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DESCARTES & EFIMOD: An Integrated System for Simulation Modelling and Exploration Data Analysis for Decision Support in Sustainable Forestry

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Abstract: Decision support in sustainable forest management (SFM) has some specific features: a) it can perform quantitative prediction of forest ecosystem dynamics under different scenarios of SFM; b) it can spatially combine the predictions of different scenarios on the territory of a forest unit to support decision-making. We represent the integration of simulation modelling with the exploratory spatial data analysis (ESDA). The EFIMOD 2 is a spatially explicit individual-based ecosystem model, which was run for simulation of forest ecosystem dynamics at stand level on the territory of a state forest in Central European Russia. The DESCARTES software system designed to support visual exploration of spatially referenced data was used to analyse the results of the simulations. The results of long-term simulations were analysed by DESCARTES as a set of various maps and graphs. The ESDA with the interactive visualisation gives a possibility of direct representation of time series and spatial patterns of forest dynamics in a graphical form allowing analysis of the dynamic trends and the effectiveness of various silvicultural regimes. The representation of spatially distributed time series of ecosystem dynamics on maps and the spatial combination of different forest attributes give an opportunity to explore a diversity of ecosystem reactions in various forest compartments. Actually, it allows decision making to analyse spatial combinations of various strategies, and zoning of the forest area, and to take into account forest productivity, soil change, carbon balance, forest biodiversity criteria, and indicators of SFM.

Keywords: Forest simulation models; Forest landscape; Exploratory data analysis; Sustainable forest management; Decision-making; Expert system

1. INTRODUCTION

Forest ecosystem models (see reviews by Ågren et al. [1991], Chertov et al., [1999a]) are operating with forest patches corresponding to the level of a forest stand. They are usually used to analyse the impacts of different cutting systems, of forest disturbances, of natural development, climate change, and carbon balance. Now, there is an understanding that forest ecosystem modelling can be a practical tool for the prediction of both forest growth and soil nutrition in the changing environment under new silvicultural regimes.

Obviously, the next step is to use the modelling predictions for decision-making in forestry taking into account a shift of modern silvicultural paradigm from wood-production forestry to sustainable forest management (SFM). Details and definitions may be found in the Helsinki Process [1995]. The new paradigm of SFM needs prediction of both tree growth and change of ecological characteristics of the ecosystem in relation to biodiversity, ecosystem stability and carbon budget. However, applying modelling for forest decision-making is still rare. Perhaps, the FORCYTE by Kimmins [1995] is the only system of forest decision-making based on simulation modelling.

Actually, the decision-making in forestry has been developing independent of predictive modelling, and it mostly uses traditional growth tables. Arvanitis [2000] highlighted the importance of combining GIS with remote sensing technology for decision support systems (DSS) in forestry. A combination of multi-criterial optimisation with elements of spatial analysis in the landscape level for ecologically based silviculture is now being intensively developed (Baskent and Jordan [1995]; Kangas et al. [2000]). In Canada, Erdle and Sullivan, [1998] made a significant contribution to contemporary stand and landscape based forestry design. The planning system MONSU by Pukkala [1993], developed and used in Scandinavia has combined multi-criteria optimisation, GIS and data visualisation. However, the role of the modelling component in these systems is still negligible.

The important feature of the modelling approach is that a model produces a lot of various characteristics of the simulated forest.Produced results are usually complex and multidimensional: several attributes are simulated for many years according to different scenarios of modelling. Respectively, analysis becomes a non-trivial task. It becomes necessary to have a convenient tool to look into data from different perspectives, calculate derived attributes, analyse the dynamics of values, reveal relationships between variables, etc. Especially important is a possibility to study spatial distribution of values and analyse spatial relationships. Such operations are usual in ESDA – the Exploratory Spatial Data Analysis.

So far, ESDA still has not been applied to problems of decision-making in forestry. Chertov et al. [2002] has attempted to apply the interactive visualisation and ESDA to SFM problems.. This work is promising in combining simulation modelling in the level of a forest management unit with ESDA using dynamic graphical and cartographic representations of the simulation.

