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Integrating forest simulation models and spatial–temporal interactive visualisation for decision making at landscape level

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Abstract

The article represents an attempt to integrate long-term forest ecosystem modelling with modern techniques of exploratory data analysis. The idea of the integration was to build up a prototype system for forestry decision-making at landscape (forest enterprise) level to support the spatially oriented tasks arising from Criteria & Indicators (C&I) of Sustainable Forest Management (SFM). A model test was performed on a small forest plot consisting of various stands (forest inventory compartments) with two scenarios of silvicultural regimes. A combined spatially explicit forest simulation model EFIMOD 2 and the DESCARTES software system designed to support visual exploration of spatially referenced data were used in the experiment. The visualisation of simulation results on a sequence of interactive maps. It also allows direct representation of time series and spatial patterns of forest dynamics in a graphical form, and analysis of the dynamical trends under various silvicultural regimes. The diversity of ecosystem reactions in various stands was explored, and the possibilities for spatial combination of various strategies and zoning of the forest area were tested. We are sure there is a need to create a new, user-friendly modelling system integrating forest ecosystem models with exploratory data visualisation for methodologically easy and expressive decision-making based on expert evaluation and a long-term simulation at the forest enterprise or landscape level. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Recently, new goals in forest modelling have arisen as a result of the ecologically oriented paradigm of Sustainable Forest Management (SFM). A new class of problems appear because of a necessity to compromise ecological and economical criteria of SFM at areas of forest management units, landscapes and regions. It is necessary for ecologically and economically oriented decision-making to combine an optimum variety of silvicultural regimes in the forest. Actually, it is a spatial task requiring new specific methodology and instruments.

The role of simulation modelling as a predictive tool for SFM has been recently strongly promoted (Baskent and Jordan, 1991; Jordan et al., 1995; Andersson et al., 2000; Kellomäki, 2000) as an alternative to traditional growth tables. The importance of GIS combined with remote sensing technology is also highlighted for elaboration of decision support systems (DSS) in forestry (Covington et al., 1988; Curry et al., 1994; Arvanitis, 2000). A combination of multi-criteria optimisation with elements of spatial analysis on the landscape level for ecologically based silviculture is now being intensively developed (Clements et al., 1990; Davis and Martell, 1993; Baskent and Jordan, 1995; Kangas et al., 2000). A formal methodology of DSS for SFM based on the optimisation technique has also been recently declared (Varma et al., 2000). A significant contribution to elaboration of contemporary stand and landscape based forestry design has been achieved in Canada (Booth et al., 1993; Erdle and Sullivan, 1998). The planning systems Monsu (Pukkala, 1993) and ASIO (Næsset, 1997) elaborated and used in Scandinavia that yielded multi-criteria optimisation, GIS and illustrative data visualisation. However, a role of modelling component at landscape level is still rare. Perhaps, the FORCYTE by Kimmins (1995) is the only system of forest decision-making based on simulation modelling. We do not know any example of application of interactive visualisation and exploratory data analysis (EDA) to SFM problems.

Until now, the ecosystem modelling and EDA developed independently. However, the combination of these approaches seems to be promising because of the possible gain due to spatial representation and analysis of a set of forest simulation time series. This has led to authors proposing integration of forest ecosystem modelling and EDA to test the merit of this approach at a level of an array of forest stands. We hypothesised the effectiveness of the representation of the results of long-term simulation of individual stands ('compartments' in forest inventory, 'patch' in landscape ecology) on a forest map. The map should be processed by EDA to find out compromising silvicultural decisions for SFM.

The level of the basic forest unit (stand, inventory 'compartment') can now be modelled well in relation to the problems of the stand's productivity in different climatic and site conditions (see the reviews by Ågren et al., 1991; Liu and Ashton, 1995; Ryan et al., 1996; Chertov et al., 1999a). Moreover, there are combined models which are able to describe the biological turnover of the elements; first of all, carbon and nitrogen, in the 'soil–forest' system (Ågren and Bosatta, 1996; Chertov et al., 1999c; Friend et al., 1997; Goto et al., 1994; Kellomäki et al., 1992, 1993; Levine et al., 1993; Morris et al., 1997; Pacala et al., 1993; Tiktak and Van Grinsven, 1995). They allow an estimation of the forest productivity, carbon and nitrogen dynamics, and water regime in the forest ecosystem. Mostly the ecosystem models at the stand level are applied for the evaluation of operations of forest management for optimisation the productivity, influence of global climate change and to maintain forest biodiversity.

Recently, there were two different approaches to develop forest landscape (forest enterprise, region) models (Flechsig et al., 1994; Acevedo et al., 1995; Chertov et al., 1999a): (1) compilation of Markov chain models, sometimes with aggregation of stand level models (Logofet and Lesnaya, 2000); and (2) direct use of stand-level models in large territories, which can be seen as a connected set of stands, using modern computer facilities. The second approach is promising for the combination of ecosystem modelling with EDA.

Computational methods are widely used for problem solving in various areas of human activity. For applying computational procedures to spatially referenced data, the spatial component should be represented in a symbolic form appropriate for machine processing (for example, in the form of a neighbourhood matrix or spatial predicates and functions). Usually, extensive computations are needed for obtaining such representations from digitised spatial data. For each particular kind of spatial relationship a special algorithm has to be developed. See, for example, Zhang and Griffith (1997) for the algorithm for deriving a neighbourhood matrix from a spatial database (ArcInfo™ coverage files). An exhaustive symbolic representation of *all* spatial information is never achieved. This even appears to be principally impossible due to the very nature of space as a continuous and multifaceted phenomenon. Therefore, typically only a small part of spatial relationships existing in a data set are symbolically encoded and involved in data analysis. Often a computational method suggested for analysis of spatial data is strictly suited to account for just one particular kind of spatial relationship.

In contrast, an appropriate *visual representation* of spatial data, such as a map, can be isomorphic to space and thus capable of preserving all spatial relationships. Hence, a map can be regarded as a model of a spatial phenomenon facilitating its study. However, such a representation is only perceivable by human eyes, and can therefore be used only by a human analyst. For example, a person can easily check neighbourhood relationships of objects, adjustment of polygons, closeness of areas, etc. Therefore, it is crucial to combine computational processing with visualisation of spatial data and visual analysis of them by an expert.

The role of visual representations has been acknowledged for a very long time, but only recently information visualisation and EDA on the basis of graphics have emerged as a branch of scientific research (Card et al., 1999). Computers made possible such features of graphical presentations that are now considered as indispensable for supporting data analysis: high user interactivity, easy transformations of raw data (calculations of changes, proportions, etc.) and graphical presentation (change of symbolism, setting scale, viewpoint, etc.). Especially important are multiple dynamically linked views on the same data when changes in one display are immediately propagated to all others.

