and landscape-based forestry design has been made in Canada (BOOTH *et al.*, 1993; ERDLE and SULLIVAN, 1998). Planning systems MONSU (PUKKALA, 1993) and ASIO (NAESSET, 1997) have been used in Scandinavia. These systems integrate multi-criteria optimization, GIS and illustrative data visualization. However, the role of modelling components in these systems is still negligible, and visualization is used typically only for illustration purposes, not for data analysis.

The role of visual representations for data analysis has been acknowledged for a very long time. However, only recently has information visualization and exploratory spatial data analysis (ESDA) emerged as a branch of scientific research based on interactive and dynamic graphics (CARD *et al.*, 1999). Computer graphics are now indispensable for supporting data analysis by high user interactivity, easy data transformation (calculations of changes, proportions, etc.), and modification of graphical representation (change of symbolism, setting scale, viewpoint, etc.). Multiple dynamically linked views of the same data are especially useful when changes in one display are immediately reflected on all others (ROBERTS, 1998).

The idea of ESDA and data visualization has recently spread from the realm of statistics to cartography (MacEACHREN, 1994; MacEACHREN and KRAAK, 1997). Cartographers have recognized the demand for new software allowing specialists in various disciplines (i.e. not only professional map designers) to generate maps and use them as tools facilitating 'visual thinking' about spatially referenced data. In order to play this role effectively, a map requires two principal additions: interaction and dynamics. Several research groups have developed novel interactive thematic mapping techniques and tools, e.g., CDV (DYKES, 1997), Descartes (ANDRIENKO and ANDRIENKO, 1999), and GeoVistaStudio (TAKATSUKA and GAHEGAN, 2002). Integrating geovisualization with data mining (HAN *et al.*, 1997; ANDRIENKO *et al.*, 2001b) provides further opportunities for discovering interesting patterns in large volumes of spatial and thematic information.

Unfortunately, standard GIS software does not effectively support interactivity and dynamics of screen maps. Few attempts have been made to design and implement highly interactive user-friendly GIS. In particular, ESRI's ArcGIS software includes an extension module for geostatistical analysis (KRIVORUCHKO and GOTWAY, 2002). However, interactive methods for ESDA are still rarely available to the general public in commercial software. Interactive visualization using the spatial analyst extension in ArcGIS is available only to users willing to purchase it separately. So far, ESDA has not been applied to decision-making in forestry. The first attempts to apply interactive visualization and ESDA to SFM problems appeared recently (PALENOVA *et al.*, 2004; CHERTOV *et al.*, 2002; KOMAROV *et al.*, 2002).

Development of local level C&I for SFM in the frame of modern information technologies such as mathematical modeling, GIS, DSSs, ESDA would allow their usage as a tool for effective long-term planning, selection and substantiation of strategies for SFM. The application of C&I for SFM is possible through using this new technologies. Such instrument is necessary since this is the level where real landowner is convinced to make decisions on 1) to take into account C&I for SFM while elaborating strategies of forest exploitation and 2) to experience the influence of different technologies of forest management onto state of forest ecosystems (not only productivity but also biodiversity and associated with it sustainability).

This paper describes the results of an analysis of changes in forest biodiversity quantitatively estimated by monitoring a dynamics of various indicators at different scenarios of forest management using a sample forest stand of FMU located in the Moscow region (Central European Russia).

METHODOLOGY

Simulation model FORRUS-S

FORRUS-S has been designed for simulation modeling of forest stands and analysis of the dynamic processes in forest ecosystems (CHUMACHENKO *et al.*, 2003; CHUMACHENKO *et al.*, 2000; CHUMACHENKO *et al.*, 1997; CHUMACHENKO, 1998; CHUMACHENKO, 1993; PALENOVA *et al.*, 2001). The model utilizes the forest inventory data available for virtually all Russian territory. FORRUS-S consists of models 'Natural Development', 'Exogenous Influence' (including silvicultural activities) and a service block comprising GIS and a set of accessory programs: reference databases, analytical modules for recoding and visualization of output information etc.

The model of natural development of multi-species unevenaged stand utilizes the principle of subdivision of the space into discrete three-dimensional elements. This approach makes it possible to consider the available photoactive radiation (PAR) in the zone of active growth in a tree crown, and also to take into account spatial heterogeneity of growth conditions such as relief and soil characteristics. Since within the zone of mixed coniferous–broad-leaved forests in European Russia the PAR is the main limiting factor, it is recalculated at each step. The model 'Natural Development' uses the technique of ecophysiological (explanatory) modeling and consists of 4 submodels: 'Light', 'Growth', 'Natural Thinning' and 'Natural Reproduction'. Correspondingly, the model performs simulation of substantial processes being carried out in forest: growth increment, endogenous thinning (mortality) and natural reproduction of a forest stand.

The modeling is based on repeated calculations of the current growth increment (by diameter and height) and thinning out in terms of 3D crown structure. The calculations are performed for each cohort (a group of individuals of same species and age) in a multi-species unevenaged stand. Growth increment values are calculated based on the influence of the local light environment on a tree crown with implications for properties as degree of closeness, species interactions and availability of basic resources (soil, water and nitrogen). Information on availability of resources is formed on the base of forest inventory data of the model object. Using the model dynamics of basic forest inventory parameters (height, diameter, age, forest stock etc.), and changes in species and age composition of the stand are forecasted. Growth increment, thinning and natural regeneration are modeled with the step equal to 5 years.

Model 'Exogenous Influence' supplements the computer program package FORRUS-S by the possibilities of solving various applied tasks, e.g., modeling of different variants of intermediate cutting, cleaning cutting, silvicultural activities, forest fires etc. This model consists of submodels 'Final Felling', 'Cleaning Cuttings' and 'Silvicultural Activities' that process output data from the model 'Natural Development'. All programming algorithms of these submodels are based on the regulations for silvicultural activities officially recommended for European part of the Russian Federation (EUROPEAN PART OF RUSSIAN FEDERATION, 1993a; EUROPEAN PART OF RUSSIAN FEDERATION, 1993b; EUROPEAN PART OF RUSSIAN FEDERATION, 1994). Model 'Exogenous Influence' can be enabled or disabled at any step of FORRUS-S operation.

A set of FORRUS-S tools was developed for analysis of various output databases and forecasted maps produced by means of GIS-technology and 3DVisualization System. For analysis of large data sets in FORRUS-S an analytical module was developed. It ensures processing of information from databases using specific algorithms and its visualisation by means of GIS and business graphics software. There is a possibility for using interactive parameters selection and visualisation modes. But it is necessary more powerful analytical system for the tasks, therefore it is loaded the simulation results into the CommonGIS system.

