Math. Model. Nat. Phenom.
Vol. 4, No. 5, 2009, pp. 53-71
DOI: 10.1051/mmnp/20094504

System analysis and mapping of interaction mechanisms of natural processes in mountainous-taiga landscapes

S. Myasnikova*

V.B. Sochava Institute of Geography, Irkutsk, Russia

Abstract. A spatial and temporal diversity of processes and phenomena is observed in mountain-taiga landscapes as the object of management. A knowledge of the mechanisms of their interactions makes it possible to effectively manage these processes and phenomena. The methodology of system analysis and mathematical models of interaction mechanisms are used in the analysis of these phenomena. A visualization of modelling results is carried out using geoinformation mapping methods.

Key words: system analysis, modelling of interaction mechanisms, geoinformation mapping
AMS subject classification: 91D20

1. Introduction

The ever increasing human-caused transformation of environment dictates a need to create objective models for assessment and forecasting of the actual consequences and outcomes of such an impact. The basis for the creation of such models is provided by system analysis which is intended to develop models and methods of automatic processing of data on natural-social systems. Geoinformation modelling and mapping is becoming an essential tool for real-time, scientifically-grounded solution to problems of this kind.

*E-mail: tyara@irigs.irk.ru

1.1. Origin of the problem

In the mid-20th century, objects having a particular complexity were revealed by various branches of contemporary science, and the analytical method turned out to be inefficient in gaining a better understanding of them. It was necessary to develop a different methodology, properly a new science of a fully dialectical approach to any object under study. System analysis, which harmoniously incorporates operations research theory and control theory has become such a methodology.

Natural processes and systems refer to a class of complex controlled reflexive-type systems [1], i.e., systems containing free functions used by a system in achieving its goals. The term “reflexive” underlines the simplicity of a dependence of the control function on information. When describing such systems it is necessary to rely on conservation laws, and on the feedback system (behaviour functions) which transfer the properties of each system element to all others. It should be noted that “nature” is studied and assessed from the standpoint of its suitability and usefulness for the life of humans, and in regard to satisfaction of their needs. The feedback system is evident in this case, namely, society’s health depends on environmental conditions, whereas the quality of natural environment depends on society. This implies that human activity is capable of causing global changes in qualitative and quantitative characteristics of the balance of matter and energy in nature both globally and locally (“ozone holes”, extensive deforestation, etc.).

System analysis, when used in studying complex interaction mechanisms operating in the natural environment, provides a means of elucidating the regularities of its functioning and creating comfortable living conditions. Based on the above line of reasoning, this paper examines the mechanisms through which nature is evolving as an objective reality, with due regard for the influence of society’s needs on this process. Nature management implies exerting some action on the system of society-environment interactions in order to regulate the satisfaction of the needs natural resources, the properties and qualities of natural objects, as well as to preserve and, where possible, to increase the natural resources. Scientifically-grounded management of the processes by which the natural environment is acted upon, in turn, must take into consideration its self-regulatory capability under “disturbing effects”.

As part of the development of scientifically-grounded stewardship methods of nature management, the **problem** is formulated as a contradiction between the need for effective organization of natural system management and the existing methods of describing and modelling them, and between the need for sustainable development of nature and society and the absence of effective systems of territorial management.

Here the **purpose** is to find adequate methods for quantitative description of the interaction mechanisms of natural processes in the particular geographical situation for an optimization of their utilization and sustainable development.

In accordance with the problem formulated, this study addresses the following **issues**:

1. To reveal the modelling content of the interaction mechanisms of natural processes.

2. To develop and implement methods of information support of models based on a geoinformation system (GIS) database.

3. To realize the sequence of procedures of system analysis for the creation of the model.

4. To carry out mapping of optimal norms of effects on mountain-taiga landscapes, based on modelling results.

5. To demonstrate the possibilities of improving the nature management planning and stewardship tools using the system analysis methods and GIS technologies.

1.2. Geographical background

There are different interpretations of the notion “system analysis” and of the sequence of stages identified and ordered in an appropriate way, with relevant recommended methods or procedures used to accomplish them [2, 3, 4]. English-speaking authors [5, 6, 7, 8] are inclined to prefer system analysis and its use in the analysis and designing of engineering systems and organizations. Russian authors [9, 10, 11] pay more attention to the theory of system analysis, the definitions of philosophical categories such as “system”, “element”, “part”, and “the whole”, and to the possibility of using it in projecting natural, social and other systems. Central and common to them is the use of a system methodology in solving complex problems.

In scientific literature, practical implementation of methods of system analysis involves solving problems in physical geography and ecology [12], system mapping [13], management and banking [14], software development [15, 16], medicine and epidemiology (for assessment of the state of epidemic process, its prediction and selection of optimal methods for conducting antiepidemic campaign), as well as in sustainable management of wetlands [17], in identifying environmental quality indices [18], etc.