The notion of EDA and data visualisation has lately spread from the realm of statistics to cartography (DiBiase, 1990; MacEachren, 1994; MacEachren and Kraak, 1997). Cartographers have recognised the demand in a new software allowing specialists in various disciplines (i.e. not 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. Unfortunately, widely spread Geographical Information Systems (GIS) do not sufficiently support interactivity and dynamics of screen maps. Few attempts have been made to design and implement highly interactive user-friendly GIS. Thus, dynamic linking between various displays is available in some spatial analysis systems integrated with ArcInfo: xGOBI (Cook et al., 1997) and SAGE (Haining et al., 1996). Dynamic change of symbolism was implemented using Tcl/Tk in the CDV system (Dykes 1997). Intelligent map design and interactive manipulations with maps were implemented in Java in the DESCARTES system (Andrienko and Andrienko, 1999a). However, all mentioned systems are developed in academy as research prototypes, and proposed methods are still not available to the general public in commercial software.

Logically, the following task can be formulated: to integrate on a forest map the development of ecosystem represented by simulated time-series of vegetation-soil with EDA. In this case, we expect a synergetic effect of a combination of these approaches that can significantly help in realising criteria and indicators of SFM. The aim of this integration should not be a spatial analysis itself as a final goal, but its use for understanding dynamic trends at the landscape level to be implemented for SFM. In this context the analysis of the landscape mosaic could be considered as a combination of stand simulation with interactive visualisation and EDA.

The parameters of the system consist of two groups. The first group of the parameters (numerical attributes) represents initial data of forest inventory with stand characteristics of every compartment and the results of the simulation. These parameters allow evaluation of temporal trends of forest growth, soil changes and carbon balance. An expert in forest ecology and environmental sciences should compile the second group of the parameters using interactive visualisations and EDA. For this purpose, the expert should use criteria of SFM and available information on correlation of biodiversity, forest health, and recreational use of forests with simulated ecosystem parameters.

The overall objective of the work is to integrate long-term forest ecosystem modelling with modern techniques of information visualisation and EDA. We implemented a prototype model system for decision support in sustainable forestry at the landscape (forest enterprise, region) level. The model test was performed on a small forest plot with different stands. The goal of the test is to demonstrate the possible methodology and advantages of combination of forest ecosystem modelling with a spatial–temporal visualisation system. Two scenarios of silvicultural regimes were considered. In the model test we considered only two conflicting criteria of SFM Helsinki Process, 1995; Montreal Process, 1995) with their interaction: (1) carbon sequestration in forest ecosystem (as stand biomass plus soil organic matter); and (2) wood production (as a wood biomass taken away).

2. Material and methods

Data of simulated long-term landscape dynamics for the mosaics of different stands at the test forest plot were analysed using information visualisation and EDA. Below we describe the ecosystem simulation model used, visualisation software system, simulated forest area and the general procedure of the analysis.

2.1. Model of the forest ecosystem EFIMOD II

The individual-based spatially explicit combined model of tree/soil system, EFIMOD II (Chertov and Komarov, 1997; Chertov et al., 1999c), was used for the simulation of stand and soil dynamics for all the forest compartments (individual stands) of the test plot. The model allows both short- and long-term simulation at stand level, which allows long-term resource acquisition and sustainability. It is a model of forest ecosystem, and is not only a stand growth simulator. The model is based on the concept of a single plant ecosystem (SPE) (Chertov, 1983, 1990) in which a single higher plant occupies a certain space in the aboveground environment and in the soil. The SPE can be treated as an elementary cell of a forest ecosystem, and the ecosystem itself can be represented as a group of SPEs, in which the trees are located in 'personal soil pots'. Pot size (area of nutrition) depends on the root mass and the rate of nutrient consumption. It changes continuously as the tree grows, reflecting the competition for soil nutrients and water. EFIMOD II simulates biological productivity of the tree and the soil processes of every SPE taking into account the competition for light and soil available nitrogen among tree's neighbours. 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 application of the model showed high sensitivity of stand and soil to tree nitrogen response, climate and soil (and their complex interactions), nitrogen input from the atmosphere, stand density and pollution (Chertov et al., 1999b). The output parameters of the EFIMOD II are number of trees per square unit, the carbon contents in the different tree compartments, and total amount and sequestration of carbon and nitrogen between different soil compartments.

2.2. DESCARTES as an instrument of visual exploratory analysis

DESCARTES (Andrienko and Andrienko, 1997, 1999a) is a software system specially designed to support visual exploration of spatially referenced data. DESCARTES combines traditional GIS services with two innovative features: (1) automated presentation of data on maps; and (2) facilities to interactively manipulate these maps. Incorporating generic knowledge on map design (an expert system on thematic cartography) into the system enables 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 a considerable amount of time.

The system provides highly interactive, dynamic data displays. It incorporates various interactive techniques for map manipulation that can enhance the expressiveness of maps and thus promote data exploration. An example of such a technique is linking between multiple complementary data displays (maps, scatter plots, plots of parallel co-ordinates, etc.) by identical marking of corresponding parts. When the user points with the mouse cursor on some object on any of the displays, this object becomes simultaneously highlighted in all the displays. Such linking makes it possible to integrate the information contained in individual views into a coherent image of the data set as a whole. Other examples are: (1) visual comparison when the map is dynamically repainted to represent values larger than a user-specified reference value in one colour and smaller values in another colour; (2) interactive dynamic classification when objects on the map are classified depending on values of a single numeric attribute. DESCARTES also includes more sophisticated visualisations for multivariate analysis such as dominant attribute calculation, analysis of similarity in multidimensional space, multiple attribute classification, etc.

Currently, a work is being done on extending DESCARTES towards dealing with spatial–temporal data, i.e. spatial data that vary in time. Analysis of such data requires simultaneous representation of their spatial, temporal and thematic aspects. A general approach to representation of spatial–temporal data is map animation. However, animation alone is insufficient for comprehensive data analysis. It can produce a strong visual effect on a viewer when it demonstrates some rather apparent dependencies and trends like urban growth, or shrinkage of forest areas. However, it is poorly suited for making comparisons between states of a phenomenon at different times and detecting previously unknown changes. Therefore, the extension of DESCARTES for time-series data (Andrienko et al., 2001) combines map animation with interactive thematic maps, dynamic statistical graphics, and advanced controls for manipulating them. In particular, the system automatically designs so-called change maps representing amounts and locations of attribute changes for a given time period. These components as well as interaction between them are specifically designed in order to support visual investigation of changes in data, the ultimate goal being to help users to reveal spatial–temporal trends. To summarise, the important features of the system are:

- automatic design of valid map presentations of the data;
- complementary role of different displays: the map represents the spatial component of data while the time plot supports study of evolution of attribute values;
- dynamic link between the displays provides easy navigation and access to data, and help in understanding of complex spatio-temporal relationships;
- transformable dynamic displays expose changes and thus help to detect errors and anomalies in data and generate plausible hypotheses to explain findings.