2. MATERIAL AND METHODS

2.1 Simulation model of the forest ecosystem EFIMOD 2

The individual-based spatially explicit combined model of tree/soil system, EFIMOD II (Chertov and Komarov [1997]; Chertov et al. [1999b]), simulates the stand as a population of "single plant ecosystems" (SPE). The idea is that a single plant occupies a certain space in the above-ground environment and the soil. The SPE can be treated as an elementary cell of forest ecosystems, and the ecosystem itself can be represented as SPE groups where trees are situated in "individual soil pots". The pot size depends on the root mass and the rate of nutrient consumption. The competition takes place for available light and for the redistribution of available nitrogen coming from tree's area of nutrition. The flowchart in Fig.1 shows the processes over one year. The potential growth is evaluated as maximal yearly biomass increment per leaf/needle biomass. Current increment is reduced due to local shadowing and amount of available nitrogen in soil. It is reallocated between different tree compartments with some adaptations. The model system uses forest inventory data as input parameters. Output variables are the inventory stand data, pools of carbon and nitrogen in the stand and soil, CO_2 flux, available N and some other characteristics. EFIMOD II comprises the tree growth module and the soil module based on the authors' model of soil organic matter dynamics ROMUL (Chertov et al. [2001]).

As a result of the individual-based structure of the model the different types of cuttings are included into the model. The previous applications of the model showed high sensitivity of the stand and soil to tree nitrogen response, climate and soil (and their complex interactions), nitrogen input from the atmosphere, stand density and pollution.

It should be noted that we use the individual-based model for simulating the dynamics of a homogeneous stand, which is described by standard inventory data. Further we treat the group of adjacent stands as a territory, which can be analysed by GIS or special software for visualisation.

2.2. DESCARTES as an instrument of visual exploratory analysis

DESCARTES (Andrienko and Andrienko, [1999]) is a software system specially designed to support visualisation of spatially referenced data. DESCARTES combines traditional GIS services with two innovative features: (1) automated presentation of data on maps; and (2) tools to interactively manipulate these maps. By incorporating generic knowledge on map design (an expert system on thematic cartography) into the system, we enable automated mapping. DESCARTES selects suitable presentation methods according to characteristics of the variables to be analysed and relationships among those variables. The cartographic knowledge of DESCARTES allows non-cartographers to receive appropriate presentations of their data, and the automation of map construction saves considerable time. The important feature of DESCARTES is that it is able to handle and process complex multidimensional tables describing time-series of spatially referred data. Thus, the system:

- is able to generate and display automatically correct graphical and cartographical representations of selected subsets of data;
- allows interactive manipulation of maps and graphics and dynamic linking between various displays;
- has convenient tools for calculating derived attributes and thus decreases the dimensionality of the analysed data set;
- has explicit representation of time, which allows dynamic data presentation with user-controlled animation.

Besides visualisation and interactive manipulation of data displays, DESCARTES offers additional helpful facilities for exploratory data analysis: it supports queries, calculations, and methods for multi-criterial spatial decision making (Jankowski et al. [2001]).

2.3 Initial characteristics of simulated plots

The forest selected for the simulation modelling and ESDA is situated 100 km South of Moscow on the Central East European Plain. These managed forests represent mosaics of stands of different age and composition depending upon previous clear cuttings and type of forest regeneration. The Silver birch, Scots pine and Norway mixed stands are dominant in the forest accompanied by the broad-leaved species (oak, lime, and maple). Four management blocks consisting of 108 forest