System analysis in this paper implies a discipline dealing with decision-making problems where the selection of an alternative involves analyzing complicated information of a different physical origin [1]. System analysis may be arbitrarily divided into two parts which follow each other [13]. The first part includes substantive (expert) analysis comprising the following stages: problem statement, formulation of the goals, formulation of tasks, and definition of criteria and of the methods of problem-solving. The second part is as follows: a mathematical experiment begins with the creation of the model for a given “problem”; after that, it is provided with information support and is investigated, the possible strategies are analyzed, the optimal control problem is solved, and this ends with decision-making. Models in this case serve not only to obtain accurate characteristics but also to make estimates such as to be able to see the allowable limits of actions or the capabilities of processes under investigation, and their development tendencies, including for an optimization of some of the actions. It is optimal control of natural systems that permits identification of their self-regulation potentials and avoid destruction or depletion of these systems in the process of exploitation. Self-regulation of a system implies its ability to preserve typical features of this system at a definite level in the process of its functioning.

2. Model and methods

This paper outlines the technique of implementing the system analysis procedures for solving problems based on modelling of interaction mechanisms of natural processes. Geoinformation mapping methods (mathematical models of mechanisms, and maps of their geoinformation support and presentation of modelling results) will help combine the procedures of systems analysis and mapping.

Modelling has its origins in the through theory of interaction mechanisms; using the structure of a process under study as the base, this theory would suggest natural methods of modelling different mechanisms without resorting to additional hypotheses [19]. An example of such models is provided by gravitational models of population relocation and migration, and by schemes of economic and financial regulation mechanisms. In nature, regulation mechanisms are represented by matter-energy cycles, and by recovery processes in ecosystems after disastrous impacts (tree-cutting, fires, destruction caused by pests and pollution of the ground-level air, etc.). In biology, the concept of homeostatic regulation [20] corresponds best to this approach, representing the mechanisms by which a constancy of internal characteristics of living organisms is maintained. Asymptotic methods of investigating stability of the movement in a local vicinity of the equilibrium point enjoy wide application in this research area, which is used in describing natural systems [21, 22].

The system theory of interaction mechanisms describes the behaviour of objects in the phase space of their independent characteristics. The elements of modelled systems are represented by the deviations of values of an object's characteristics from equilibrium ones within the domain of definition (of existence of the object). The whole set of allowable deviations of the state of the system from the equilibrium one determines the layer of the space of states (Fig. 1). All this space stratifies according to the particular equilibrium state to which the object tends. Different objects can have similar characteristics (correspond to the same point of the phase space), yet they can refer to different layers if they tend to different targeted states. This means that the layers of states of states overlap rather than intersecting [23].

The interaction is represented by superimposing the regions of existence and reciprocal influence of different objects, which is specified by oriented graphs of the interaction (Fig. 2), where the nodes are layers, and the arrows indicate the action of a layer upon a layer. The connections (impacts) are described by different-order differential equations "in the deviations" where a change of any characteristic, for example, is a function of deviation of values of all the other characteristics from equilibrium ones.

Specifically, an example of the territorial interaction is provided by the "nature (3) – society (1) – production (2)" relation. Production is a link mediated through action, and nature is the synthesis of management. This arrangement of the arrows of the graph simulates the process of nature management, whereas the reversal of the arrows simulates the environmental protection.

The basic law of a system's behaviour in the vicinity of the equilibrium point describes changes of the measure of deviation from an equilibrium R_i as the result of a disturbance of equilibrium

$$\frac{dR_i}{dt} = HR_i, \tag{2.1}$$

where H is a constant which, in the general case, has a complex value on which the type of behaviour of the object depends.

One of the simplest variants of the right-hand side of equation (2.1) is a linear combination

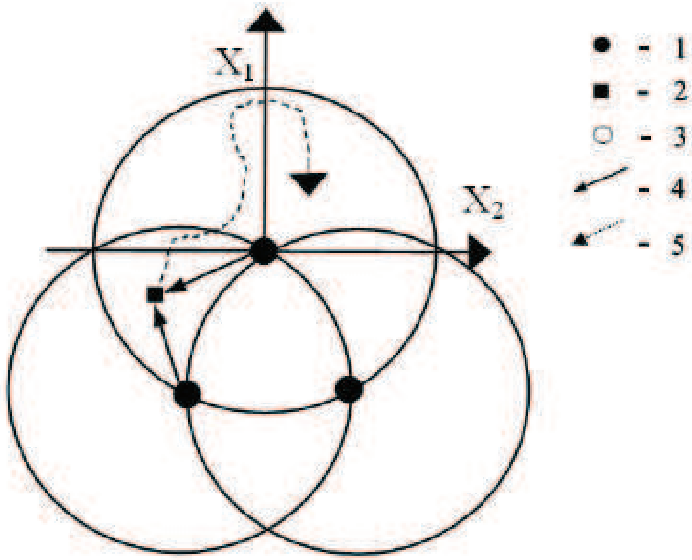

Figure 1: Schematic representation of the system's behaviour model: 1 – equilibrium state; 2 – object under study; 3 – layer of the space of states; 4 – deviation of characteristics of the object under study from equilibrium ones; 5 – trajectory of object movement

