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Geovisualization of forest simulation modelling results: A case study of carbon sequestration and biodiversity

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Abstract

Sustainable forest management requires new tools to analyze spatial and temporal forest dynamics and to examine those forest parameters that are related to sustainability. We built a prototype system for data analysis and decision-making at forest enterprise level by integrating a forest ecosystem model EFIMOD-PRO (long-term prediction of forest growth and soil development) with an interactive visualization system CommonGIS for analysis of spatially and temporally related data. Using the prototype, a case study in Central European Russia simulated four silvicultural regimes over 200 years: natural development, selective forestry, legal forestry according to the Russian forestry legislation, and illegal forest practice. Exploratory analysis of the simulation results demonstrated that (1) natural stand development is the best alternative for carbon sequestration; (2) legal forest management is the best regime for timber production; (3) selective forestry combines the advantages of two previous strategies, and can be the best strategy for implementing sustainable forest management; and (4) 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

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forest ecosystem models with exploratory data visualization for the analysis and expert evaluation at the local level. The prototype can be used to present ecological and silvicultural consequences of various management practices to stakeholders and differing social groups, thus stimulating effective decision-making for sustainable forestry.

Keywords: Simulation modelling; Silvicultural strategies; Geovisualization; Exploratory spatial data analysis

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1. Introduction

The new paradigm of sustainable forest management (SFM) requires effective predictions of tree growth and dynamic ecological characteristics. There are two principal criteria for sustainable forest management that are new to forestry: biodiversity and carbon balance (Helsinki Process, 1995; Montreal Process, 1995). The biodiversity criterion emphasizes protecting the diversity of living organisms in the forest. The carbon balance criterion addresses the problem of climate change and the role that forest ecosystems play in sequestering carbon in forest biomass and soil.

During the past three decades many forest ecosystem models have been developed (see, for example, review by Chertov et al. (1999a)). The current models mostly operate with small forest patches corresponding to the level of a forest stand. Modelling has been used to analyze the impacts of different harvesting systems, forest disturbances, natural development of forests, climate change and carbon balance. Forest ecosystem modelling can effectively extend traditional growth functions and tables to predict forest growth and soil nutrient cycling in changing environments and new silvicultural regimes (Andersson et al., 2000; Kellomäki, 2000).

The forest ecosystem modelling is usually applied to decision-making in forestry on the level of a single forest plot. One example of a system for forest decision-making based on single stand ecosystem modelling is FORCYTE (Kimmins, 1995). In Russia, Chumachenko et al. (2001) used silvicultural tree growth model for large territories (the ensemble of stands: forestry unit or landscape) for the evaluation of different silvicultural strategies. The landscape level decision support was considered in the study of a specific problem of forest boundaries detection (Scillag et al., 2001). Etienne (2003) proposed a decision support approach for forest management in mountain regions.

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 on 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 (see GeoMiner: Han et al., 1997; Descartes & Kepler: 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 geo-statistical 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 (Chertov et al., 2002; Komarov et al., 2002). These studies demonstrated the potential of combining simulation modelling at the forest management unit 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 presentation of simulation parameters in various silvicultural scenarios allows easy verification of model and source data, and supports extraction of knowledge about forest dynamics from the simulation results.

In this paper we show how uniting forest ecosystem simulation with ESDA (Chertov et al., 2002) can be valuable for analyzing various silvicultural strategies. The goal of this study is to investigate possible practical implementation of sustainable forest management concepts in Eastern Europe. We analyzed three criteria of SFM: carbon sequestration in forest ecosystems, forest productivity, and biodiversity. We also examined representing simulation results in a form that could facilitate participatory decision-making at the forest unit level (forest territory or enterprise, landscape) by forest environmentalists and forest managers.