Recently developed 3DVisualization System supplements FORRUS analytical module. The system was designed as a tool of visual analysis of forest inventory data and evaluation of simulation experiments performed by FORRUS (CHUMACHENKO and ZOBKOV, 2003). 3DVisualization module creates 3D image of a selected sector of the modeling area. Forest stands are visualized taking into account individual characteristics of each tree. These characteristics are calculated based on forest inventory data and reference data bases of FORRUS. Tree images are placed on a 3D image of real area relief which is digitally modeled according to a topographical map. The visualization is performed based on forecast databases, so that the system allows step-by-step representation of forecasted change in the stand structure. Several visualization regimes implemented in 3DVisualization allow obtain a dynamically changing image. The first, 'realistic' regime represent 3D image of the whole visualized space viewed from an arbitrary point. Point of view can be freely raised up or lowered down, zoomed in and out, or rotated. The second, 'dissection' regime allows to get a 3D image of a narrow slice of any selected by user forest stand. This regime can be useful for more detailed visual analysis of horizontal and vertical structure of a stand. The third 'mapping' regime is useful for detailed analysis of spatial distribution of species, since it provides 2D sketch of crown projections. Visualization system is running on actual time scale and built using OpenGL.

CommonGIS

CommonGIS (ANDRIENKO and ANDRIENKO, 1999; ANDRIENKO and ANDRIENKO, 2003; ANDRIENKO *et al.*, 2003) is a system designed to support visualization and analysis of spatially and temporally referenced data. It combines traditional GIS services with two innovative features: (1) tools to interactively manipulate dynamically created thematic maps; and (2) tools for visual analysis of time-related data sets (georeferenced time-series data tables). CommonGIS is able to handle process and visualize complex multidimensional tables describing time-series of spatially referenced data using maps and statistical charts. It allows interactive manipulation of maps and graphics, and dynamic linking of complementary displays. The system is time-aware, and therefore supports dynamic data presentation with user-controlled animations (ANDRIENKO *et al.*, 2001a). CommonGIS also includes convenient tools for real-time calculation of derived attributes.

Figure 1 shows a screenshot of a data analysis session in the CommonGIS system. The user selects a single attribute (e.g., stand density) for analysis in three management scenarios (to be described later). The selected data is visualized using a panel that unites three linked unclassed choropleth maps with common attribute scales and legends, e.g. the coloring and attribute values are consistent across all the maps. Because data have a temporal dimension, two options are provided: (1) apply automatic or user-controlled animations (by selecting time points for visualization using video recorder-like controls) and (2) calculate derived attributes that reflect temporal sequences of values. For example, median values over a selected time period are shown in Figure 1.

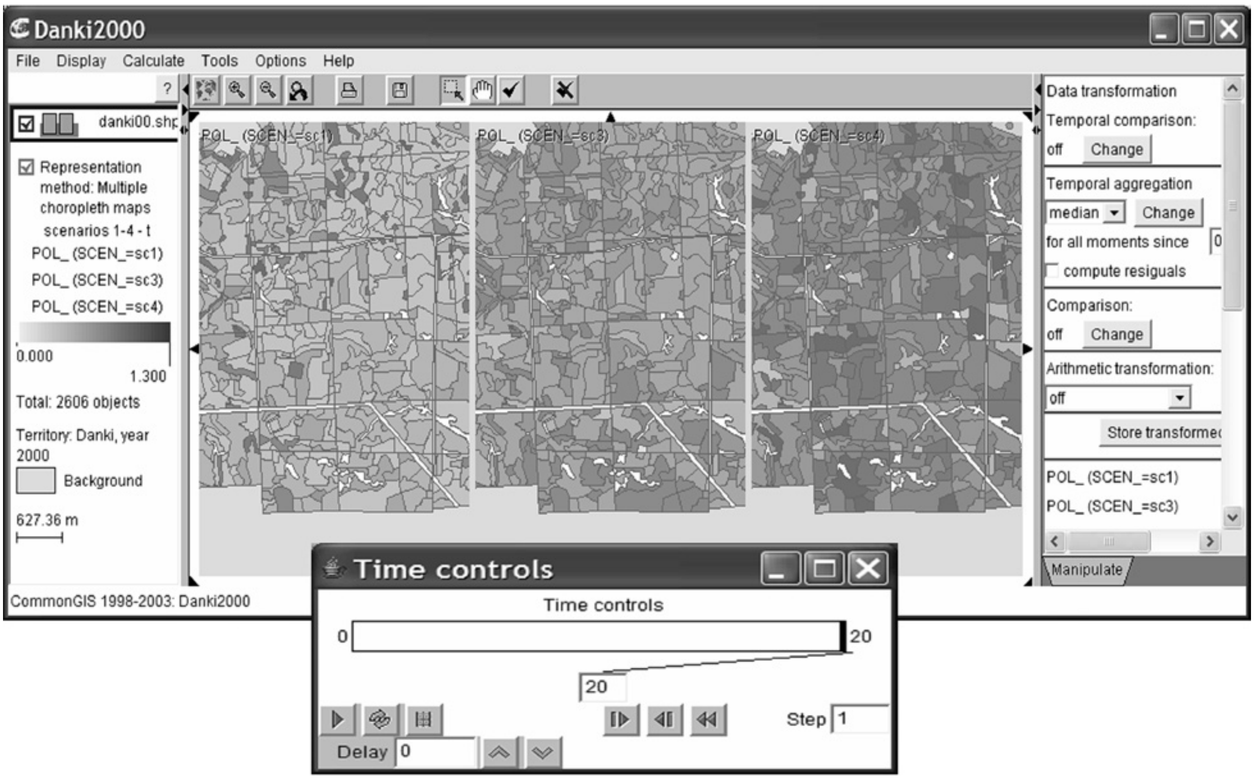


Figure 1. User interface of geovisualization in CommonGIS. The window includes maps of the selected attribute (forest density) for a given time point, legend (on the left) and data manipulation and transformation controls (on the right). Controls for selection of time points and animation are shown at the bottom of the map window. Modeling results after 20 modeling steps, fragments of forecasted maps of forest density in the stand for Dankovskii forest district at different modeling scenarios: (A) –'Legal practice', (B) – 'Illegal practice', (C) – 'Protective'.

The user selects this transformation using "Temporal aggregation" controls on the right panel. The map is immediately updated to show the transformed values. It is important that one can experiment with different data transformations without leaving the map display (e.g., smoothing over a time period, calculation of absolute or relative changes, comparison to reference objects or specific values, comparison to mean/median value, arithmetic transformations of attribute scale, etc.) Thus, it is possible to transform maps of attribute values to maps of changes of values over a time period (change maps) by a single mouse click. Data transformation can be combined with animation, e.g. it is possible to animate a map of changes, etc.

The CommonGIS system supports interactive analysis of spatial and temporal data using a variety of visualization. The system is implemented in Java and can be used as a stand-alone application or as an applet within Web browsers (http://www.ais.fraunhofer.de/and).

Case study area

The computer experiments were carried out using sample data of Experimental Forestry 'Russkii Les', located south of Moscow region in the coniferous – broad-leaved forest zone. The duration of vegetation period is 170-180 days, average precipitation 491 mm. Soils consist of sod-podsolic soils (93.7%), gray forest soils (3.4%), other are wetlands. Soil drainage is generally poor and well, soil texture is mostly loamy and sandy. The total area of the FMU is 69,200 ha, forested area is 63,800 ha. In average, the stand is composed of: 50% birch, *Betula pendula* Roth and *B. pubescens* Ehrh., 20% *Norway spruce*, *Picea abies* (L.) Karst, 10% Scots pine, *Pinus sylvestris* L., 7 % aspen, *Populus tremula* L. with small proportion of oak, *Quercus robur* L. and small-leaved lime, *Tilia cordata* Mill. Average age is 53 years, the stand density is high (0.73 in the Russian scale from 0 to 1.0) average stand quality index is 1.4, annual increment makes 4.0 m^3 per ha. The territory of 'Russkii Les' forestry has been subjected to severe anthropogenic impact (ploughing up, fires, repeated cutting). At present time, zonal type forests are absent from the area of the experimental forestry. The Dankovskii district of 'Russkii Les' forestry with area of 7351 ha was chosen as a modeling object. The standard input data (forest inventory descriptions of strata, forest stand maps) by a year of 2000 were used for modeling.