of different forces that are determined by the degree of deviation of the system's parameters from equilibrium. In such a case, the working equation becomes [19]:

$$\frac{d^i R_i}{dt^i} = \sum_{j=1}^{n} a_{ji} R_j - u_i, \tag{2.2}$$

where i is the order of derivatives $(i = 0,\ 1,\ 2,\ 3)$, and $\{a_{ji}\}$ are the interaction coefficients (effect of the *j*-th component of the system on the *i*–th component). The variable $u_i\,(t)$ is a function of management reflecting external (including organizational and natural) effects. The equilibrium state of the system depends on its value when, for example, the resource base or the investment level increases. In addition to the regulation action $u_i\,(t)$, the specific character of the territory and objects of management is also taken into consideration through the coefficients $\{a_{ji}\}$ and the initial (starting) development conditions $R_{0i} = R_i(0)$. The coefficients must all be included on the list of geographically parameters to be determined through identification and typification of local conditions and acting groups of interests (components).

Equations of the form (2.2) allow problems of optimal management problems to be specified and solved using Pontryagin's maximum principle [24, 1].

Individuals and populations of large animals [34], the structure of implementation of the estimate of budgetary revenues and expenses [35], the structure of resources of three types of species (deciduous, light-coniferous, and dark-coniferous) can be regarded as model objects to better understand the development patterns of geographical situations and behaviour mechanisms of com-

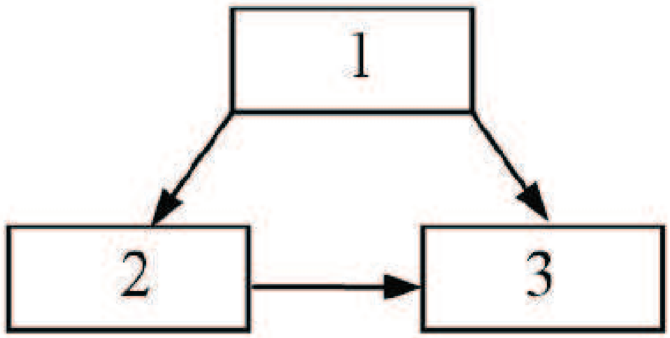

Figure 2: Oriented diagram of interaction

plex biosocial systems in different environments. Observations of them in a native environment for them provide a means of formulating and verifying special hypotheses which can be used as the basis for mathematical behaviour models representing interaction mechanisms of systems and taking into account the local conditions of their vital activity.

2.1. Mathematical models of recovery of forest resources

The Khilmi model [25] of accumulation of forest resources is the simplest model of behaviour of natural systems: $\frac{dW}{dt} = \lambda(W_0 - W)$. In biology, a model of such a type is called von Bertalanffy's equation. Equilibrium in this model is achieved at $W = W_0$. Therefore, the deviation level from equilibrium is $R = W - W_0$. Hence, the Khilmi equation in accepted terms is: $\frac{dR}{dt} = -\lambda R$, i.e., in (2.2) i=1, $a_{11} = -\lambda$, and $u_i\left(t\right) = 0$. A limiting deviation for the equilibrium $R_m = W_0$, and the limiting rate of change $V_m = \lambda W_0$.

In the more complicated example, when investigating the ecological interaction mechanisms it is customary to consider three groups of forest types (deciduous, light-coniferous, and dark-coniferous) which determine through this interaction the abundance of each particular group. The proportion of the species in the composition of a forest stand is used as the abundance index. Different combinations of these proportions correspond to different situations and to different state variables of each group of species within the set of allowable states.

The process of progressive-age succession begins after fires or tree-cutting (a deviation from the equilibrium state) with the restoration of deciduous forests in which pine and larch predominate. Because of their higher productivity and longevity, they substitute aspen and birch at different locations. These processes are complicated by repeated creeping fires resulting in destruction largely of deciduous forests and dark-coniferous regrowth. Under favourable conditions regrowth of fir, spruce and Siberian stone pine is well renewed under the crown of deciduous and light coniferous forests, forming a second layer of tree stand. At the age of 150-200 years dark-coniferous forests are represented by aboriginal fir-Siberian stone pine stands with the inclusion of spruce.