2. Materials and methods

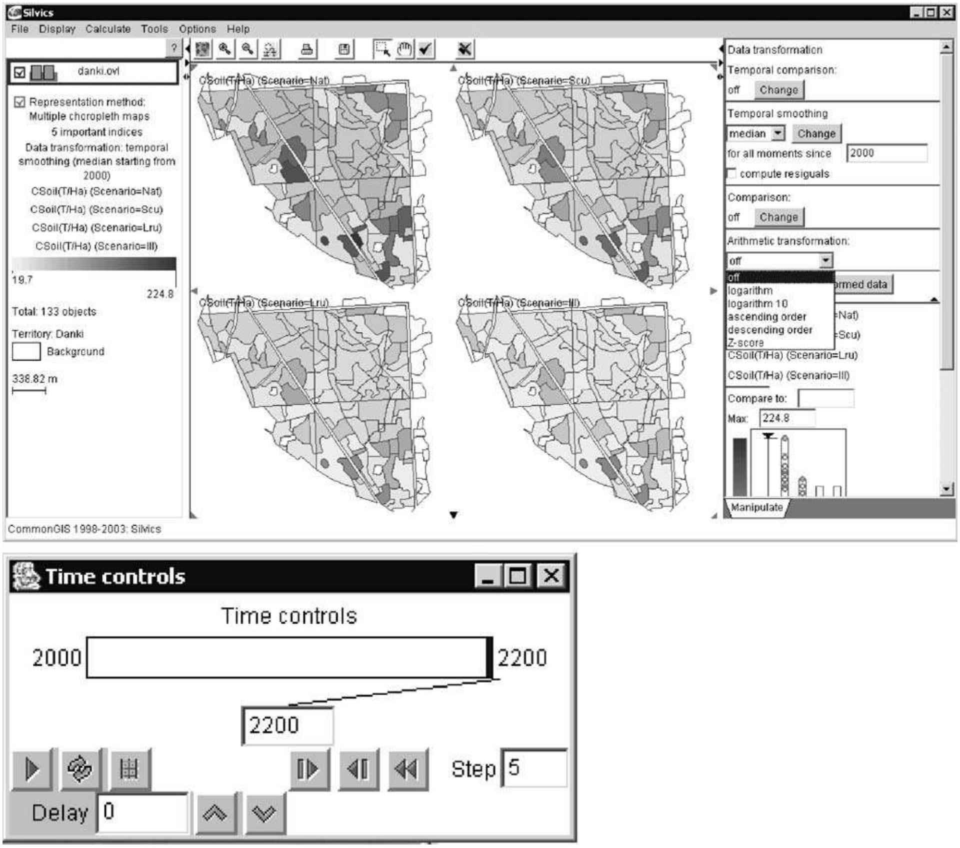
2.1. Simulation model EFIMOD PRO

The EFIMOD 2 model (Chertov et al., 1999b; Komarov et al., 2003) was developed for describing tree (stand) growth and biological turnover of carbon and nitrogen in boreal and temperate forest ecosystems. It is a spatially explicit stand-level simulator. The soil sub-model simulates organic carbon dynamics and nitrogen availability by tracking the main components of carbon and nitrogen budgets in forest ecosystems. EFIMOD 2 performs short- and long-term simulations of natural and managed forest ecosystem dynamics over a wide range of forest sites, climatic conditions and silvicultural regimes. It calculates dendrometric parameters for every tree, total growing stock, and carbon pools of tree biomass of a stand, coarse woody debris and soil organic matter. EFIMOD 2 was used to develop EFIMOD PRO for long-term simulations of a large set of individual stands comprising a forest enterprise or landscape. The EFIMOD PRO version of the model has additional modules for compiling cutting regimes, simulating a large number of forest stands in a forest management unit, and processing output data.

2.2. CommonGIS

CommonGIS (Andrienko and Andrienko, 1999; 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 (geo-referenced 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.

Fig. 1 shows a screenshot of a data analysis session in the CommonGIS system. The user selects a single attribute (e.g., accumulation of soil carbon) for analysis in four management scenarios (to be described later). The selected data is visualized using a panel that unites four 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 Fig. 1. The user selects this transformation using “Temporal aggregation” controls in 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 ob-



☑ Representation method:
Multiple choropleth maps
5 important indices
Data transformation: temporal smoothing (median starting from 2000)
CSoil(T/Ha) (Scenario=Nat)
CSoil(T/Ha) (Scenario=Scu)
CSoil(T/Ha) (Scenario=Lru)
CSoil(T/Ha) (Scenario=III)
19.7
224.8
Total: 133 objects
Territory: Danki
Background
338.82 m

Data transformation
Temporal comparison: off
Temporal smoothing: median
for all moments since 2000
☐ compute residuals
Comparison: off
Arithmetic transformation: off
Compare to:
Max: 224.8

Time controls
2000 2200
2200
Step 5
Delay 0

Fig. 1. User interface of geovisualization in CommonGIS. The window includes maps of the selected attribute for a given time point (shown in the center), legend (on the left) and data manipulation and transformation controls (on the right). Controls for selection of time points and animation are shown below the map window.

jects 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 techniques including thematic maps (classed and unclassed choropleth maps, cross-classification 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 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).

2.3. *Case study area*

The forest enterprise selected for modelling is located 100 km south of Moscow on the Central East European Plain. It possesses a continental climate and contains both coniferous and broad-leaved forests. The State Forest "Russky Les" occupies the left bank the Oka River with sandy and loamy sod-podzolic soils (Alfisols). The territory's forests were intensively exploited since the 17th century, especially in the 20th century. Secondary forests are now widespread in the "Russky Les". Silver birch (*Betula pendula* L.), Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. Karst.) mixed stands dominate the forests and are accompanied by broad-leaved species (oak, lime, ash, and maples). Young stands (<40 years of age) occupy 12% of the enterprise area, mean-aged stands (40–60 years) occupy 53%, and pre-mature stands (60–80 years) cover 35%. Generally, the forests have high density and productivity.

2.4. *Simulation scenarios*

Four management blocks in the "Russky Les" state forest were selected for the case study. They contain 104 forest compartments (stands) comprising 300 ha. The selected forest is typical among forest enterprises with regard to stand composition, forest age, and soils. Current inventory data were used as initial input parameters for the simulations:

- compartment area (ha),
- forest site type,
- soil climate scenario identification number (different for dry, mesic and wet sites),
- soil organic matter (SOM) pools in organic layer and mineral topsoil (kg m^{-2}),
- nitrogen of SOM in the same horizons (kg m^{-2}),
- mean stand height (m) and mean stand diameter (cm) and their standard deviations,
- number of trees per ha (for every tree cohort, classified by species and age class).