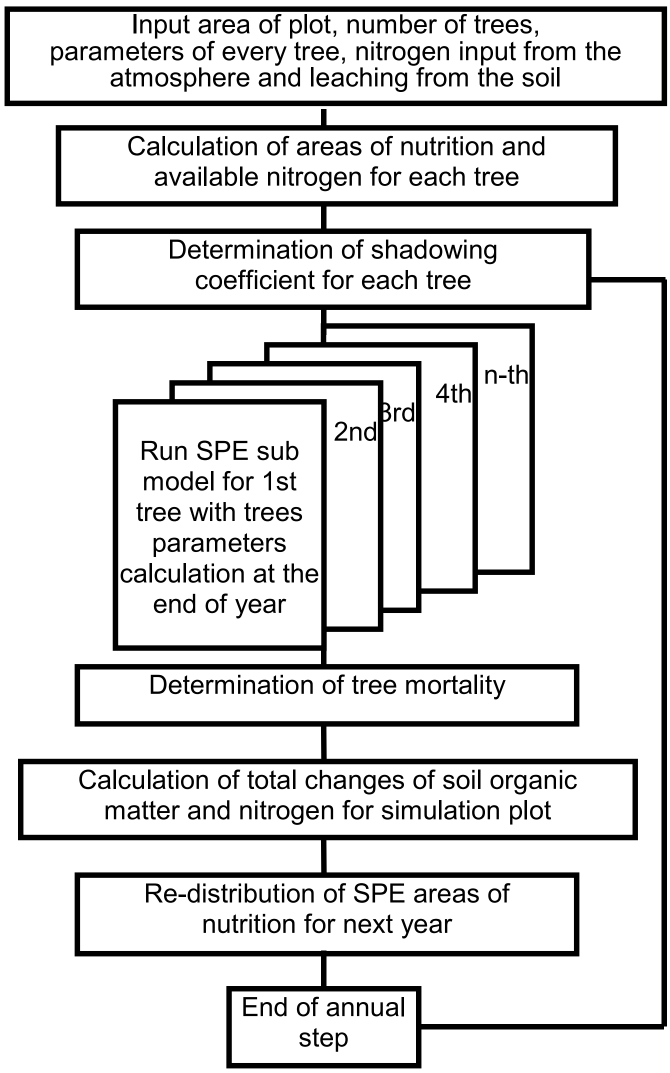

Figure 1. Flow-chart of year step of the EFIMOD model.

compartments (stands) have been selected for the test. The following parameters have been used as input data for the simulation: compartment area (ha), forest site type, soil climatic scenario, soil organic matter (SOM) pool in organic layer and mineral topsoil (kg m^{-2}), nitrogen of SOM in the same horizons (kg m^{-2}), mean stand height (m) and diameter (cm) with their standard deviation, and number of trees per ha.

2.4 Simulation scenarios

Consider three different simulation scenarios for 50 years of forest ecosystem dynamics based on a part of "Russky Les" data.

The first scenario assumes full protection of the forest in all compartments without cutting. The impact of natural disturbances, the catastrophic windfall and forest fires have generally not been included in the simulation scenario. This exclusion of disturbances reflects the real situation in the Moscow region in not too old, mixed stands.

The second scenario has a final clear-cut at the stand age of 80 years with successful natural regeneration. The specific feature of this regime is that all cutting residues stay on the clear-cut area for the decomposition to exclude element loss and soil deterioration. No forest fires and pest invasions have been simulated and we suppose that forest regeneration is successful and result in the formation of young mixed stands with planted conifers as a dominating species. This regime corresponds to the criteria of conservation of soil nutrients at SFM.

The third scenario represents the recent Russian forest management legislation. It has also a final clear-cutting at 80 years with the natural regeneration as in the second scenario. However, all residues after final cutting (leaves and branches) are burned, that is removed from the clear-cut area with the loss of carbon and nitrogen in the scenario implementation.

3. RESULTS AND CONCLUSIONS

The EFIMOD 2 runs have been performed for 50-years stand growth and soil changes in every forest compartment and three scenarios of forest management. The simulation results for one year time steps and for every forest compartment contain standard dendrometric characteristics of the every tree cohort (mean height, diameter, tree numbers and growing stock), their biomass, dead wood mass, mass of cut wood (volume, biomass and nitrogen), SOM and soil nitrogen mass. The output data for biomass and SOM pools are expressed in kg per forest compartment and kg per hectare.

The outputs were visualised with a set of maps for the simulated forest section using the DESCARTES. The interactive maps of different attributes with graphical presentation of time series for every forest compartment have been presented allowing: (1) map animation with a given temporal step; (2) visualisation of change maps representing absolute or relative changes in the attribute data for a given time period; (3) display of maps with diagrams representing dynamics of changes for each spatial object; (4) display of dominant species map with selected threshold – to study biodiversity. An expert (forest manager, forest ecologist) looks through sequences of these maps evaluating the temporal trends of the attributes and change of their spatial patterns. After the visualisation and the analysis, the expert gives conclusions on optimal (trade-off) scenario or combination of scenarios based on the criteria and indicators of SFM that correspond to the visualised attribute. The visualisation is then repeated for all attributes and their various combinations. After all, the conclusions are given on the optimal regime (a set of regimes) that harmonises criteria of biodiversity, wood production, and carbon sequestration. Actually, this work represents anintegration of the intelligent computer system with the personal skills and preferences of the expert in the field of sustainable forest management for direct informal decision-making.