These interactions are described by the generalized Khilmi equation (a variant of the general scheme of modelling (2.2)) in the form of a systems of linear differential first-order equations on the bounded closed existence domain of a system of this type with fixed coefficients for each age stage of recovery, a group of forest types, and the site class:

$$\begin{aligned} \frac{dX_1}{dt} &= a_{11}X_1 + a_{21}X_2 + a_{31}X_3 + u_1, \\ \frac{dX_2}{dt} &= a_{12}X_1 + a_{22}X_2 + a_{32}X_3 + u_2, \\ \frac{dX_3}{dt} &= a_{13}X_1 + a_{23}X_2 + a_{33}X_3 + u_3 \end{aligned} \tag{2.3}$$

Here $X_i\,(t) = R_i(t) - R_{i0}$ is the deviation of the volume stand $R_i(t)$ of the *i*-th group from the equilibrium value of R_{i0}; a_{ji} corresponds to the interaction coefficients of the *j*-th and *i*-th groups of forest types, and $u = \{u_i\}$ stands for the control action (tree-cutting $u<0$, and promotion of growth $u>0$). The left-hand side of the interaction equation (2.3) involves changes of variables with time, and the right-hand side includes the influences of the values of the variables on these changes [26].

2.2. System analysis of the mechanisms of progressive-age dynamics of taiga forests

A set of procedures of system analysis can vary with the type of problems to be solved. The sequence of system analysis procedures which is used this paper is presented in Figure 3. Implementation of these procedures implies the creation of *special technologies* consisting of many stages, at each of which the process of information transformation incorporates different mechanisms based on special geographical knowledge and mathematical methods of the analysis. These technologies (of information and non-information contents) are based on using GIS and refer to a broad class of GIS technologies. GIS technology is a powerful modelling tool which ensures both attributive and spatial requirements to objects and make it possible to perform a geographical analysis in order to determine the spatial connections of objects located on the territory as well as the process of organization of handling information on its transformation to gain qualitatively new knowledge.

The first stage, the generation of the information object, coincides with the technology of creating a GIS project where a GIS territory becomes an invariant in all subsequent transformations which generate variants of new information. Therefore, this technology is created not for a particular problem but for a complex of problems. Such a GIS must contain the entire body of basic information (the topographic and landscape basis, the natural and economic infrastructure, space images, the forest inventory database, the socio-economic description of residential centres, etc.) which is potentially necessary for solving various problems related to territory management [27, 28].

Based on GIS information that was sorted out and put conveniently in a unified form, it is easier to formulate problems and define the goals and objectives. It is the stage of setting the problem that calls for the sorting of GIS information according to the particular uses of geographical information. That is, when progressing along the chain of system analysis procedures, the degree of modification of information is enhanced, compared with basic information, is changed through the use of special data and knowledge, as well as of the data conversion software.

2.3. Identification of the model

Figure 3 presents the general scheme of implementation GIS technologies for the solution of various problems. One of the uses of geographical information in solving optimal managment problems is illustrated in Figure 4. The upper row in Figure 3 shows the scheme of model identification (2.3) from GIS data:

1. Plots of the states of volume stands are plotted for different groups of species, groups of types, and site classes (Fig. 6). Each forest stand within a single group of forest types (roughly corresponding to the group of geographical facies as regards the scope of the notion) is represented in Figure 6 as a single dot (the volume stand per unit of area for a given group of species in a given forest management unit). This is a set of values of $R_i(t)$ for a fixed t. It is evident that for different forest management units under the same conditions there is a huge spread of values which is usually interpreted as the "observational error", and the variation of the mean values of the variable is used as the resulting tendency. The question naturally arises: Does the variation of the mean describe a change in some real situation?

2. Envelopes of the resulting set of dots are retrieved. Parameters of the observed ecosystems as recorded in the GIS database objectively (with the known accuracy of forest assessment) reflect the state of biogeocenoses. Even within one group of even-aged forest types there can occur a significant spread of indices associated with the characteristics of the initial conditions of forest rehabilitation, of the local specificity of species interaction, etc. The behaviour of all biogeocenoses is described by equations of the form (2.3) with the variable $R_i(t)$ and the interaction coefficients a_{ji}. However, if they refer to one type of system, i.e. have the same characteristic properties (intensity, resistance, controllability, etc.), all these systems turn out to be equivalent, no matter the extent to which they differ in their parameters. Mathematically [29], this means that the variables $R_i(t)$ of different biogeocenoses are linearly dependent. A great number of behaviour trajectories of one-type ecosystems $R_i(t)$ densely cover the "characteristic of volume stand – time" space, showing different values of the volume stands of a particular species. For any t there will always be the largest volume stand $R_{mi}(t)$ in a set of realizations $R_i(t)$ of behaviour of one-type ecosystems at different locations. The curve $R_{mi}(t)$ is regarded as the envelope of a set of all possible trajectories $R_i(t)$. It is known [29] that the equation of the envelope $R_{mi}(t)$ is the solution to the initial equation (2.3) with corresponding parameters a_{ji}.

   Having mass data stored in the GIS database, it is possible to reconstruct the curve of maxima $R_{mi}(t)$ for one-type situations (groups of forest types).