Four simulation scenarios were compiled as alternative options for sustainable forest management:

1. *Natural development* (Nat). This scenario prevents cutting in all forest compartments.
2. *Russian legal system* (LRU). This scenario permits managed forests with four thinnings (at 5, 10, 25, and 50 years), a final clear cutting (90-year age for conifer and oak, 60-year age for birch and lime), and natural regeneration by the target species with a mixture of deciduous species. In these forests, clear cutting must be followed by obligatory forest regeneration, either natural undergrowth or forest planting.
3. *Selective cutting system* (SCU). This scenario creates a managed forest with two thinnings in young and mean-aged stands, and then selective cuttings after the stand reaches the age of 80 years (each 30 years in uneven-aged stands, intensity is 30% of basal area from above).
4. *Illegal practice* (ILL). This represents heavy upper thinning and removing of the best trees, and clear cutting without careful natural regeneration, often dominated by deciduous stands.

All residues after the final harvest (leaves and branches) in LRU and ILL scenarios are removed (burning on clear-cut area). This treatment follows the Russian legislation, but causes a loss of carbon and nitrogen from the forest ecosystem.

These scenarios reflect existing and theoretically possible silvicultural regimes in the simulated forest. A 200-year period was selected because it is a period when so-called ‘managed’ even-aged forests will be fully transformed into ‘close-to-natural’ uneven-aged forests in the Nat scenario (Razumovsky, 1981).

2.5. The general scheme of analysis

Because EFIMOD PRO is a spatially explicit model of carbon and nitrogen balance, we have selected for analysis three main criteria for SFM (carbon balance, wood productivity, biodiversity) and the set of model output parameters listed below. During the analysis we have taken into account that carbon sequestration is reflected in the parameters of carbon pools and accumulation in stands and soil. We evaluated forest productivity using the data on biomass at the end of simulation (Figs. 2 and 3) and on the pools of harvested wood (not shown in the figures). Biodiversity was assessed from stand composition (proportion of deciduous species and mixed stands in the territory), proportion of old-growth forests, and amount of dead wood in the forest.

The simulation results were loaded into the CommonGIS system. The resulting table includes the following attributes for each of the four scenarios, 104 forest stands, and 41 time points within the 5-year time step:

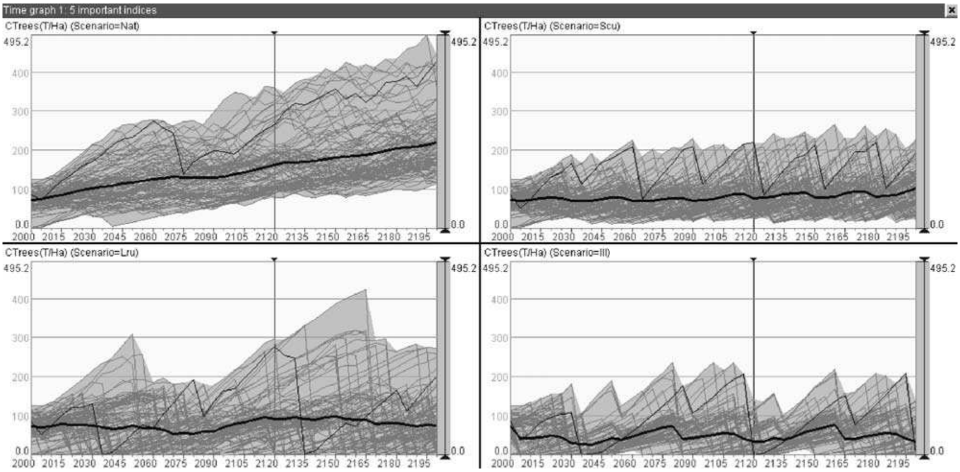


Fig. 2. Time graphs represent profiles of time series for each forest compartment in four management scenarios. Thick black lines in each graph show median time-series. For better comparison, the four graphs share a common scale. This feature can be switched off for detailed consideration of separate graphs. Time graphs are dynamically linked with maps: pointing to any forest compartment on the map results in highlighting of corresponding lines on all graphs, and vice versa (note thin black line that corresponds to one of the forest compartments that was selected on the map). This feature allows easy identification of outliers, comparison of time series for selected forest compartments, and general characterization and comparison of scenarios.