Consider the data on dead wood as an example of the application of the DESCARTES system. The dead wood is an important indicator of forest biodiversity providing habitat for numerous detrital biota. The measure of dead wood pool can give a relative evaluation of biodiversity in the studied forest presented as a set of separate stands. This data are represented in Fig. 2 and 3.

Fig 2 shows the difference between the accumulated dead wood under natural development and in the scenario with cutting at the end of simulation. Additionally, it displays the graph of the trends in dead wood accumulation in relation to the age of clear cutting (abscissa) in the forest compartment. The figure indicates that the pool of dead wood is generally higher in the clear-cut scenario where we do not simulate thinning with wood removal. The graph displays an interesting detail: the later the time of clear cutting (left side of the graph)

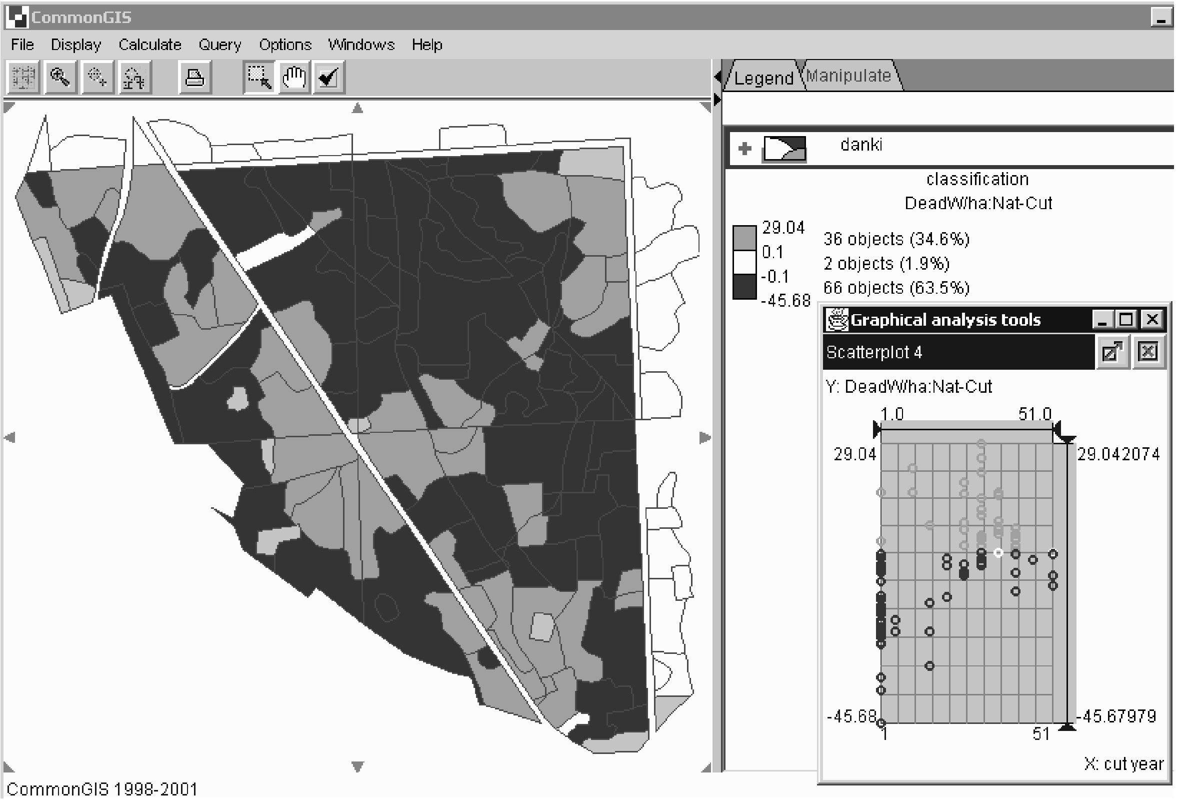

Figure 2. Difference of accumulated dead wood between natural development and cutting scenarios at the end of simulation.