3. Stages of progressive succession are identified, and the influence coefficients of equation (2.3) are calculated for each stage [26, 28]. Considering the curve of maxima $R_{mi}(t)$ to be the envelope curve, the set of coefficients a_{ji} of the system of equations (2.3) is determined

by the multiple regression methods for each stage of progressive succession. Stages are identified according to the periods of time within which a high multiple correlation is maintained for each equation of (2.3).

4. The limitations $u_{\min} \leq u \leq u_{\max}$, i.e. the minimum and maximum economic loads, are imposed on the managment (control). According to (2.3), any constant control action makes a system's equilibrium state shift toward some or other direction.

5. The maximum of functional influence of different-species volume stand on different (including economic) processes for the period of rehabilitation time $T = 500$ year is used as the optimality criterion of managment (control):

$$J = \int_0^T (a_1 X_1(t) + a_2 X_2(t) + a_3 X_3(t))dt \to \max, \tag{2.4}$$

where a_i is the importance (influence) coefficients of the volume stand of the *i*-th group of species on different processes. Then the value of J has the meaning of the total effect for the aforementioned period of time, for instance, the total water runoff per unit of forest area or the income from recreational utilization of forests. In each process, any species has its own significance and plays a definite role.

6. The solution to the optimization problem as formulated in (2.3)-(2.4) begins with the development of the Hamiltonian function (see Fig. 4):

$$H = -(a_1 X_1(t) + a_2 X_2(t) + a_3 X_3(t)) + \sum_{i=1}^{3} (a_{1i} X_1 + a_{2i} X_2 + a_{3i} X_3 + u_i)\varphi_i(t), \tag{2.5}$$

represented by the sum of the integration element (2.4) and the products of additional variables φ_i, and by the right-hand sides of the equations of the system (2.3).

According to Pontryagin's maximum principle, the optimal regime of functioning of this system is observed at those values of u which ensure the maximum value of

$$H = \sum_{i=1}^{3} \varphi_i(t) u_i(t) + ...$$

It is clear that a maximum H occurs at $\varphi_i > 0$, when $u = u_{\max}$, and at $\varphi_i < 0$when *u* =*u*min. At $\varphi_i = 0$, there arises an uncertainty of the solution which requires a special treatment. Thus the variable $\varphi_i(t)$has information content, suggesting the manner in which the system can be controlled. It is reasonably safe to suggest that the higher is the absolute value of $\varphi_i(t)$, the more categorical (unambiguous) is the recommendation that the control be maintained at a particular level; therefore, the value of $\varphi_i(t)$can be called the *parameter of categoricity of managment*.

7. The rate of change of $\varphi_i$is inferred from the equation $\varphi_i'(t) = -\frac{\partial H}{\partial X_i}$:

$$\begin{aligned}\varphi_1' &= a_1 - a_{11}\varphi_1 - a_{12}\varphi_2 - a_{13}\varphi_3,\\ \varphi_2' &= a_2 - a_{21}\varphi_1 - a_{22}\varphi_2 - a_{23}\varphi_3,\\ \varphi_3' &= a_3 - a_{31}\varphi_1 - a_{32}\varphi_2 - a_{33}\varphi_3.\end{aligned} \tag{2.6}$$

The variable $\varphi_i(t)$ is a function of time and can take either positive or negative values on different time intervals; therefore, the control solutions imply the switchover from minimal to maximal control, and vice versa, i.e. it is always necessary to act according to the situation. The solution to the differential equations (2.3) and (2.6) is inferred numerically by forward calculation for (2.3) and backward calculation for (2.6) over time.