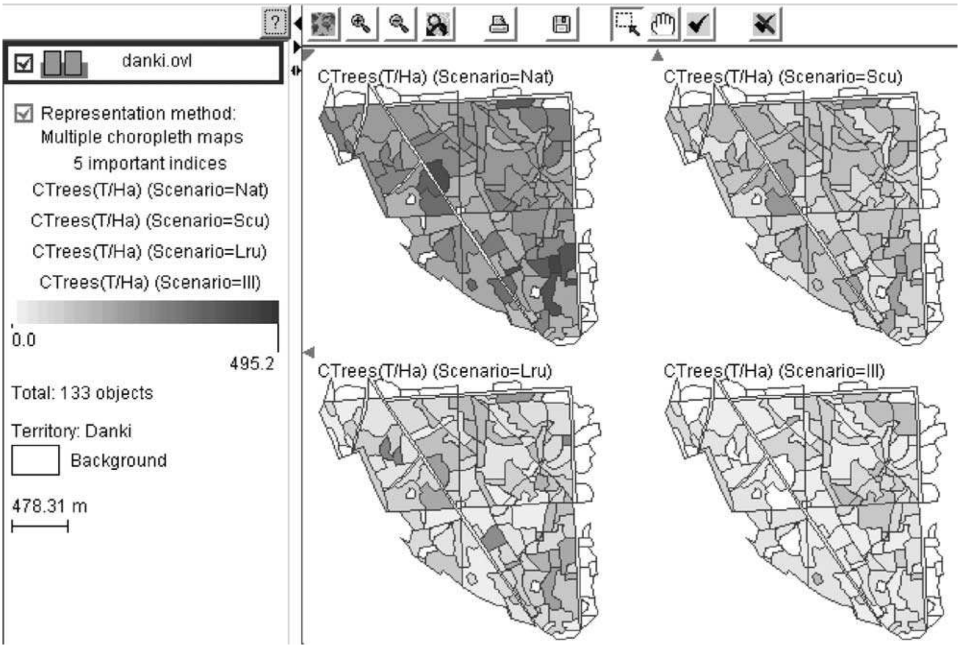


Fig. 3. Accumulated biomass carbon in the stands in different scenarios at the last time step of simulation (t/ha).

- stand biomass carbon and nitrogen;
- biomass and nitrogen of tree components and stand composition by forest elements (tree cohort of one species having the same age and position in the tree canopy);
- SOM carbon and nitrogen;
- SOM and nitrogen of different soil horizons;
- carbon dioxide emission from the soil;
- soil available nitrogen.

For the analysis of biodiversity similar tables have been produced with two additional dimensions: species (6) and age groups (13).

Graphs representing time series for every forest compartment have been combined with interactive maps representing different attributes, their combinations, and aggregated values:

(1) choropleth maps representing values of a given attribute for selected scenarios and points in time;
(2) change maps that are automatically calculated for pairs of time points selected by a user;
(3) dominant attribute maps (Andrienko and Andrienko, 2001) representing which species has the biggest amount of carbon for each forest compartment;
(4) automated and/or user-controlled animation of maps of the above mentioned types;
(5) maps with diagrams representing change dynamics of an attribute for each forest compartment.

Graphical presentation of time series using temporal curves (Fig. 2) was used as a powerful instrument for data cleaning and validation, and for model verification. Dynamic maps and tools for aggregating and transforming attribute values helped uncover interesting patterns in the simulation results. A variety of visualization techniques used in our study allowed looking at data from different viewpoints, thus helping to reveal mistakes in data, bugs in software, and unexpected behaviors. The authors played the role of experts and decision makers in the study.

3. Results

3.1. Carbon pools

The naturally developing forest has the highest pools of tree carbon within the simulated forest (Figs. 2 and 3). The maximal carbon accumulation under the protective regime occurred in the period between 100 and 150 years and is approximately two times higher than at 200 years. This can be explained by a steady increase of stand biomass in dense, even-aged old-growth stands (actually still 'managed'), but later these stands start their transformation to uneven stands with a loss of accumulated biomass. The lowest values of stand carbon were observed in the illegal regime of forest management.

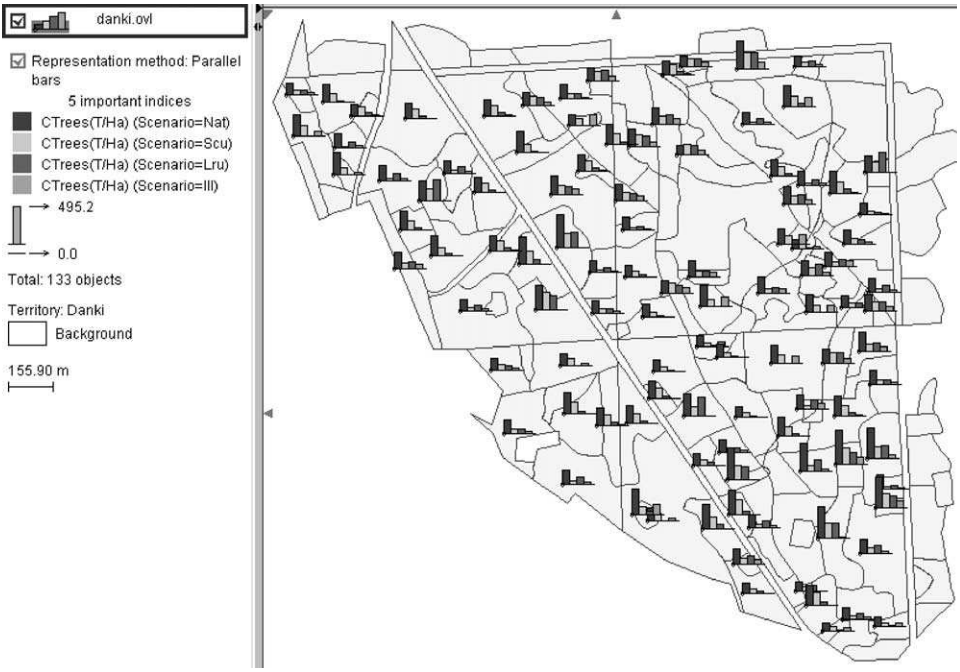


Fig. 4. Stand carbon in different scenarios at the end of simulation.