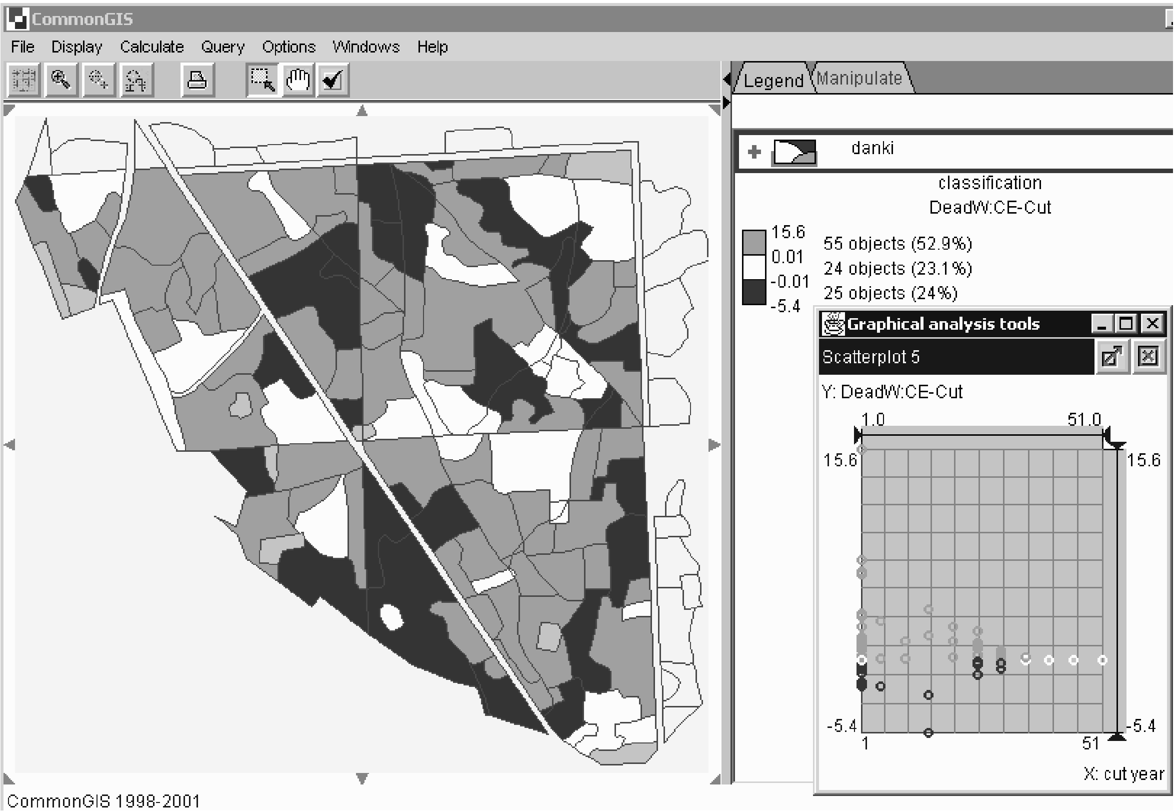

Figure 3. The relative advantage of ecologically oriented clear-cutting scenario in relation to Russian legal practice.

the larger the pool of dead wood after the clear cut. These trends can be explained by the effect of natural mortality in young and middle-aged stands after cutting. The development of natural stands was in a phase of low natural mortality in middle-aged and old forests with dead wood increasing during the last years of simulation only.

Fig. 3 demonstrates the relative advantage of ecologically oriented clear-cutting compared to the legally accepted practice in Russian. Generally, the pool of dead wood is consistently higher in the ecological approach, perhaps due to a higher rate of natural mortality. The spatial heterogeneity of dead wood accumulation is significantly higher when we compare different cutting systems. The pattern of this mosaic needs additional analysis in relation to dynamics of the stand age structure. Actually, the described trends of dead wood accumulation reflect certain contradictions in the dead wood dynamics. We can conclude that the protective forest regime in middle-aged and not too old stands has no advantage versus the clear-cut system in case there is no thinning.

One can see that exploratory analysis of simulation results allow us to learn more about the dynamics of forest growth. However, complex processes are usually described by complex multidimensional data sets. Respectively, it is rather an art than technology to find a useful sequence of analytical operations that can lead to interesting results. Just a tight integration of the modelling software with a visualisation system is not sufficient. Having huge amounts of original and derived data, one should not get lost in the complex analysis space. Our goal is to build an intelligent system that will incorporate heuristics into exploratory spatial data analysis, and will automatically guide forest experts in the process of exploration and analysis of modelling results.

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