Besides visualisation and interactive manipulation of data displays, DESCARTES offers additional helpful facilities for exploratory data analysis: support of queries, calculations, and methods for multi-criteria spatial decision making (Jankowski et al., 2001). These tools were not utilised in the experiment due to its limited character (only two scenarios considered), but they have a great potential for real-life multiple criteria decision support.

2.3. Initial characteristics of the simulated forest

The test forest plot has an area of 25 ha, and is situated in the south boreal sub zone of the East European Plain. The territory has a moderate continental climate with a mean annual temperature of 4.0 °C, mean temperature in July of 16.5 °C, a mean temperature in January of −7.0 °C, annual precipitation of 750 mm, growing season of 165 days. The forest area is a part of a moraine plain with a small water flow in a shallow valley. The plain has loamy well-drained podsolic soils, and the slopes of the valley have sandy well-drained soils (humus-iron podsols). Two compartments have poorly drained peat gley soils. The loamy well-drained soils have a pool of soil organic matter (SOM) of 7–10 kg m^{-2}, sandy soils 6.5–8 kg m^{-2}, and peat soils have a SOM pool of 12.5 kg m^{-2}. The variety of soil conditions determines the different forest productivity.

South boreal pure coniferous and mixed forests, dominated by Norway spruce, Scots pine and Silver birch, represent the vegetation of the sample plot. This is so-called 'managed forests' representing mosaics of stands of different age and composition in dependence of previous clear cuttings and type of forest regeneration. The initial data and spatial mosaics of forest ecosystems (compartments) are represented in Table 1 and Fig. 1.

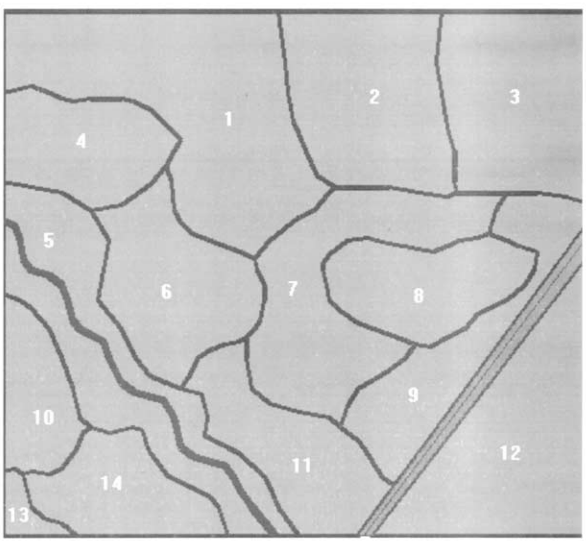


Fig. 1. The map of simulated site.

2.4. Simulation scenarios

The simulation of 50 years of forest ecosystem dynamics in the landscape described above has been performed under different silvicultural regimes. We suppose this time span is a minimal one for 'long-term' simulation. The EFIMOD II has run the two following forest management scenarios.

The first scenario represents an example of a clear-cut system at the stand age of 70 years with succeeding natural regeneration. The specific feature of the regime is that all cutting residues stay on the clear-cut area for decomposition to prevent element loss and decreasing soil fertility. No forest fires and pest invasions have been simulated and we suppose that forest regeneration is successful with formation of young mixed stands. So this regime is an example of a 'good' traditional forestry for wood production only, and it even corresponds to criteria of conservation of soil nutrients at ecologically oriented silviculture. Three compartments with young stands stay untouched because they did not reach 70-years of age.

In contrast, the second scenario is the full protection of the forest in all compartments on the plot without any cutting. Correspondingly, the age of stands increased by 50 years. The oldest one reached an age of 140 years that corresponds to old-growth even-aged forest. The stage of 'untouched, virgin' old-growth uneven-aged forest did not achieve with this simulation because of the too short time span of the simulation. 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 region under consideration in not too old, mixed stands. That is, there is a small rate of windfall and absence of ground forest fires as a result of effective fire control.

Table 1
Stand and soil characteristics

No of compartment	Area (ha)	Species*	Number of trees per ha	Age of species	Mean value and standard deviation		Soil and initial soil organic matter (kg m^{-2})
					Diameter (cm)	Height (m)	
1	3.2	Spruce	1000	40	13 (8)	14 (9)	Well drained loamy, 9.5
		Birch	1400	45	14 (8)	16 (9)	
2	2.4	Birch	15 000	5	1 (0.4)	1.6 (0.6)	The same, 8.5
		Spruce	3000	10	1 (0.4)	1.4 (0.5)	
3	2.5	Spruce	5000	25	8 (3.5)	7 (3)	The same, 7.1
4	0.9	Pine	700	30	12 (5)	11 (4)	Well drained sandy, 7.5
		Spruce	500	25	8 (3)	9 (4)	
		Birch	650	30	10 (4)	12 (5)	
5	1.3	Birch	1200	40	10 (4)	10 (4)	Poor drained alluvial, 12.5
		Pine	300	50	14 (6)	11 (4)	
6	1.8	Pine	1100	50	17 (7)	16 (7)	Well drained sandy, 8.0
		Spruce	600	30	12 (5)	10 (4)	
7	2.0	Spruce	900	40	14 (5)	15 (5)	Well drained loamy, 8.5
		Pine	300	50	18 (6)	17 (6)	
		Birch	250	50	15 (5)	16 (5)	
8	1.7	Birch	450	70	20 (6)	15 (5)	Poor drained peat, 12.5
		Pine	400	95	20 (7)	14 (6)	
9	1.8	Birch	5000	20	8 (3)	5 (2)	Well drained loamy, 7.5
		Spruce	2000	25	4 (1)	3 (0.7)	
10	1.4	Pine	700	70	22 (9)	19 (8)	Well drained sandy, 7.4
		Birch	300	70	20 (8)	17 (7)	
11	1.9	Pine	3000	15	8 (3)	7 (2.5)	The same, 6.5
		Spruce	2500	15	3 (0.8)	3 (0.7)	
		Birch	2000	20	7 (3)	8 (3)	
12	2.4	Birch	900	30	14 (5)	14 (6)	Well drained loamy, 9.5
		Spruce	500	30	10 (4)	9 (4)	
13	0.4	Spruce	450	50	20 (8)	15 (6)	The same, 10.0
		Birch	550	55	18 (8)	17 (7)	
14	1.3	Pine	600	50	16 (7)	16 (7)	Well drained sandy, 8.0
		Spruce	400	40	16 (7)	14 (6)	
		Birch	50	50	18 (8)	17 (7)	

Note: Pine, scots pine *Pinus sylvestris* L., Spruce, Norway spruce *Picea abies* L.(Karst.), Birch, silver birch *Betula pendula* L.