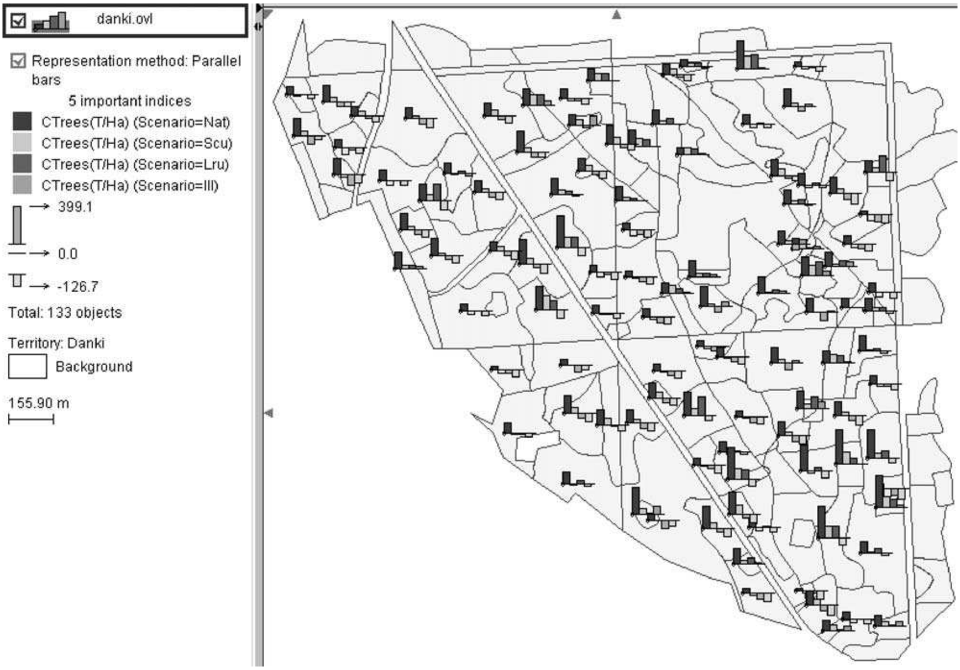


Fig. 5. Difference between final and initial stand carbon in the four scenarios. This map was automatically produced from the map shown in Fig. 4 when the user transformed attribute values for the 200th year of simulation to differences between values for 200th and 0th years.

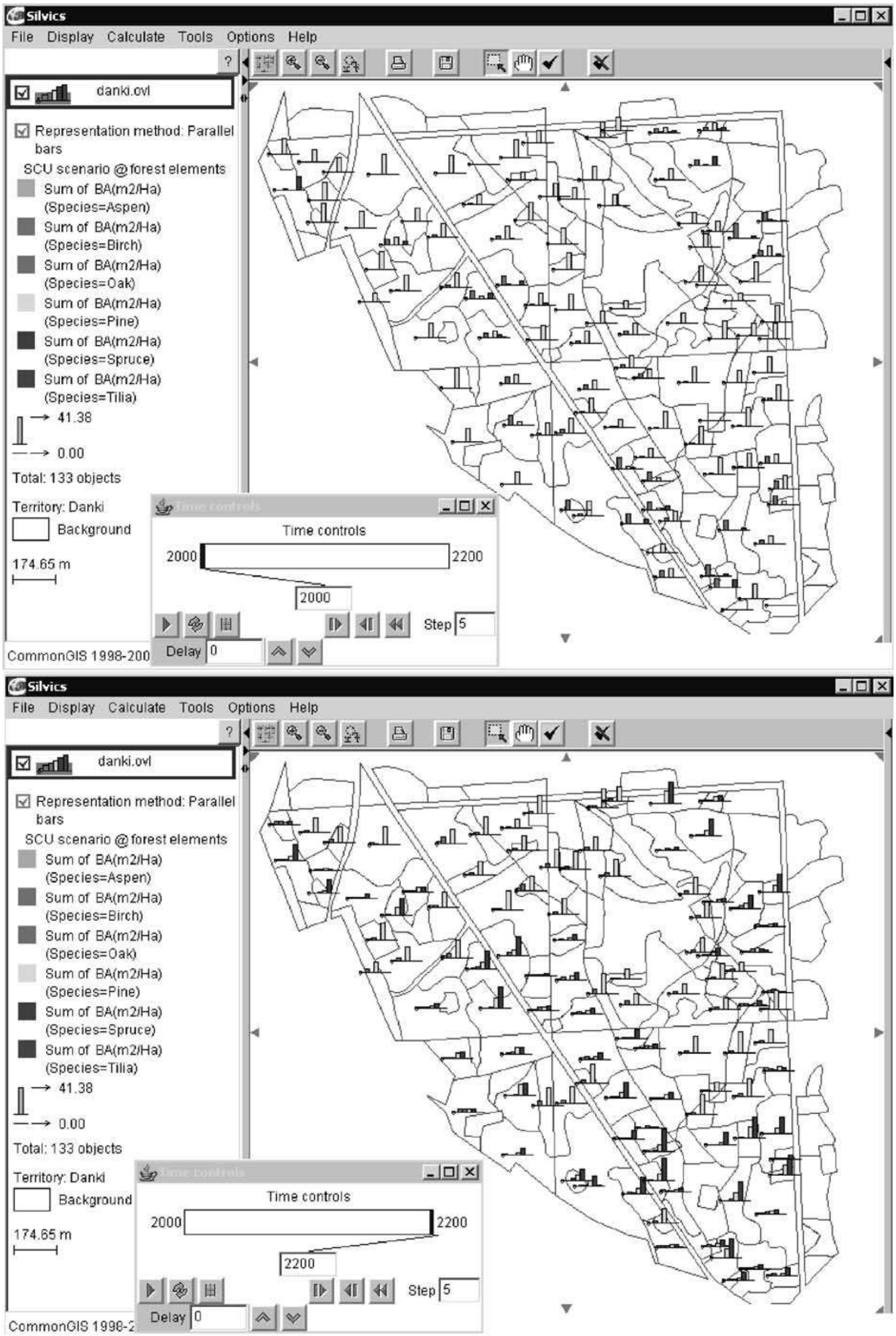
Values for tree carbon at the end of the simulation for the four scenarios are shown in Fig. 4. Fig. 5 displays the tree carbon change over the 200-year simulation. Significant differences for forest stands arise due to different soils and different types of cuttings. It is clearly seen that natural development and selective cutting strategies have advantage in comparison with standard cuttings, which are wide-spread in Russia. The soil carbon pool (see Fig. 1) also increases under the protective regime without cutting and in the selective cutting scenario.