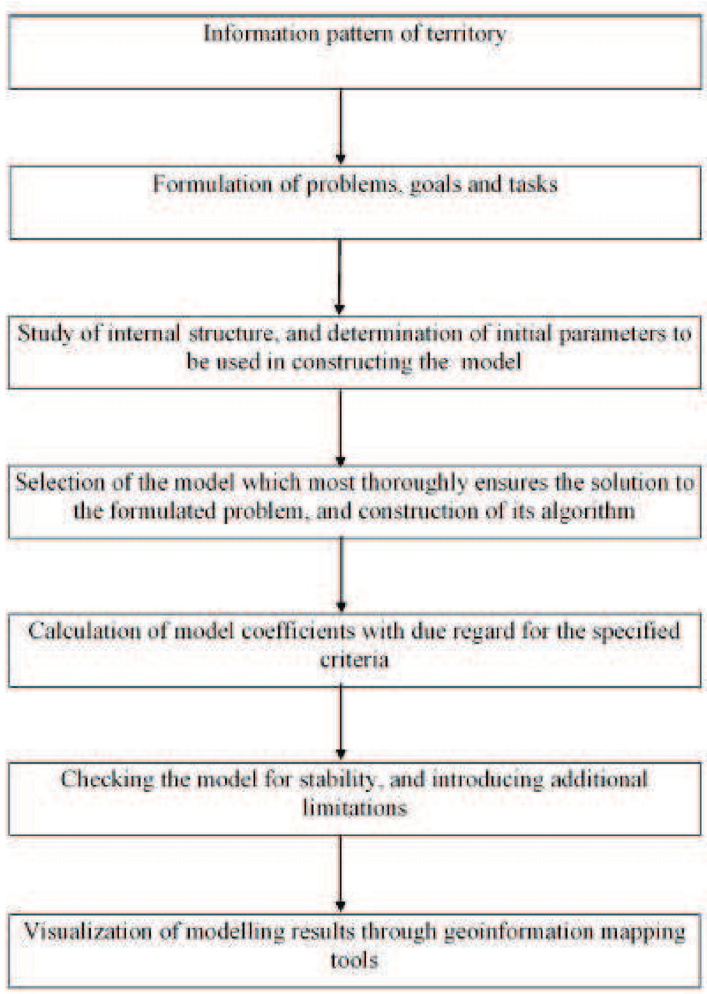

Figure 3: Schematic representation of the sequence of system analysis procedures for geoinformation modelling and mapping of interaction mechanisms of natural systems

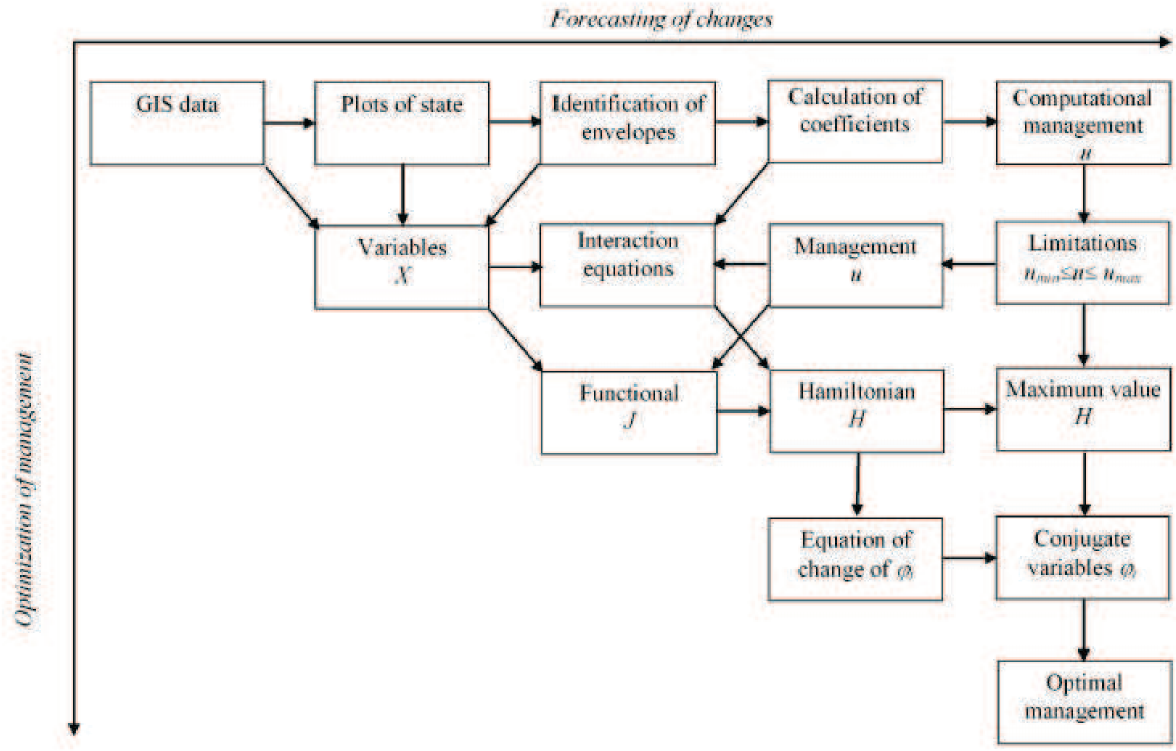

Figure 4: Scheme of geoinformation modelling of optimal regimes of nature management [30]

3. Results

Progressive-age dynamics of resources of mountainous-taiga forests on the Khamar-Daban range (Slyudyanka forestry of the Irkutsk region) was analyzed as a case study. These forests refer to several prevailing groups of forest types (Fig. 5).

Forest management data for the year 1980 that are aggregated in the GIS database for individual forest compartments in the Slyudyanka district, were used [31]. Mountainous relief, the varying climatic conditions, and a diversity of the biota are responsible for the complex landscape structure of the territory, with a high degree of contrast. An altitude difference of nearly 1900 m on the northern macroslope of the Khamar-Daban range gives rise to a zonality, with a succession of geosystems from low-mountainous taiga to golets alpine-type geosystems with the mountainous tundra.