2.5. The general scheme of analysis

The sequence of operations for the spatial–temporal analysis of the results of simulation on the model forest landscape (as an ensemble of independent stands) was as follows:

1. For each scenario, EFIMOD II calculated main ecological parameters for every stand: total carbon accumulation in a stand and in a soil, and the carbon of wood removed from the compartment by cutting. The simulation results were expressed as values of parameters in kilograms per hectare, and then re-calculated as tons per area of each forest compartment. It should be pointed out that simulated soil organic matter (SOM) represents a sum of SOM in mineral soil, in organic layer (forest floor and litter), and in coarse wood debris. A 5-year time interval was used for output data.
2. The results obtained by EFIMOD II model loaded into DESCARTES system for visual data exploration.
3. Observe and analyse the results using the following procedure. An expert looks through sequences of maps representing some attribute or aggregation of attributes consistently at all given scenarios. Different viewing modes were available: (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) map with diagrams representing dynamics of changes for each spatial object. After visualisation the experts gave conclusions on optimal (compromise) scenario from the viewpoint of C&I of SFM corresponding to the visualised attribute. The procedure was repeated for all other attributes and their various combinations. Finally, conclusions were given on the optimal regime (a set of regimes) that harmonises criteria of carbon sequestration and forest productive function. It should be particularly pointed out that individual preferences of the expert/decision-maker were taken into account (reflecting, for example, local environmental and socio-economic conditions, national traditions, etc.)

3. Results

The general results of 50-year simulation and explorative analysis of the data are represented in Table 2 and Figs. 2–6.

Among all output attributes of EFIMOD II simulations, we selected the attributes relevant to carbon dynamics. In total, we considered 28 simulated time series for the examined forest plot in two scenarios with three variables per scenario: amounts of carbon pools in trees, soil, and removed cut wood. This is a bulky set of data that is difficult to analyse in a tabular form. Especially difficult is the combination of spatial and temporal interpretation at the set of forest compartments. Table 2 shows the general statistics and general trends in the forest. The statistics shows that extraction of 145 tons of carbon with wood (675 m^3 of wood) for 50 years resulted in a decrease of 1.8 times of total carbon pool in forest ecosystems due to strong decreasing of tree biomass. However, the response of different compartments varies considerably.

At the beginning of the EDA, we visualised data obtained as time series for tree and soil carbon pools (Fig. 2). The overall view clearly shows significant difference between the silvicultural regimes tested. There is a strong decrease in the carbon pool in the tree biomass after cuttings in the first scenario. However, the differences of soil carbon are not so apparent to see with the exception of compartments 5 and 8, which have poorly drained peat soils. In this case a slow decomposition of cutting debris leads to accumulation of carbon just after harvesting in the first scenario. Afterwards, the SOM pool strongly reduced under young stands.

Fig. 3a reflects the loss of tree biomass in the same manner as in the Fig. 2a and b. The reason is that clear cuttings determine the contrast differences in this case. The next step of the EDA is the visualisation of carbon pools difference in soil between first and second scenarios. This difference indicates various type of soil carbon accumulation before and after cutting, demonstrating loss of carbon in the first scenario. The figure clearly shows that the soil carbon loss is strongly different in various forest compartments, being largest

Table 2
General results of forest ecosystems 50 years simulation

No.*	Year	C in trees 1	C in soil 1	C away	Total C 1	C in trees 2	C in soil 2	Total C 2
1	1	457.40	152.00	0.0	609.40	430.72	152.00	582.72
	51	48.80	161.20	34.9	244.90	445.76	174.40	620.16
2	1	17.30	102.00	0.0	119.30	17.30	102.00	119.30
	51	56.90	90.50	0.0	147.40	56.90	90.50	147.40
3	1	148.60	88.80	0.0	237.40	149.75	88.75	238.50
	51	0.00	97.10	11.5	108.60	150.75	97.75	248.50
4	1	41.10	33.80	0.0	74.90	40.68	33.75	74.43
	51	6.30	25.80	4.7	36.80	65.79	32.58	98.37
5	1	42.50	81.20	0.0	123.70	42.90	81.25	124.15
	51	52.70	118.70	6.1	177.50	77.61	175.76	253.37
6	1	209.40	72.00	0.0	281.40	209.40	72.00	281.40
	51	34.80	72.50	18.4	125.70	245.52	68.04	313.56
7	1	148.60	94.00	0.0	242.60	148.80	95.00	243.80
	51	30.30	86.00	14.4	130.70	197.40	96.00	293.40
8	1	0.00	179.80	10.5	190.30	160.31	106.25	266.56
	51	37.60	228.70	10.5	276.80	128.18	272.17	400.35
9	1	98.30	63.80	0.0	162.10	98.30	63.80	162.10
	51	105.70	78.60	0.0	184.30	105.70	78.60	184.30
10	1	0.00	112.10	13.5	125.60	192.08	52.50	244.58
	51	51.20	50.10	13.5	114.80	207.76	47.04	254.80
11	1	105.30	61.80	0.0	167.10	105.30	61.80	167.10
	51	102.30	73.20	0.0	175.50	102.30	73.20	175.50
12	1	132.96	114.00	0.0	246.96	133.44	114.00	247.44
	51	17.28	114.00	16.1	147.38	218.88	113.52	332.40
13	1	38.16	20.00	0.0	58.16	38.16	20.00	58.16
	51	8.80	18.36	3.9	31.06	52.80	18.64	71.44
14	1	97.11	52.00	0.0	149.11	96.98	52.00	148.98
	51	26.65	40.04	11.2	77.89	152.36	42.12	194.48
Total	1	1536.73	1227.30	24.0	2764.03	1864.12	1095.10	2959.22
	51	579.33	1254.80	145.2	1834.13	2207.71	1115.42	3323.13