3.2. *Wood production*

Selective forestry and Russian legal forestry demonstrated the highest wood production. Additionally, both regular management regimes (LRU and SCU) produced similar amounts of used wood. Illegal forestry practice (ILL) exhibited high wood production during the first 20 years of simulation, then harvested wood volume remains permanently low, and total wood production over the 200 years is the lowest among the three scenarios.

3.3. *Spatial mosaic of stands and stand composition*

Spatial mosaics of forest and stand composition are different for the different scenarios. The legal Russian clear-cut system (LRU), with successive natural regeneration of conifer-



danki.ovl

☑ Representation method: Parallel bars

SCU scenario @ forest elements

▨ Sum of BA(m2/Ha) (Species=Aspen)

▨ Sum of BA(m2/Ha) (Species=Birch)

▨ Sum of BA(m2/Ha) (Species=Oak)

▨ Sum of BA(m2/Ha) (Species=Pine)

▨ Sum of BA(m2/Ha) (Species=Spruce)

▨ Sum of BA(m2/Ha) (Species=Tilia)

→ 41.38

→ 0.00

Total: 133 objects

Territory: Danki

☐ Background

174.65 m

Time controls: 2000 – 2200; 2000; Step 5; Delay 0

danki.ovl

☑ Representation method: Parallel bars

SCU scenario @ forest elements

▨ Sum of BA(m2/Ha) (Species=Aspen)

▨ Sum of BA(m2/Ha) (Species=Birch)

▨ Sum of BA(m2/Ha) (Species=Oak)

▨ Sum of BA(m2/Ha) (Species=Pine)

▨ Sum of BA(m2/Ha) (Species=Spruce)

▨ Sum of BA(m2/Ha) (Species=Tilia)