Simulation scenarios

The modeling was carried out at the following scenarios of forest management: A) 'Legal practice': complete cycles of all silvicultural measures according to the current regulations and specifications of Russian Forest Service, this scenario permits managed forests with thinning, a final clear cutting, and natural regeneration with planting; B) 'Illegal practice': forest management with infringement of the current specifications, heavy upper thinning and removing the best trees, clear cutting with destroying natural regeneration without planting; C) 'Protective': natural development with formation of unevenaged multi-species stands, this scenario prevents cutting in all forest compartments. The algorithm of cleaning cutting simulation was earlier described in more details (KOROTKOV *et al*. 2001). A 100-year period was selected (20 steps of modeling).

The scheme of analysis

At present, it was developed a number of algorithms to compute a set of indicators for evaluation of one of criteria for SFM – Criterion 1 "Conservation of biological diversity"' (MONTREAL PROCESS, 2003). Development of these algorithms assumed 1) specific output data format of the model; 2) criteria and approaches to evaluation of biodiversity, proposed by Russian forestry specialists, silviculturists, and geobotanists (ZAUGOLNOVA, 2000; SMIRNOVA, 2004; SMIRNOVA, 1994); 3) international C&I for SFM (BEAR, 1998; MONTREAL PROCESS, 2003; MINISTRY OF AGRICULTURE AND FORESTRY OF FINLAND, 1993). For evaluation and forecasting of biodiversity, it is suggest the following parameters of output database: number of tree species in different storeys of forest canopy, forest density, share of area occupied by individual tree species, by single- or multi-species forest strata (poor or mixed forest stands), by species with different life strategies, by tree species typical for different stages of succession, by stands with different age structure, by 1-2-3-storeyed stands.

As a state of forest ecosystems is described by multiple parameters and C&I will have to serve as instruments for assessment of quality of operational planning of silvicultural activity, and a tool for decision-making at FMU level, methods for obtaining an integration estimate must be developed. Studies of that kind are being conducted at regional level (MENDOZA and PRABHU, 2000; VARMA *et al*., 2000). As a suggestion using the computer package CommonGIS, an instrument for obtaining an integration forest biodiversity estimate and for interactive analysis of spatio-temporal data for this integration evaluation.

As mentioned above, input and output data of programme set FORRUS-S are forest inventory data. For description of the state of forest ecosystems it was engaged extensive datasets. For instance, the initial state of the modeling object having area 7351 ha is described by databases on 2262 forest strata (or forest compartment - the primary unit of forest inventory, planning and management in Russia) each characterized by 176 fields. Every step of simulation modeling provides forecasting database of the same size. The simulation results were loaded into the CommonGIS system. It is used a variety of visualization techniques including thematic maps (classed and unclassed choropleth maps, cross-classification maps, dominant attribute maps, and numerous diagram-based techniques) and statistical graphics displays (dot plots, histograms, cumulative frequency curves, scatter plots, parallel coordinate plots, table lens, and time graphs).

The comparative analysis of changes of forest biodiversity parameters is given according to different scenarios of modeling. The demonstration of the dynamics of some parameters is below. The pictures were prepared by means the CommonGIS and accessory programs of the FORRUS-S.

RESULTS

According to the purpose of this study were estimated ecosystem, structural and species diversity on a base of forest inventory and modeling data for a case study.

Species diversity

It was estimated species diversity of different storey for each forest stratum by number of tree species. This parameter may be represented, for example, as change of area occupied by multi-species (more than three species) forest stands. Dynamics of this parameter for 100 years, or 20 modeling steps, ahead at different scenarios are shown in Figure 2. The forecast demonstrated that forest tree species diversity is significantly higher in case of natural development. Illegal cutting leads to substantial decreasing of number of multi-species strata. Modeling of the full cycle of silvicultural activities as well causes depletion of multi-species strata.

Other mode to evaluate tree species diversity is possible through calculation of dominance level of single tree species in the forest stand. This parameter values vary between level 5 when a single species constitute up to 80-100% of total stock of the stratum, to level 1 when each of species of the stratum constitutes no more than 10% of the total growing stock. The forecast of dominance level of single species in the forest stand after 20 modeling steps is represented as a fragment of classed thematic choropleth maps of Dankovskii district (Figure

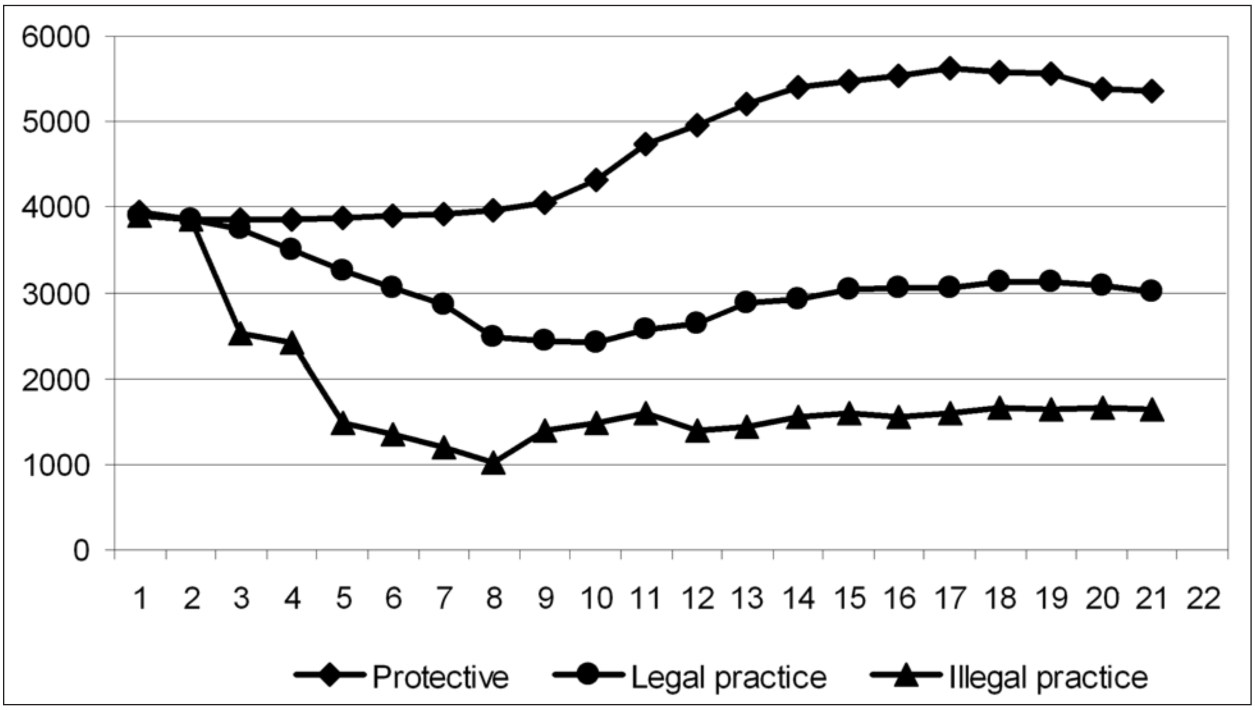


Figure 2. Dynamics of species diversity of overstorey by number of tree species for 100 y ahead (20 steps of modeling) at different scenarios of modeling. Y axis is area (ha) occupied by multi-species stands (more than 3 species).