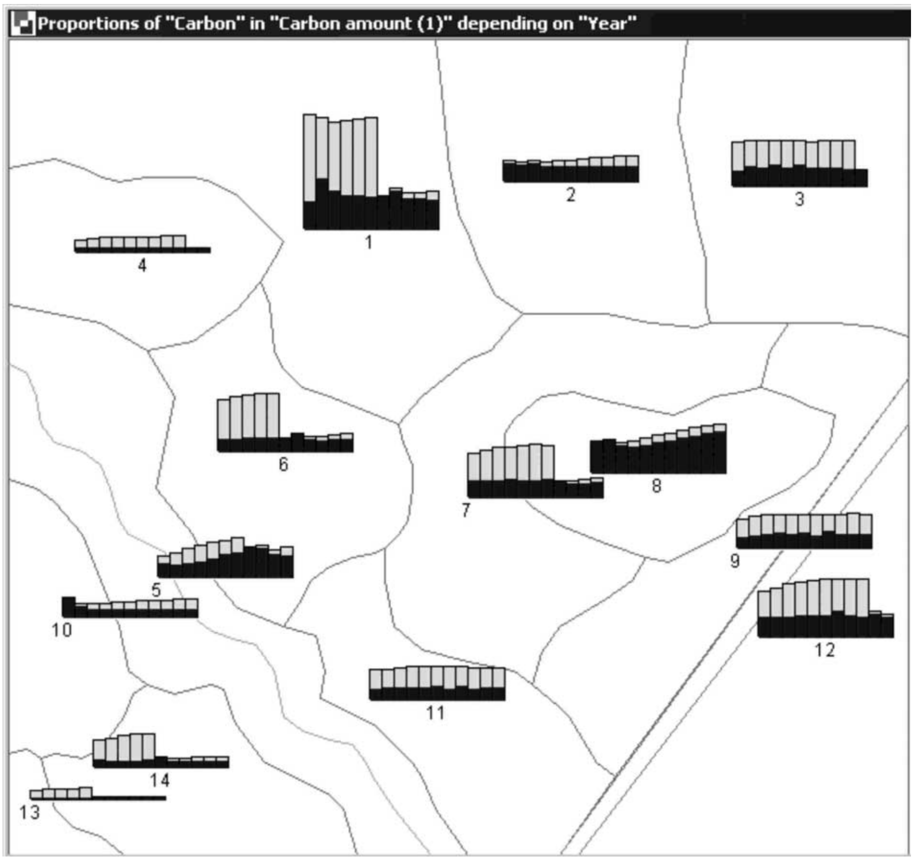
Note: No., number of compartment; Year, year of simulation; C in trees 1, carbon in stand in 1st scenario; C in soil 1, carbon in soil in 1st scenario; C away, carbon of wood removed by cutting in 1st scenario; Total C 1, total carbon pool in the compartment in 1st scenario; C in trees 2, carbon in stand in 2nd scenario; C in soil 2, carbon in soil in 2nd scenario; Total C 2, total carbon pool in the compartment in 2nd scenario.

in poorly drained soils, and lowest in sandy soils. For example, the large difference of soil carbon dynamics in the eighth compartment (characterised by poorly drained soils) is determined by forest cutting at the beginning of simulation in the first scenario. Therefore, an accumulation of slowly decomposing cutting debris (branches and leaves) leads to an increase in soil carbon just after the cutting in comparison with the second scenario. Then, the soil carbon pool decreases because the young stand here has a low litter input to soil. The overall view in this case allows easily classification of types of carbon accumulation dynamics in forest soils in different sites and silvicultural regimes.

The spatial patterns of soil carbon dynamics at the end of the simulation can be seen in Fig. 4. This visualisation consists of two parts: (1) a map showing changes during a 50 years period; and (2) a time plot representing dynamics of changes of soil carbon for each forest compartment. There is a link between the map and the plot allowing simultaneously highlight the compartment and corresponding time series. For example, the eighth compartment is highlighted in Fig. 4 by the arrow on the map, and the corresponding line is in bold on the graph. The map supports visual analysis of the changes of carbon pools in different compartments: compartments with stable soil can be visually separated from compartments with positive or negative soil carbon dynamics.

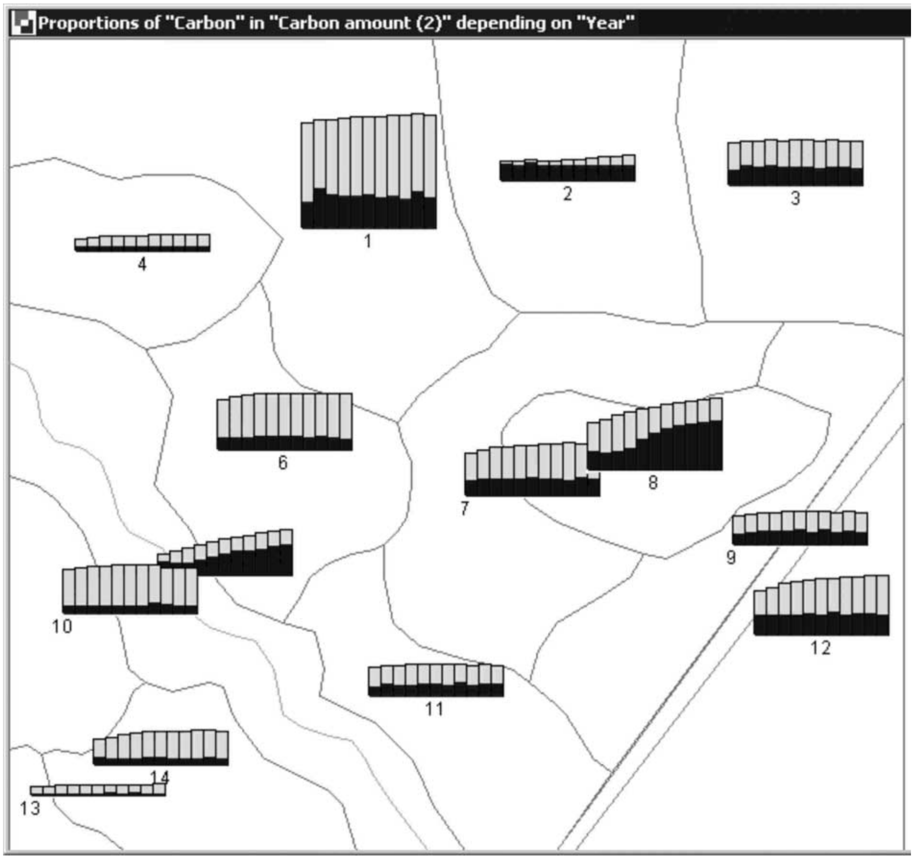
This visualisation shows a comparison of two strategies on the soil carbon pool: we can see spatial mosaics of different forest compartments with various sensibility in the landscape. The more sensitive carbon dynamics in relation to cuttings is found in poorly drained sites in valley and in depression (compartments 5 and 8), although there are two compartments with positive trends after cutting among sandy soils of valley slopes (compartments 6 and 10). This reflects different soil susceptibility of various landforms in the landscape to the same type of anthropogenic impact.