→ 41.38

→ 0.00

Total: 133 objects

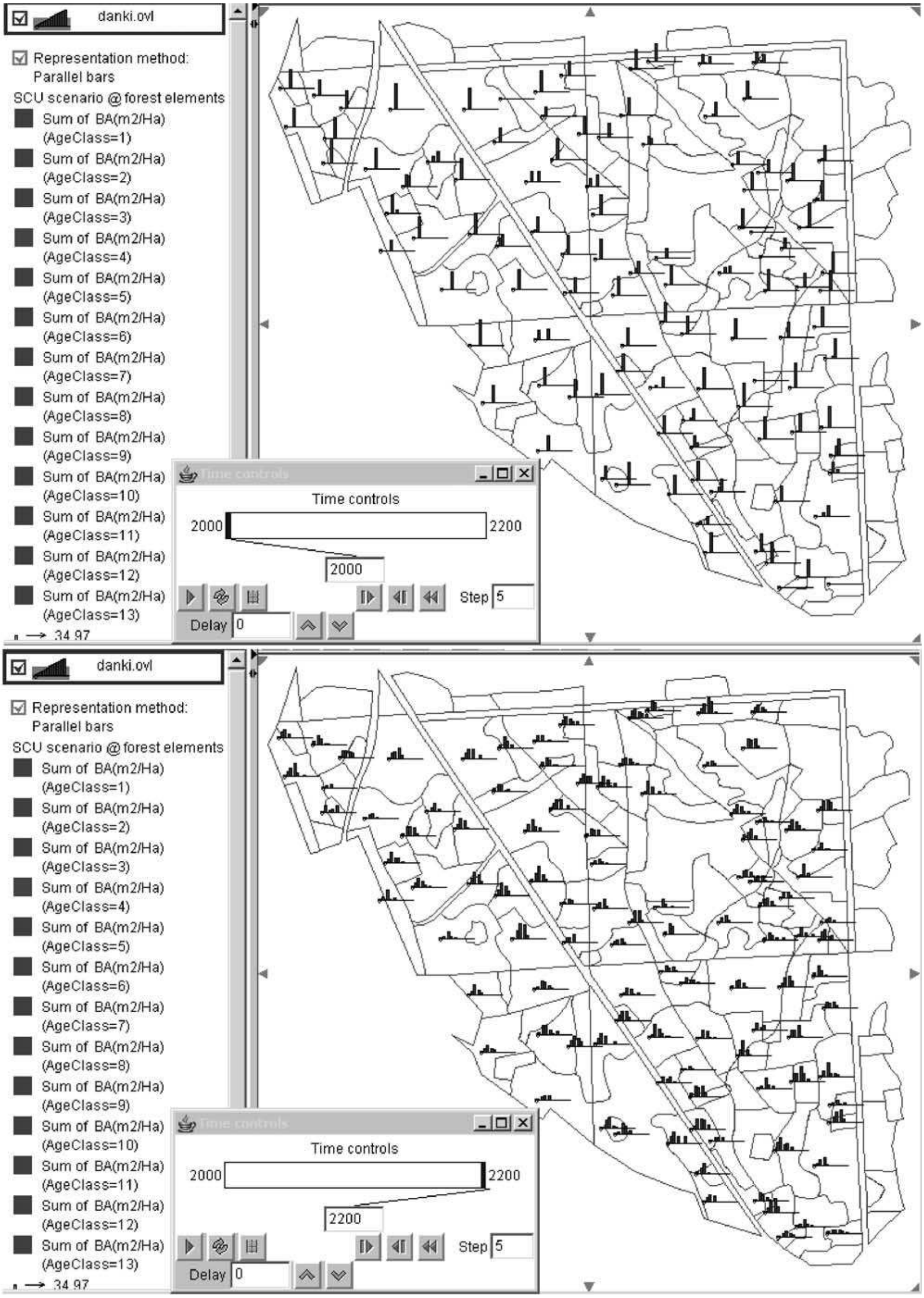
Territory: Danki

☐ Background

174.65 m

Time controls: 2000 – 2200; 2200; Step 5; Delay 0

Fig. 6. Basal area (m^2/ha) accumulated for all species at the beginning and at the end of simulation in SCU scenario.



☑ danki.ovl

☑ Representation method:
Parallel bars

SCU scenario @ forest elements

■ Sum of BA(m2/Ha) (AgeClass=1)
■ Sum of BA(m2/Ha) (AgeClass=2)
■ Sum of BA(m2/Ha) (AgeClass=3)
■ Sum of BA(m2/Ha) (AgeClass=4)
■ Sum of BA(m2/Ha) (AgeClass=5)
■ Sum of BA(m2/Ha) (AgeClass=6)
■ Sum of BA(m2/Ha) (AgeClass=7)
■ Sum of BA(m2/Ha) (AgeClass=8)
■ Sum of BA(m2/Ha) (AgeClass=9)
■ Sum of BA(m2/Ha) (AgeClass=10)
■ Sum of BA(m2/Ha) (AgeClass=11)
■ Sum of BA(m2/Ha) (AgeClass=12)
■ Sum of BA(m2/Ha) (AgeClass=13)

→ 34.97

Time controls

2000 – 2200: 2000

Step: 5

Delay: 0

☑ danki.ovl

☑ Representation method:
Parallel bars

SCU scenario @ forest elements

■ Sum of BA(m2/Ha) (AgeClass=1)
■ Sum of BA(m2/Ha) (AgeClass=2)
■ Sum of BA(m2/Ha) (AgeClass=3)
■ Sum of BA(m2/Ha) (AgeClass=4)
■ Sum of BA(m2/Ha) (AgeClass=5)
■ Sum of BA(m2/Ha) (AgeClass=6)
■ Sum of BA(m2/Ha) (AgeClass=7)
■ Sum of BA(m2/Ha) (AgeClass=8)
■ Sum of BA(m2/Ha) (AgeClass=9)
■ Sum of BA(m2/Ha) (AgeClass=10)
■ Sum of BA(m2/Ha) (AgeClass=11)
■ Sum of BA(m2/Ha) (AgeClass=12)
■ Sum of BA(m2/Ha) (AgeClass=13)

→ 34.97

Time controls

2000 – 2200: 2200

Step: 5

Delay: 0

Fig. 7. Basal area (m^2/ha) accumulated for all age groups at the beginning and at the end of simulation in SCU scenario.

ous and broad-leaved species, and selective forestry (SCU) resulted in complicated spatial mosaics of stands of different ages and various species compositions. Clear-cut systems (LRU and ILL) resulted in the relative dominance of 'pure' stands of different ages. Both the protective regime (Nat) and selective forestry (SCU) have a larger proportion of mixed stands in comparison with the two clear-cut regimes.

For this part of the study the dominant map technique (Andrienko and Andrienko, 2001) was used. In general, this method paints the map's forest compartments in colors corresponding to species and age groups that have maximum values for the analyzed attribute. The method takes into account several threshold values for indicating presence of different species, and for detecting mixed stands. Detailed discussion of the method is out of the scope of this paper.

Map animations suggested that spatial patterns of stand composition and age change little over the simulation period. The protective regime (Nat) demonstrated relatively uniform stand composition. Whereas, the area becomes covered by mixed forests in LRU and SCU scenarios. Illegal forestry practice resulted in the dominance of birch forests with a large proportion of clear-cut areas. These observations are illustrated in the maps of Figs. 6 and 7 shows species composition at the beginning and at the end of the simulation in the SCU scenario; Fig. 7 demonstrates changes in age structure.