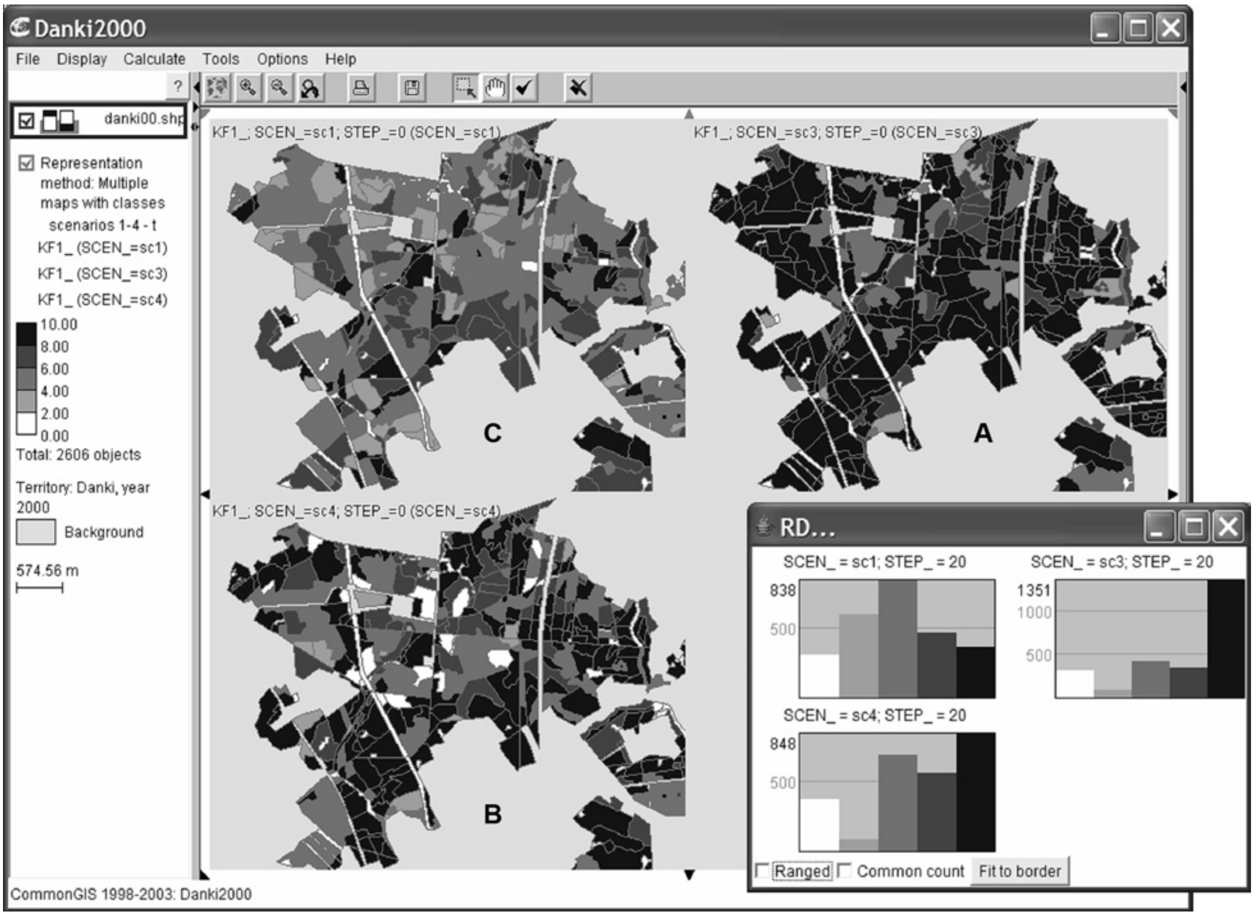


Figure 3. Fragments of classed thematic choropleth maps with modeling results after 20 modeling steps, the forecast of dominance level of single species (from low, represented by white to high – black) in the forest stand for Dankovskii district at different modeling scenarios: (A) –'Legal practice', (B) – 'Illegal practice', (C) – 'Protective'. In additional window class distribution by number of forest stratum in each class is presented for whole Dankovskii district territory.

3). Natural development leads to higher number of forest strata with mixed forest stand, whereas both legal and illegal practices lead to more strata with poor forest stand.

Structural diversity

Structural diversity of forest stands can be evaluated by several ways. One can calculate a share of area occupied by individual tree species, by poor or mixed forest stands, by species with different life strategies, by species typical for different succession stage, by stands with different age structure, by 1-2-3-storeyed stands.

For example, it was estimated structural diversity of overstorey by tree species dominants distributed with different life strategies (GRIME, 1979). Among forest trees *Quercus robur*, *Fraxinus excelsior*, *Picea abies*, *P. obovata* are competitive, *Acer platanoides* and *Tilia cordata* are tolerant, while *Betula pendula*, *B. pubescens*, *Populus tremula*, *Salix caprea*, *Ulmus glabra*, *U. laevis* represent a group of reactive species (SMIRNOVA, 1994). In climax communities, trees are represented by species of all three types of strategies. Species with competitive and tolerant strategies are predominant while the proportion of reactive species does not exceed 10-20%. (KEDDY and DRUMMOND, 1996; SMIRNOVA, 1994; WHITTAKER, 1975). Complete absence of species with reactive strategy, as well as significant increase of their rate indicates different variants of disturbed forest communities. Analysis of current state of Dankovski forest district has shown that at present forest cover is represented predominantly by reactive species such as birch, aspen, and pine, so that 72% of area is occupied by reactive species (Figure 4). This situation is evidently caused by strong anthropogenic impact (ploughing, fires, repeated cutting). A trend in dynamics of this parameter is adequately forecasted. When modeling natural development the dynamics of ratio among different types of strategies tend to approximate to values defined as characteristic for climax type of forest ecosystem. Modeling according to other scenarios leads to significantly different results. 'Ideal' forest management maintains low proportion of tolerant species while simulation of violations results in raising the rate of reactive species.