The more comprehensive illustration can be seen in Fig. 5 demonstrating the comparison of normalised total carbon pools (t ha^{-1}) in forest ecosystems. It shows the difference between the two scenarios at the end of simulation. Unfortunately, it demonstrates the permanent negative effects of clear-cut scenario on carbon pool in all ecosystems with the exception of three compartments (2, 9 and 11 with young stands) that had no cutting during the simulation period. However, there is a difference of the effect in various landscape elements: a more significant decrease is



(a)

Fig. 2. Visualisation of simulated time series of carbon dynamics in stand and soil: (a)1st scenario with clear cuttings; (b) 2nd scenario with forest protection. Light bars correspond to carbon pool in tree biomass, dark bars—to soil carbon pool. The sequence of bars for each compartment represents the age dynamics of the parameters.



(b)

Fig. 2. (*Continued*)

found in more productive ecosystems on moraine plain and valley slopes that had more high carbon pool in living biomass before cutting.

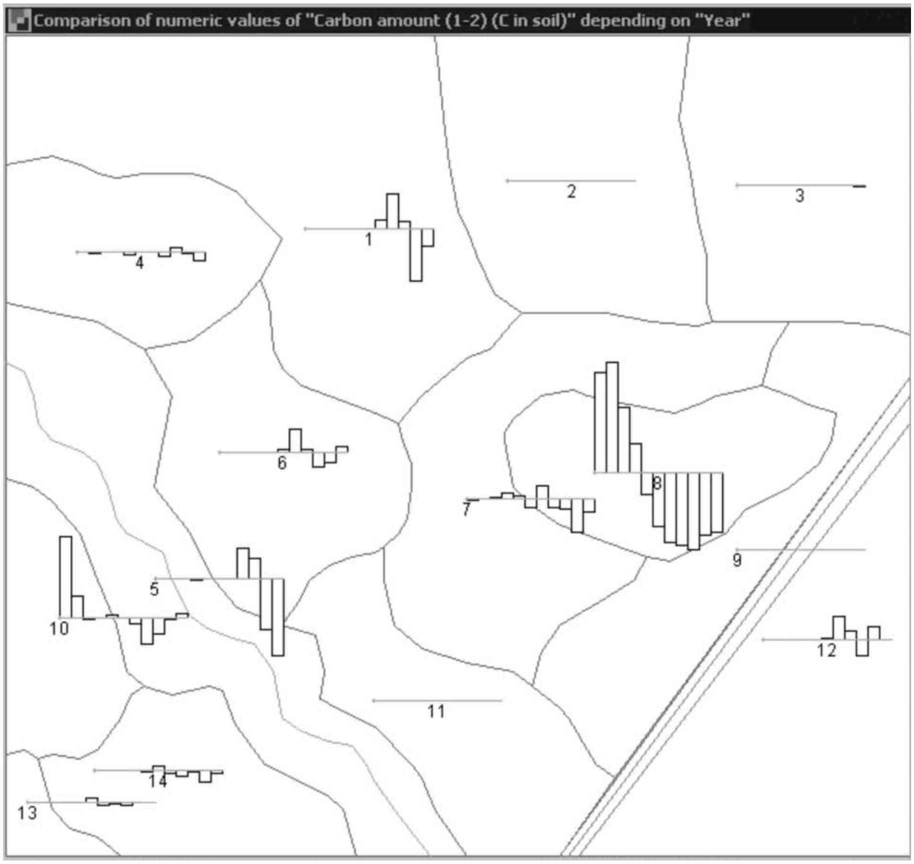
The proportion of removed wood carbon to total ecosystem carbon loss was calculated (Fig. 6a and b) for evaluation of the integral ecological effectiveness (or degree of damage) of the clear-cut system in comparison to the protective one. Fig. 6a shows an expressive picture of a proportion of removed wood carbon in total ecosystem carbon loss. There is a significant spatial heterogeneity of the effects of the cutting. The proportion of wood carbon removed with cutting varies from 7.6 to 9.8% only. Fig. 6b is a final demonstration of a great difference between the amount of removed carbon and total carbon loss in the forest ecosystem after clear cutting. For example, in compartment 1 the value of removed carbon is 34.9 ton, while the total ecosystem loss reaches 375.3 ton. The analysis of the heterogeneity and total values of removed and lost carbon in Fig. 6 shows that the greater proportion of removed carbon (i.e. the lower carbon loss) is in compartments with more successful forest regeneration just after cutting. In a case of regeneration delay (compartments 3, 4, and 5 with a 5-year treeless period after cutting) this proportion is lower because there is less biomass in young trees, and sometimes, there is soil carbon loss. It should be emphasised that Fig. 6 shows: (a) a long-term harmful effect of clear cutting in the case of removing only the cutting wood (leaves and branches stays on the clear-cut area); and (b) heterogeneity of this effects that require elaboration of compartment-based spatial approach to evaluate effectiveness of different forest strategies at the landscape level.

In the result of the experiment, we found that it was extremely useful to 'play' with different attributes and their combinations provided by DESCARTES. Thus, it is interesting to study in dynamics values of a single attribute, compare values of two attributes, check values of a derived attribute (such as value divided by area) and so on. An important feature of DESCARTES system is that it allows such operations to be done interactively. Resulting attributes can be immediately visualised and analysed using maps and different types of graphs.

Using this integration of forest ecosystem modelling and the visual exploration of data, the expert can directly achieve a decision on the preference of the strategies taking into account criteria of sustainable forestry. The benefits of the protective second strategy from the viewpoint of carbon sequestration can be clearly seen. Moreover, the combination of the strategies can be realised on a basis of expert evaluation of actual landscape structure of the forest to compromise criteria of productive function and carbon sequestration. If we exclude slopes of the valley from clear cut system in the first scenario (compartments 4, 6, 10, 11, and 14, which have a water protection function), then the total carbon sequestration in the forest will increase by 30%. A volume of removed wood carbon will be 32% less

(a)

Fig. 3. Differences between 1st and 2nd scenarios: (b) difference between carbon pool in soil organic matter; (a) difference between carbon pool in tree biomass. Positive values are up and negative are down of the base line.



(b)

Fig. 3. (*Continued*)

than in the first scenario. Other spatial combinations, for e.g., compiling: (a) protective buffer zones along the road and water flow; (b) ecological corridors; or (c) mosaics of stands with different age and species composition, will allow identification of ecologically and landscape-based solutions.