Along the shores of Lake Baikal at the foothills there occurs a mosaic pseudo-golets zone formed by dwarf Siberian mountain pine and ledum. Bogs and secondary birch woods with the hygrophilic moss and sedge cover are observed on Baikal's terraces. The forests of the coastal highland refer to taiga-dark coniferous forests, with Siberian fir totally predominating in the forest stand. Fir forests are characterized by high productivity (III site class), but they are sparse and

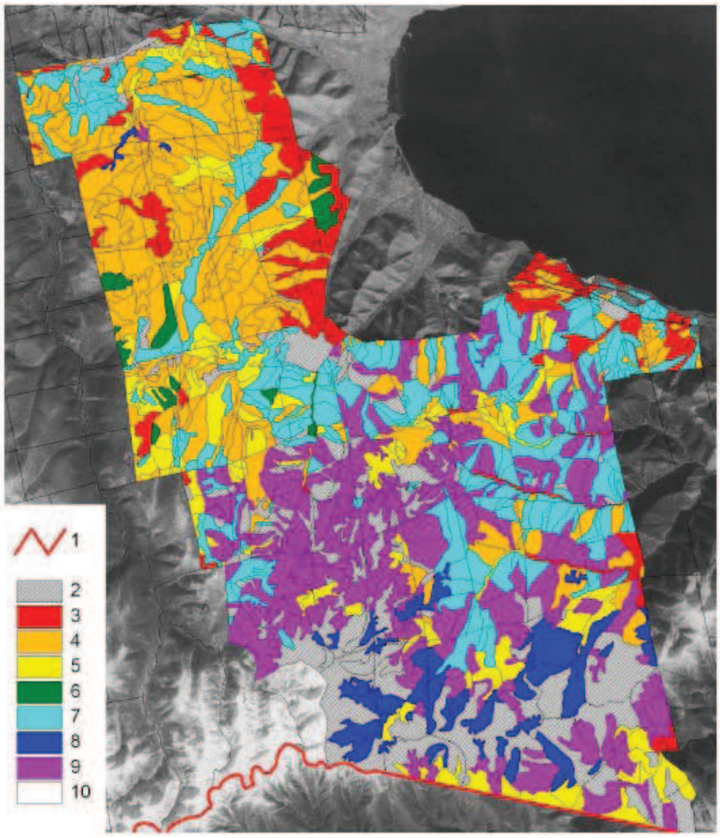

Figure 5: Groups of forest types on the model site. 1 – boundary of the Slyudyanka district; groups of types: 2 – other groups of types, 3 – forbs; 4 – cowberry-true mosses, - 5 – true mosses; 6 – tall grass; 7 – ledum; 8 – lichen-dead cover; 9 – mountainous-stony; 10 – compartment network of neighbouring forest districts.

uneven-aged. Fir forests are the home to a large number of relicts of the nemoral floristic complex which have persisted on these territories since the end of the Tertiary period. Siberian stone pine forests: grass-true moss, bergenia and tall grasses) occur in areas with soils of small thickness.

The subalpine-subgolets zone of Siberian stone pine and fir forests lies at an altitude of 1300-1700 m above the sea level. Only fir forests reach the upper forest limit. The most common are park fir forests, with tall grasses and ferns predominating.

The mountainous-taiga altitudinal zone of vegetation stretches along the slopes at an altitude between 800 and 1500 m above the sea level. It includes fir and Siberian stone pine forests of site class III-V. The grass, true moss and bergenia types of forest are dominant. Tree-cutting and fires led to the occurrence of secondary (mainly birch and grass-true moss) forests which replaced fir forests with tall brushwood (dwarf Siberian mountain pine, and mountain alder).

The cowberry-true moss type group, unlike the other groups represented in the area, combines, according to the criterion of spatial adjacency and similarity of biogeocenotic characteristics, the cowberry-motley grass, cowberry, cowberry-true moss and bilberry type groups. The name of this

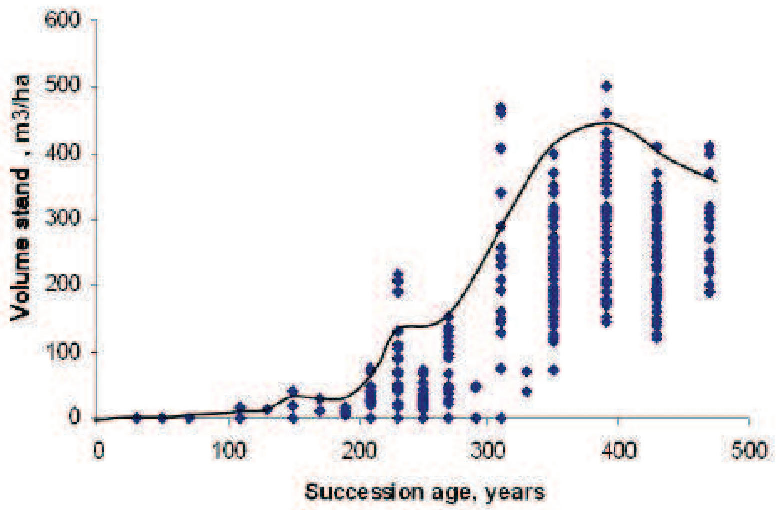

Figure 6: Changes in volume stands of dark-coniferous species with age in mountainous-taiga cowberry-true moss forests of site class III (retrieved from the GIS database for the Slyudyanka district and processed - initial data). Dots characterize the state of some forest assessment compartments, the line is the envelope of the set of these dots.