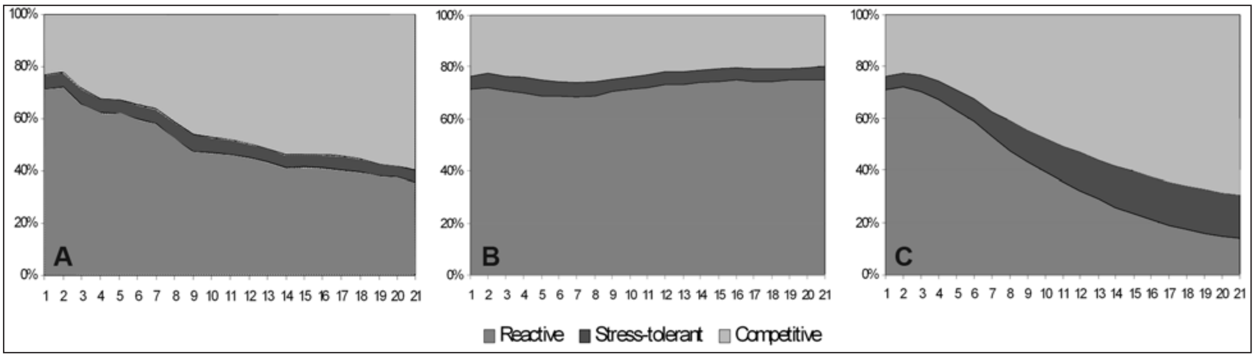


Figure 4. Dynamics of structural diversity of overstorey for 100 y ahead (20 steps of modeling) for Dankovskii district at different modeling scenarios: (A) –'Legal practice', (B) – 'Illegal practice', (C) – 'Protective'. Y axis represents proportion of area (%), occupied by tree species dominants with different life strategies.

A realistic pattern of change in structural diversity of forest stands can be monitored by FORRUS 3DVisualization System. A sample case of visualization of modeling results created by this instrument using 'dissection' mode is shown on Figure 5. The dynamics of storey structure is demonstrated for a birch stand with spruce understorey.

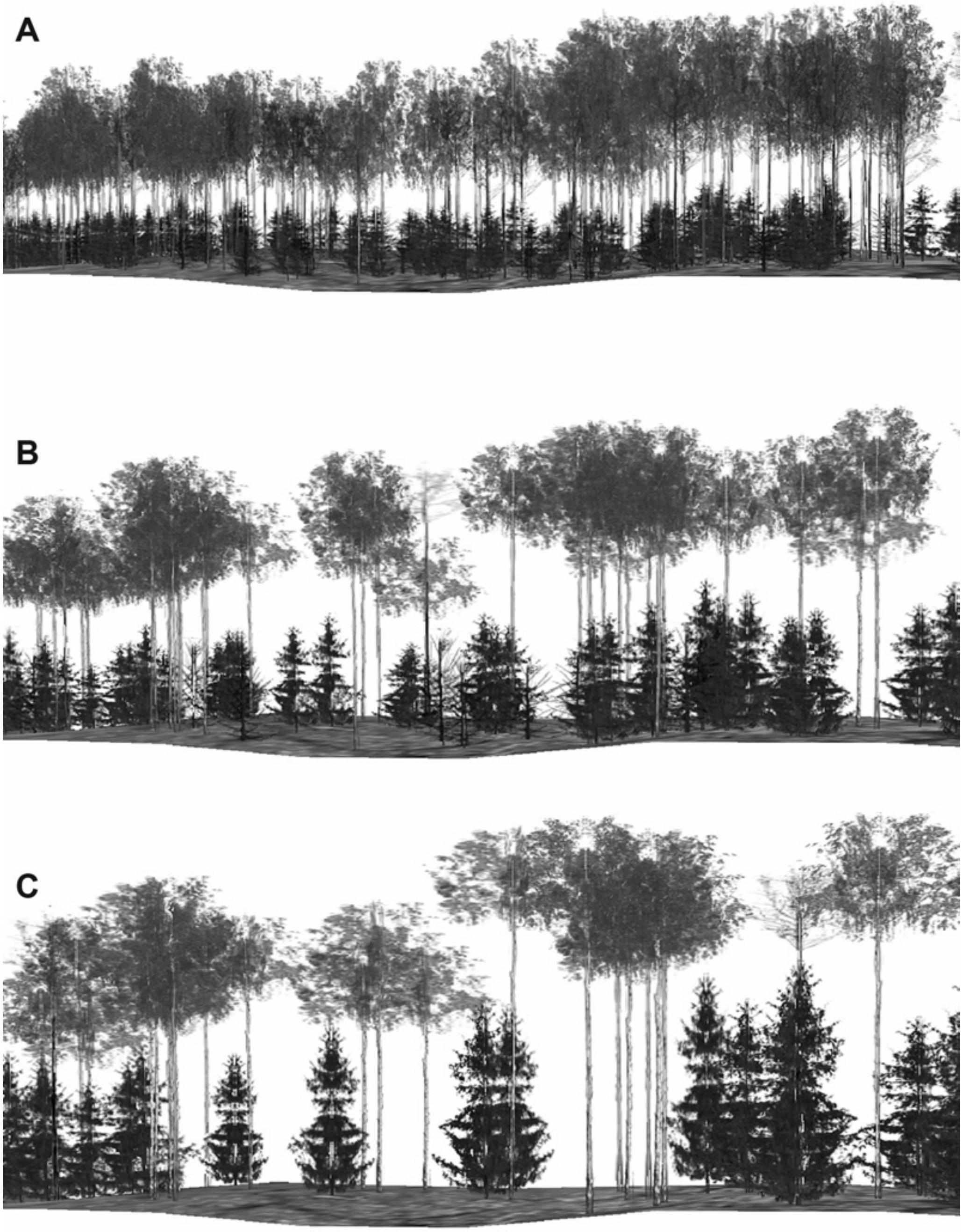


Figure 5. Representation of modeling results by means of FORRUS 3DVisualization System using 'dissection' mode, changes in a storey structure of a birch stand with spruce understorey: A – current state of tree stand, B – after 10 modeling steps, C – after 15 modeling steps.

Ecosystem diversity

The ecosystem diversity can take up as extent of area by forest type and by age class or succession stage (MONTREAL PROCESS, 2003). The ecosystem diversity of forest stand was estimated by dominant attribute maps (ANDRIENKO and ANDRIENKO, 2001) representing which species has the highest amount of growth stock for each forest stratum (not presented here). The forecasts of degree of maturity of predominant species are shown at Figure 6. The degree of maturity is calculated as ratio of age of predominant species to its cut age. Higher values of this measure are characteristic to more mature forest stands. The forecasting demonstrates that natural development leads to higher ecosystem diversity, i.e. to rising of proportion of older stands, while illegal practice results in areas occupied predominantly by young stands.

Integration estimate of forest biodiversity

First steps on the way of getting integration biodiversity estimate for individual forest stratum and for whole Dankovskii district territory have already been made, representing forecasting maps of integration biodiversity estimate for forest stratum of Dankovskii district at different scenarios of forest management. At present, the integration biodiversity estimate was obtained based on four parameters: number of tree species, complexity of storey structure, level of dominance of single species in the stand, and degree of maturity of predominant species. The results of the experiment (Figure 7) allowed obtaining a vivid map of biodiversity for the modeled territory. The obtained integral estimate is easy to understand, since CommonGIS has versatile modes of visual data analysis that allow presenting the same data set by various means in different program windows.