3.4. Dead wood pool

Data for the dead wood pool (not represented in the figures) shows that the coarse woody debris proportion consistently increases in the protective scenario (Nat). This occurs because forests transform to uneven-aged stands with high tree mortality. In mean-aged stands under the protective forestry regime, dead wood is not greater than for the clear-cut system. Some small increase in the pool of dead wood can be seen in the selective system (SCU) because natural dieback and cutting residues stay in the forest. In both clear-cut systems (LRU and ILL), the dead wood pool is rather low due to minimal natural dieback in the thinned forest and removal (burning) of cutting debris. The protective scenario and selective forest regime demonstrated higher values for their dead wood pool in comparison to both clear-cut systems.

4. Discussion and conclusion

Analysis of the simulation results for the 200 years period in the four scenarios demonstrated similar patterns of carbon sequestration as described in earlier publications (Chertov et al., 2002; Komarov et al., 2002). There is a clear advantage for the selective cutting and natural development regimes (SCU and Nat) over clear-cut systems (LRU and ILL), both in relation to stand biomass and SOM. The reduction of stand biomass in the protective scenario (Nat) at the end of the simulation corresponds to the observed and theoretically justified picture of transition from 'managed' even-aged stands to uneven-aged forests (Frelich and Lorimer, 1991; Shugart et al., 1992; Smirnova, 1994). The consistent increases in SOM pools for the Nat and SCU scenarios reflects the process of soil restoration; it is known that forest soils in the area were degraded due to irregular clear-cuts during the 17th to

20th centuries. We can conclude that the Russian legal practice (LRU) and selective regime (SCU) demonstrate significant advantages over the illegal practice for wood production.

Analyzing spatial patterns of stand composition and age show that the clear-cut system results in the formation of a complex spatial mosaic of stands with different stages of post-cutting secondary succession. This mosaic increases biodiversity because the biota and vegetation diversity of the early and late stages of secondary succession are rather different (Razumovsky, 1981; Smirnova, 1994). Even so-called ‘natural untouched’ forests have a visible proportion of secondary forests resulting from natural disturbances (Shugart et al., 1992). This phenomenon contradicts predominating public opinion about the totally negative environmental consequences of any clear-cutting regimes.

Dead wood is an important indicator of forest biodiversity, as it provides habitat for numerous decomposing biota. Measures of dead wood provide a relative evaluation of biodiversity for mosaics of numerous stands (Komarov et al., 2002). Again, Nat and SCU scenarios exhibit significant pools of dead wood as a result of natural mortality. Both clear-cut systems, with wood extraction at thinnings and final harvest, generate negligible masses of dead wood in the forest.

The simulated scenarios do not allow direct evaluation of the proportion of old growth forests in the clear-cut systems. Ninety-year rotation periods for coniferous and broad-leaved forests are not sufficient for forming true old growth forests. This proportion is really high in Nat and SCU scenarios only.

Consistent increases in soil carbon pools under the protective regime without cutting and under the scenario with the selective cutting system (SCU) also indicate increasing forest biodiversity. Higher forest soil productivity is consistent with a higher number of plant species. A comprehensive analysis of biodiversity issues in a simulated forest can be found in Khanina et al. (2003).

We found that the strategy of natural development is the best alternative from the viewpoint of carbon sequestration. Russian legal forest management is the best regime to satisfy timber production and, to some extent, forest biodiversity. Selective forestry unifies the advantages of the Nat and LRU strategies, and can be the best strategy for the implementation of SFM. The illegal practice leads to a fast decrease in productivity and biodiversity with domination of deciduous forests, and with no sequestration of soil carbon. This latter forest management alternative has an advantage for harvested wood only at the very beginning.

However, selective forestry was used in Russian forests in the 20th century only in some exceptional cases. These results provide a basis for the conclusion that the Russian legal forest regime is close to SFM. However, it does not meet the criterion of carbon sequestration, because the legal practice of burning cutting residues results in a loss of organic carbon and nitrogen from forest ecosystems.

The case study demonstrated the potential of integrating forest ecosystem models with exploratory data visualization for the analysis of long-term simulation results and expert evaluation at the local level. Interactive methods of ESDA supported data cleaning, verification and tuning of the simulation models and their parameters. We expect that this integration can be used 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 or regional level.

The paper presents our first attempt to integrate forest modelling with ESDA for a forest enterprise in Central Russia. Many new directions for this work have arisen while analyzing the results for this case study. We continue the work with the goal to develop software tools that support the full cycle of simulation, analysis, and decision-making, which includes the following stages:

1. Formulation of management strategies.
2. Simulation of forest dynamics for each of the selected scenarios.
3. Exploratory analysis of the simulation results.
4. Definition of criteria and indicators for comparison of the management strategies.
5. Evaluation of management scenarios based on the defined indicators and criteria.
6. Selection of the optimal strategy or combination of strategies using multiple criteria optimization.

We are currently developing exploratory visualization techniques that can be effectively used at all stages of decision-making processes (Simon, 1960): intelligence, design, and choice. For this purpose, we are further developing methods and tools for informed spatial decision-making (Andrienko and Andrienko, 2003) to provide support for temporally related data and problems.

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