4. Discussion and conclusion

The paper represents an attempt to integrate forest ecosystem modelling with spatial–temporal visualisation and analysis at the landscape/forest enterprise level. Actually, the task is similar to the multi-criteria optimisation used for forest planning and decision-making (Pukkala and Kangas, 1993; Pukkala et al., 1997; Kangas et al., 2000; Varma et al., 2000). The mathematical optimisation is more effective for evaluation of the well-defined forest productive functions. The visualisation gives a possibility of direct representation of time series and spatial patterns reflecting the forest dynamics in graphical form. It allows evident and easy analysis of the dynamic trends and effectiveness of various silvicultural regimes. We tried to evaluate feasibility of interactive visualisation approach as a tool for transition from forest simulation at the stand level to analysis of management regimes in the forest territory.

A test of the prototype for evaluating dynamics of carbon pools under two management regimes in a forest area of 25 ha showed very promising results. We found that some important features of the approach were efficient. Firstly, the visualisation of spatially distributed time series on the map is very efficient (Figs. 1 and 2). Secondly, the analysis of the spatial combination of carbon pools in forest compartments in the first and the second scenarios allowed to evaluate the effectiveness of various strategies. Thirdly, spatial representation of the diversity of ecosystem reactions in various forest compartments provides the possibility for spatial combination of various strategies and functional zoning of the forest. Visual representation of interactions gives an easy and clear basis for direct decision-making. The readers can try to model their decisions analysing Figs. 2–6.

In the model experiment, we analysed only the data on carbon dynamics. However, this methodology allows many other parameters to be expressed on the map. For example, we also used indices of biodiversity (species richness correlated with stand composition and SOM pool) and recreational attractiveness (scenic beauty of forest) in the experiment. Thus, significant temporal and spatial dynamics of these attributes provided valuable information for decision-making.

A huge amount of data has been calculated in the result of the simulation process. It is important to have the possibility to select automatically, or in dialog, the most important attributes for the analysis. For this purpose various methods of spatial data mining can also be applied (Andrienko and Andrienko 1999b,c). This might be a possible topic for the further development of the proposed prototype.

The model experiment on integration of forest simulation with spatial–temporal data exploration justifies a prominent role for the expert in the proposed methodology of forest decision-making. Actually, it is impossible to formalise completely all spatial and temporal problems at the landscape level. The personal skill and non-formalised experience of the expert, that reflects his/her silvicultural, ecological, economic and so-

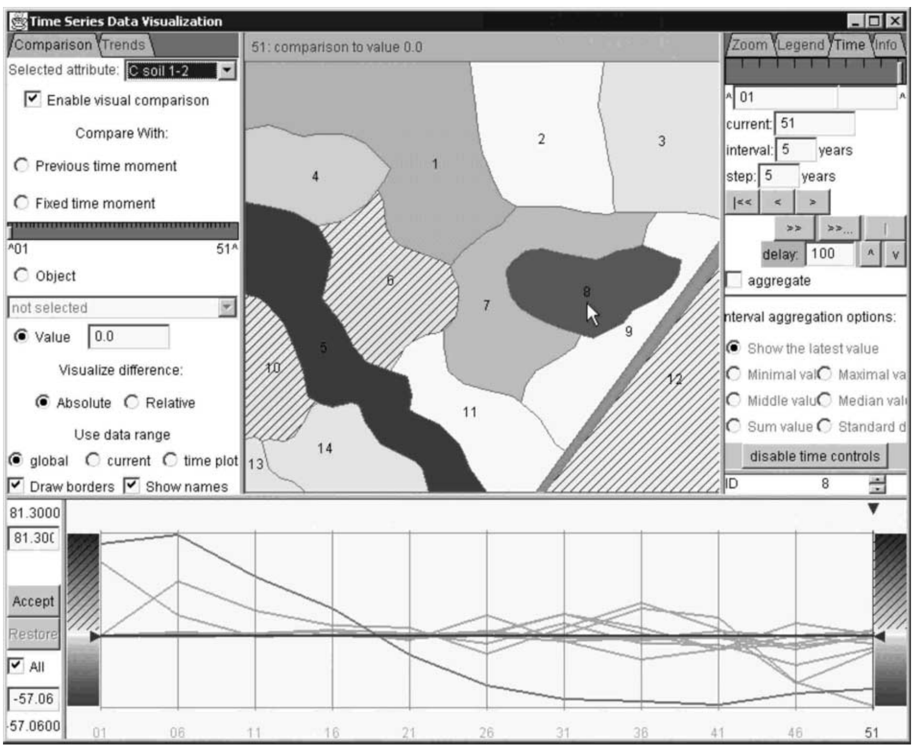


Fig. 4. Difference of soil carbon pool between 1st and 2nd scenarios (map); and temporal dynamics of the differences for every forest compartment (graphic with 5-year time interval). A scale (ton per forest compartment) is represented in the left down corner

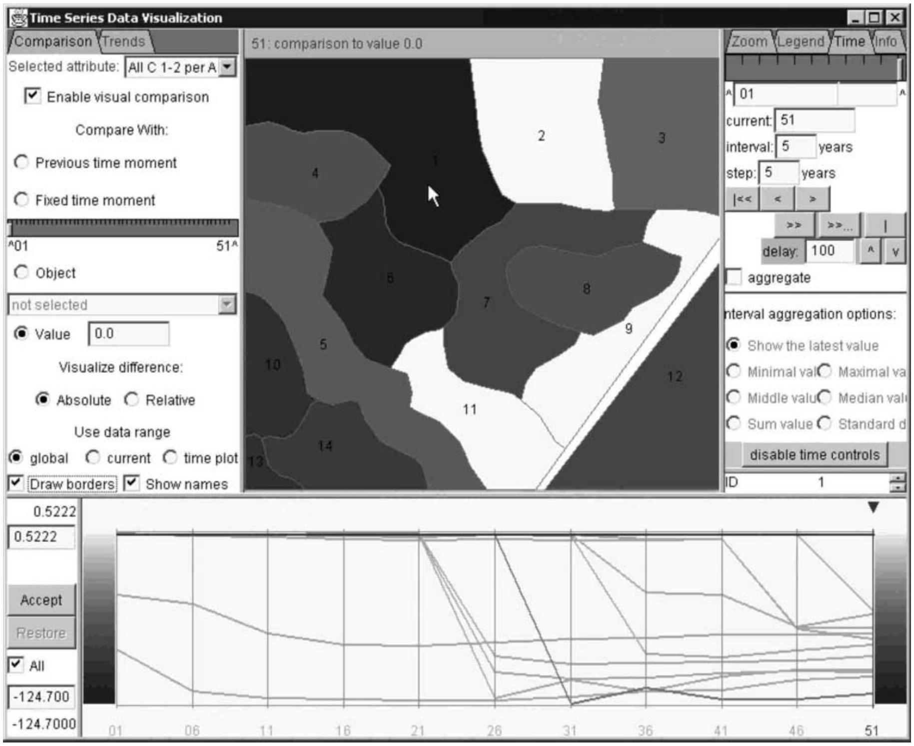


Fig. 5. Difference of normalised ecosystem carbon pool between 1st and 2nd scenarios (map); and temporal dynamics of the differences for every forest compartment (graphic with 5-year time interval). A scale (ton per hectare) is represented in the left down corner

cial knowledge, plays a crucial role in silvicultural challenge for SFM at the explorative visual analysis of long-term forest simulation data.