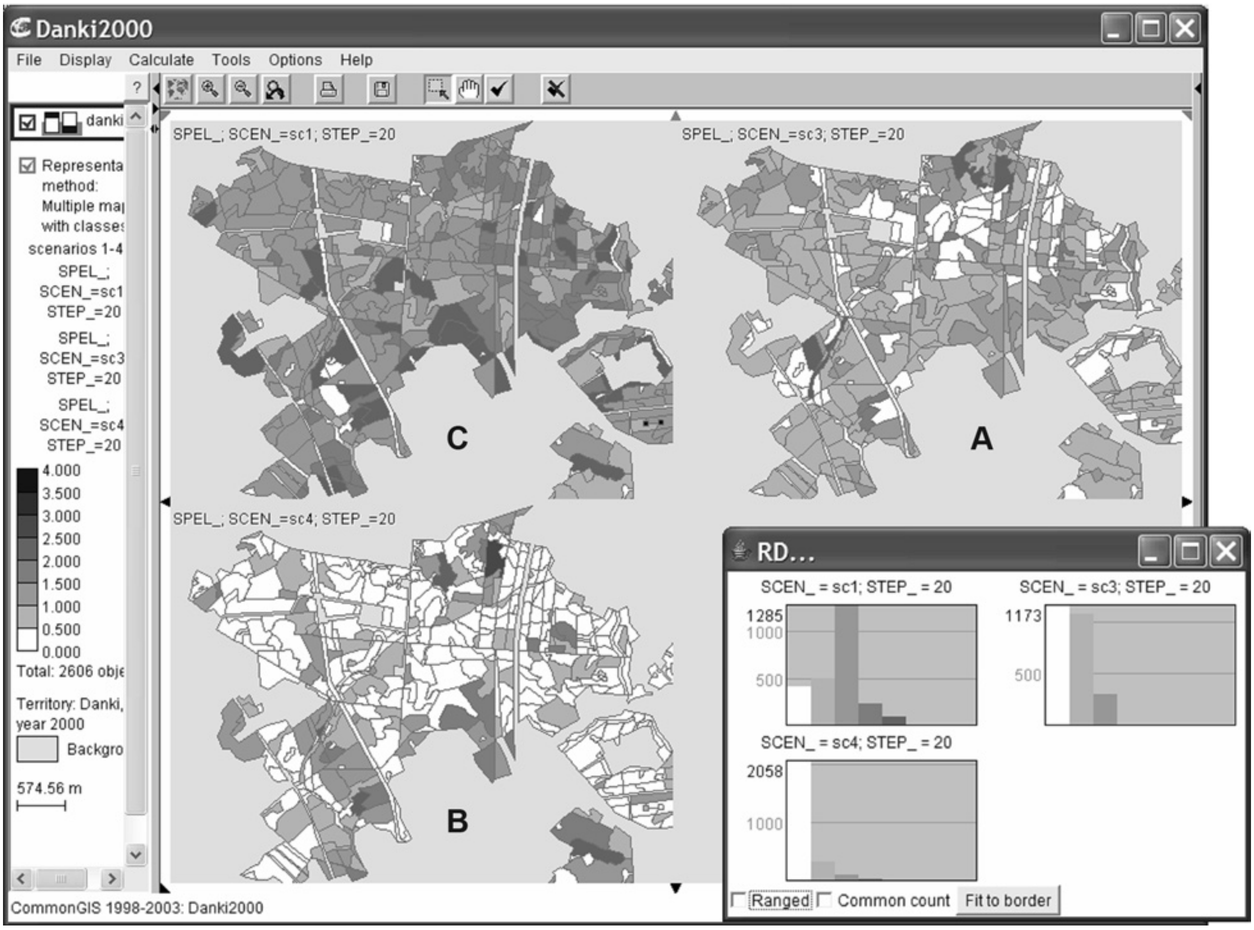
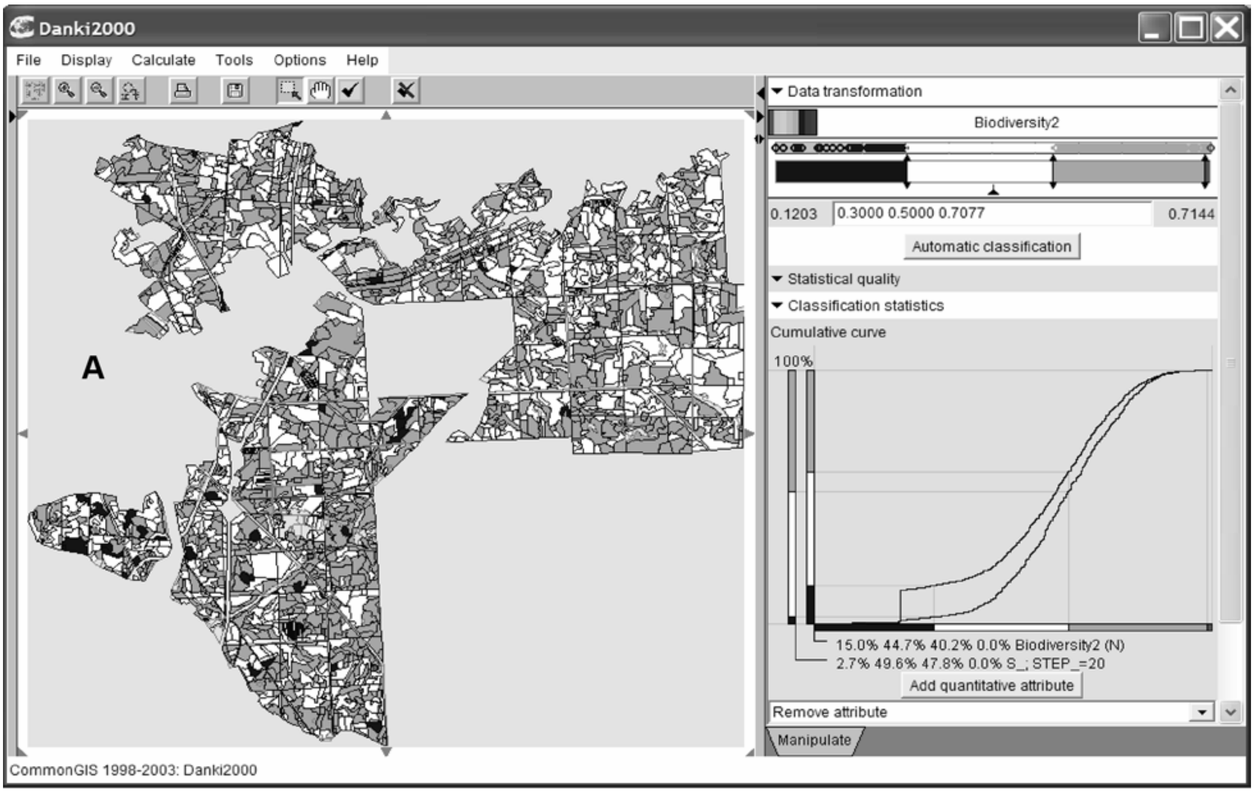


Figure 6. Fragments of classed thematic choropleth maps with modeling results after 20 modeling steps, the forecast of degree of maturity of predominant species in the forest stand for Dankovskii district at different modeling scenarios (after 20-th step): (A) –'Legal practice', (B) – 'Illegal practice', (C) – 'Protective'. The degree of maturity of predominant species is calculated as ratio of age of predominant species to its cut age: higher values (black filling of the map polygons) correspond to higher degree of maturity of predominant species of forest stand. In additional window class distribution by number of forest stratum in each class is presented for whole Dankovskii district territory.



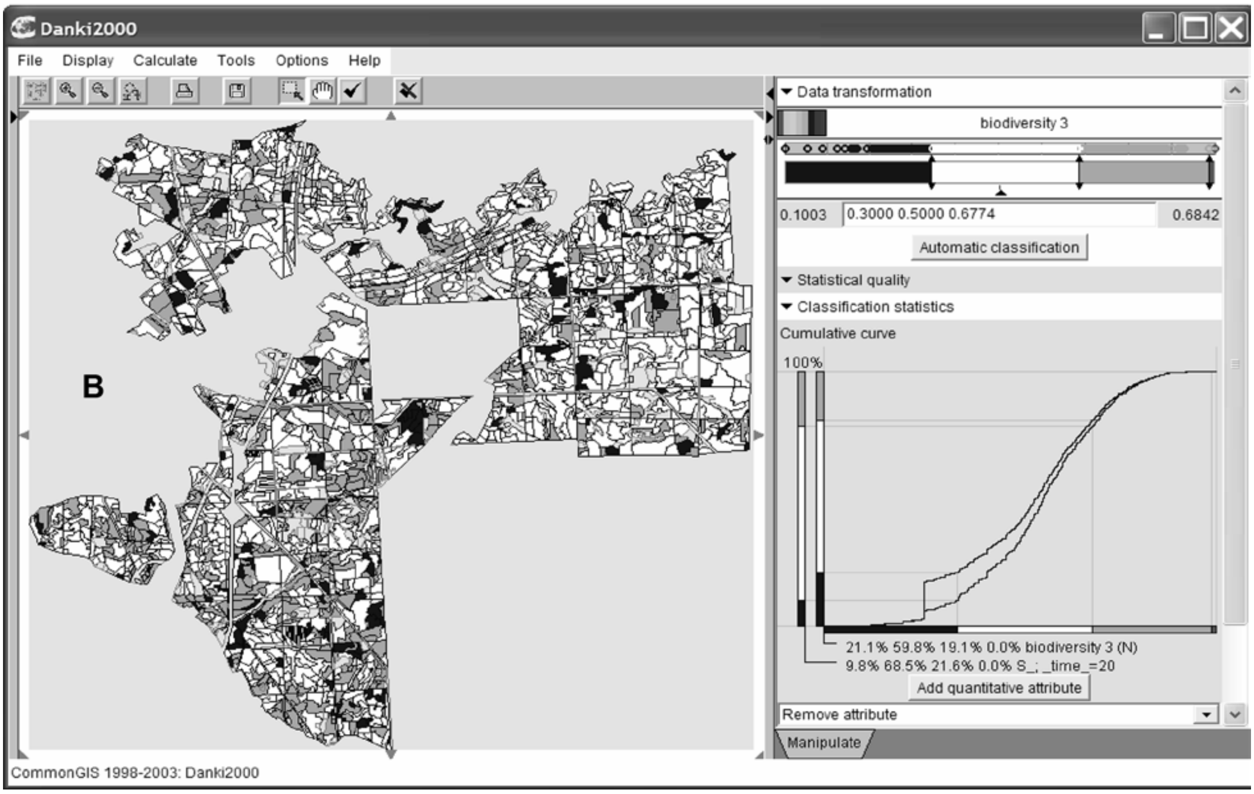


Figure 7. Modeling results: CommonGIS representation of forecasted maps for integration biodiversity estimate for individual forest strata in 100 years at different scenarios: (A) –'Legal practice', (B) – 'Illegal practice'. Higher values (grey filling of the map polygons) corresponds to higher biodiversity of forest stand. Cumulative curve in a legend window shows rate of number of strata (Biodiversity2) and proportion of area (S_) occupied by strata with different biodiversity level.

DISCUSSION

Species richness estimations calculated on the base of forest inventory data corresponded quite well with the estimations calculated earlier on the base of vegetation sample plots data (ZAUGOLNOVA, 2000). Modeling demonstrated that under natural development regime species richness of the territory is maintained at high level. Under legal forest management practice species richness can be even higher due to introduction and preservation of light-requiring species on spots subjected to cutting. Illegal cutting leads to substantial decreasing of number of multi-species strata; instead, single species strata comprised by pioneering species as birch and aspen are spreading. Tree species richness is a simple but important parameter of biodiversity estimation, since in general, in forest stands rich in tree species the highest richness in other groups of species (birds, insects, fungi etc.) is also observed (ZAUGOLNOVA, 2000). Calculation of a dominance level of single tree species in the forest stand has shown that at 20th step of modeling proportion of strata where one species is dominated by growing stock at legal practice regime is even higher than under illegal practice (Figure 3). However, species composition of these mono-dominant stands was different: in the first case they are represented predominantly by valuable species (Norway spruce, Scots pine, pedunculate oak while in the second case by much less valuable birch and aspen.

Natural development leads to more diverse ecosystem diversity of the forest stand (Figure 6): stands of different age classes are represented, and higher area is occupied by mature and over-mature forests. Aiming to research dynamics of biodiversity values, was analyzed the changing of forest types for different forest management strategies. Modeling demonstrated (not shown in the figures) that natural development leads to decreasing of proportion of light-requiring pioneer species and forest type with these species. They are being substituted by shade-tolerant final-successional species such as spruce and lime. As a result, after 20 steps of modeling forest turns to coniferous – broad-lived type that corresponds to zonal-type forests. The results of modeling of natural development (Figure 8) are supported by observations of stand development in Prioksko-Terrace Natural Reserve neighboring the Dankovskii district (ZAUGOLNOVA, 2000)