We should point out that the transition from stand to landscape level, for e.g., from forest gap to Markov chain models leads to generalisation of system parameters (Urban et al., 1991; Acevedo et al., 1995; Logofet and Lesnaya, 2000). Really, in this case there is a loss of detailed information obtained at the stand level. Hence, the proposed direct use of stand level ecosystem simulation for analysis of landscape patterns and dynamics significantly increases the value of this methodological approach. For practical implementation of the approach it is important that the decision-maker can make calculations of any parameters at the landscape/enterprise level. The other problem is the applicability of integrating simulation modelling with EDA for large areas (100–1000 stands and more). We can conclude that the approach is applicable for small and medium-sized forest enterprises (ranges and ownerships) in the majority of European countries.

The conclusions that can be drawn from the model experiment for the system implementation as a tool for decision-making are three-fold. Firstly, we do not think that this approach is an alternative to existing methods. It provides an additional tool for forest decision-making, and has potential for further development. Secondly, it was demonstrated that visualisation of results of modelling forest dynamics in multiple spatial compartments is very valuable for analysis and understanding of processes at the landscape level. DESCARTES has shown itself to be a powerful tool for visual exploration of such results as a result of its high interactivity, dynamic linkage of maps with other types of graphical displays, and support of various transformations of data and displays. Thirdly, it has become clear that

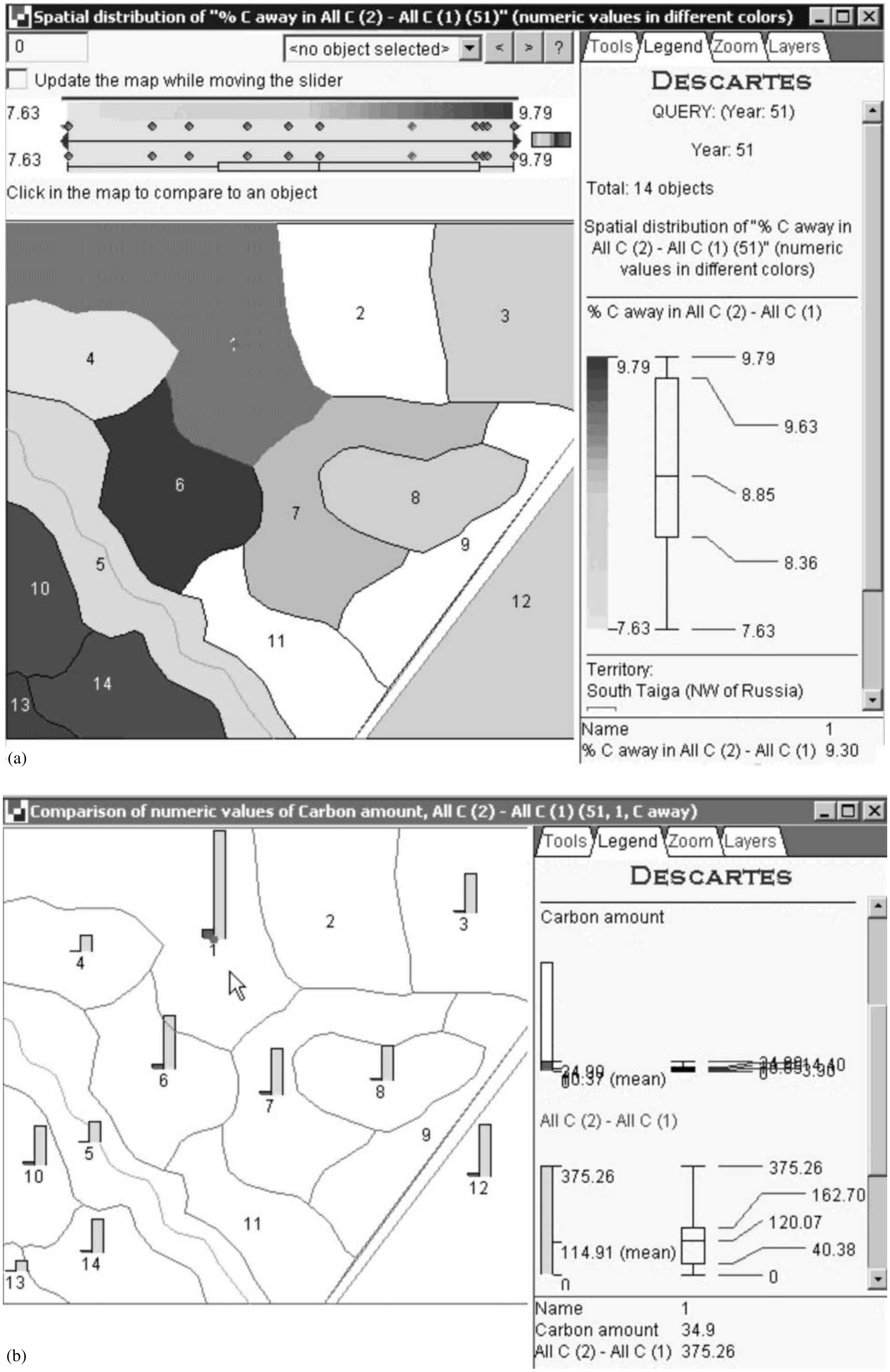


Fig. 6. Comparison of total ecosystem carbon loss (as difference between total carbon in 1st and 2nd scenarios) and carbon removed from the ecosystems with cut wood (lumber) at the end of simulation. (a) percent of removed lumber in total carbon loss; (b) values of removed carbon and total ecosystem loss after cuttings in 1st scenario, tons.

DESCARTES (as well as other existing mapping tools) do not completely meet the requirements posed by the practical tasks of SFM and research tasks of studying forest processes at different hierarchical levels. In the process of experimentation the domain experts have expressed a number of immediate remarks and wishes. For example, there is a need to compute certain types of spatial and temporal statistics.

We are sure there is a major need to create a new user-friendly modelling system that integrates various types of forest models with explorative data visualisation for methodologically easy and expressive decision-making based on long-term simulation at the forest enterprise or landscape level. We foresee that a design of such the exploratory modelling system will require significant efforts of experts in computer technology, forest ecology and silviculture. Nevertheless, this system ought to be necessary to operate with all outputs of stand level models at the landscape level. The system would be extremely useful for tactical and strategic decision-making for SFM.

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