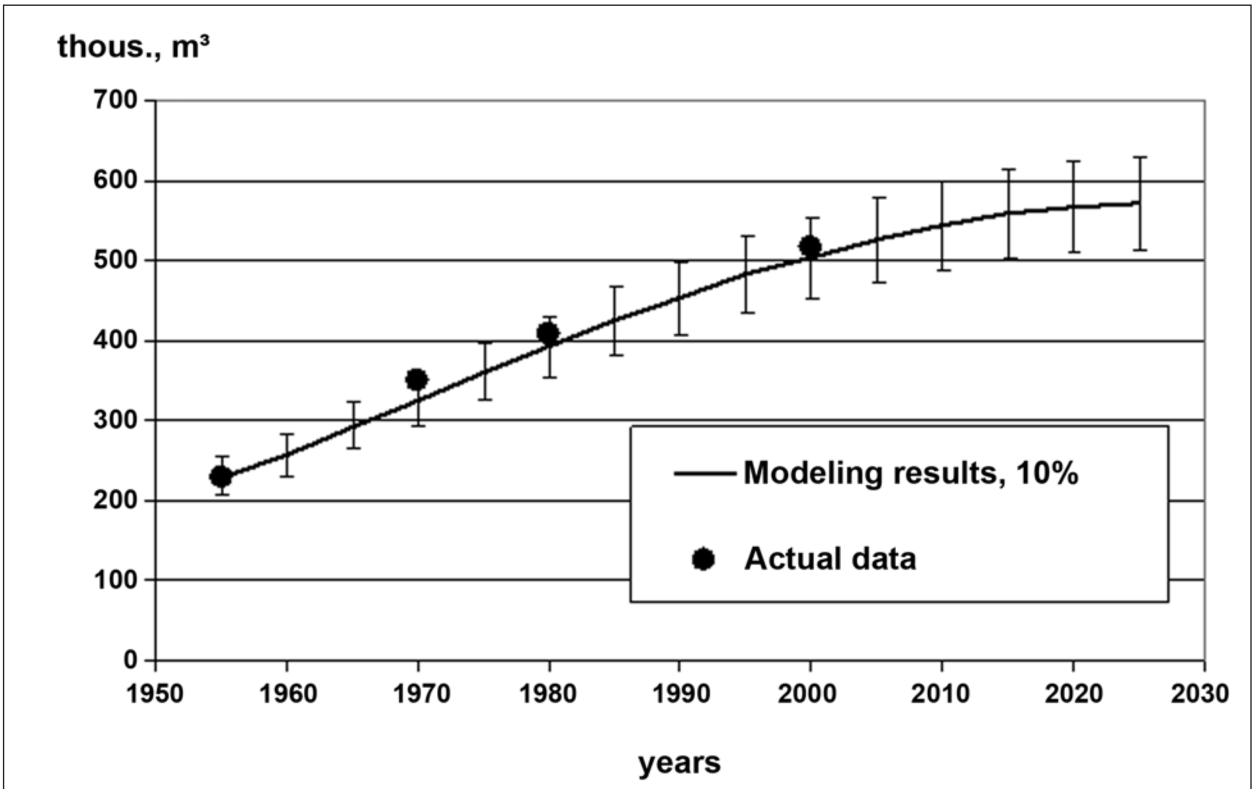


Figure 8. Comparison of modelling results and actual data from stands of Prioksko-Terrace Natural Reserve: dynamics of growing stock volume for pine stands.

At the scenario A, the complete cycle of silvicultural measures and orientation of forest management to conifer species results in more rapid reducing of proportion of birch and aspen forest. Percentage of pine also comes down as a result of cutting of mature forest stands, and due to week ability of pine to naturally reproduce in the cutover patches (reforestation measures were not simulated at this scenario). The effect of cleaning cutting could explain for drastic, as compared to the first scenario, raise of area occupied by spruce, corresponding decline of predominantly broad-leaved stands and very low rate of stands with predominance of underwood in the cutover patches. The percentage of oak forests is significantly higher than under natural development.

Forecasting at the scenario B assuming predominant elimination of economically valuable species and absolute absence of cleaning cutting in young stands leads to drastically different results. The high percentage of area occupied by small-leaved species remains intact. Later on, there occurs increase of area with predominance of small-leaved trees and shrubs, especially hazel. Predominantly broad-leaved stands are formed by sprouting and represent forests of little economic value. Thus, forest management coupled with infringement of federal regulations results in expansion of inferior stands, i.e. to gradual depletion of forest resources.

Analysis of the simulation results for the 100 years period in the three scenarios demonstrated that not all parameters selected for biodiversity evaluation reach highest values while modeling is performed under 'Protective' scenario. For integral estimate were chosen measures having different dynamics for the whole territory. Forecasted maps for integration biodiversity estimate after 20-th modeling step showed significant difference between states of modeled territory at various scenarios of forest management. Overall area of strata with high integral estimate is higher under legal practice as compared to illegal practice: 47.8% and 21.6%, respectively (Figure 7). Analysis of modeling results has shown that model adequately responds to different forestry regimes. These results can be easily interpreted in terms of population biology and ecology of forest tree species.

Exploratory analysis of the simulation results demonstrated that: 1) legal forest management does not lead to catastrophic decrease of forest biodiversity; 2) illegal forest practices leads to decreasing biodiversity; 3) legal forest management and natural stand development are the best alternative for forest biodiversity.

Selection of indices for C&I at stand level is a dynamic process depending on particular task. It cannot be standardized and formalized. Input and output databases of forest ecosystem models contain extensive information on forest ecosystem dynamics at local scale. These massive data sets as well as a necessity of getting multivariate integration estimates make a high demands to analytical tools. These instruments must be able to explore the dynamics of both quantitative and qualitative parameters, perform their spatio-temporal analysis and finally provide and visualize integral estimates. Consequently, sustainable forest management requires new tools to analyze spatial and temporal forest dynamics and to examine those forest parameters that are related to sustainability. The integrate forest modeling with ESDA are most useful for these tasks. There is a good reason to think that this technology will develop as an effective tool for the demonstration of the ecological and silvicultural consequences of various silvicultural systems to stakeholders and different social groups. The integrated system creates possibilities to explore new silvicultural approaches that can be elaborated for the practical realization of SFM at local level.

CONCLUSION

This paper suggests combining development of C&I and their introduction into forestry practice with development of forecasting simulation modeling technology and analytical tools. The results from the study indicate that these techniques are effective tools both for selecting sets of C&I and eventually for prioritizing them. Simulation modeling methods are highly transparent, easy to understand, and offer a convenient environment for participatory decision making. These are desirable features of any evaluation process but especially for a complex assessment problem such as forest sustainability.

This study demonstrated the potential of combining simulation modeling at the FMU level with exploratory visual analysis of simulation results in spatial and temporal dimensions. Interactive visualization helps experts to interpret simulation results and to formulate possible managerial decisions. Effective graphical representation of simulation parameters at various silvicultural scenarios allows easy verification of model and source data, and supports extraction of knowledge about forest dynamics from the simulation results.

Analysis of modeling results has shown that the model adequately responds to simulation of different forestry regimes. The strategy of natural development is the best alternative from the viewpoint of most, but not all parameters of forest biodiversity. Legal forest management practice is the best regime to satisfy timber production and, to some parameters of forest biodiversity. The illegal practice leads to a fast decrease in productivity and most of biodiversity parameters.

These results demonstrated that based on the data of forecasting modeling it is possible to make a sound evaluation of biodiversity at FMU level, select and substantiate necessary and sufficient number of biodiversity indicators for forest ecosystems, and provide an integration estimate of biodiversity level and other criteria of sustainable forest development at different scenarios of management. All this makes the integrate forest modeling with ESDA an effective instrument which to undertake a pilot effort between policy makers, scientists and managers to develop a prototype evaluation C&I for SFM at the FMU level. This instrument will be very useful in consecutive realization of an adaptive management approach that leads to multi-stakeholder decision-making, in which different interests and agencies work together to achieve sustainable forest management. FORRUS attempts to bridge the gap between considerable research work done on developing the framework for measuring sustainability of forest management and a lack of similar efforts in monitoring and using these indicators as a formal part of the planning system.

ACKNOWLEDGEMENTS

This study was supported in part by EU INTAS Project 01-0633 SILVICS and Russian Academy of Sciences research programs 'Dynamics of Gene Pools' and 'Management of Biological Resources' .

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Recebido em 15/11/2005
Aceito para publicação em 08/03/2007