aggregate group derives from the name of the group prevailing (in area) on this site.

A preprocessing of data was carried out according to the scheme in Figure 4 [26, 28, 32]. Information on the age of the main forest species, the species composition of forests, the total volume stand, the area of the forest management unit, and the forest type was retrieved from the GIS database of the Slyudyanka Forestry Administration. Three interrelated forest elements were identified (deciduous and light- and dark-coniferous forests) for which the volume stand was determined. In the process of interaction, these groups of species are responsible for a progressive-age succession on forest clearings and in burned-over areas where the first stage is dominated by deciduous forests, the second stage is dominated by light-coniferous biocenoses, and dark-coniferous species prevail in the final stages of development. The “succession age” of forests is made up of the age of the previous stages and the current age τ of a forest stand: deciduous $T = \tau$, light-coniferous $T = 50 + \tau$, and dark-coniferous $T = 150 + \tau$.

Changes in dark coniferous elements of forest volume stand with age *T* were analyzed by considering an example of the group of cowberry-true moss forest types which is widespread in the taiga zone of the mountains. Data were sorted according to the “succession age” corresponding to the stages of progressive succession (Fig. 6).

The envelope curve (solid line in Fig. 6) was determined; maximum values of the volume stands were taken for each age from the plotted envelope, and a series of data on changes in volume stands was generated at steps of 10-20 years, i.e. a dynamical model for a standard stand (forests which can form on a given territory under the most favourable conditions). Based on these

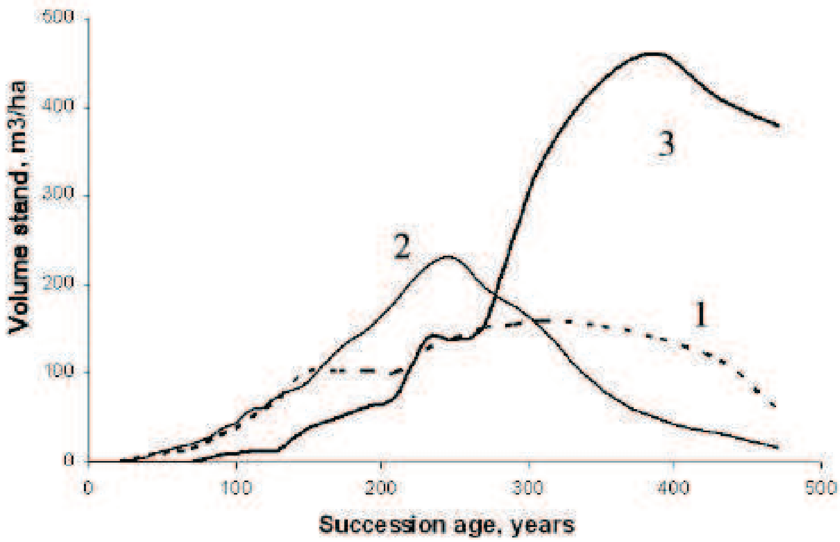

Figure 7: Changes in volume stands of mountainous-taiga cowberry-true moss forests of site class III for the Slyudyanka forestry (calculated data) according to forest elements - stands: 1 - deciduous, 2 - light-coniferous, 3 - dark-coniferous.

data, the multiple regression methods were used to calculate the values of the changes in volume stands in species per unit of time (year). After that, the coefficients a_{ji} of system of equations (2.3) were determined for each stage of progressive succession.

The resulting values of the coefficients a_{ji} were used in calculating the curves for standard changes in volume stands of forest elements for each group of types (Fig. 7). Most of these procedures are based on logic operations which are realized with software Excel in relation to the GIS database and to secondary data on the properties of the envelope lines which summarize and aggregate the data from the GIS. A recalculation is done automatically upon substituting a_{ji} into the initial table.

A comparative analysis showed that the calculated data (Fig. 7) are in good agreement with the initial data (Fig. 6); consequently, the mathematical models that have been developed for the interaction mechanisms of the components of the territorial system objectively reflect the regularities of the ongoing processes and provide a means of regulating them.

Calculations of the auxiliary variables $\varphi_i(t)$ were carried out for different groups of forest types on the assumption of an optimal functioning of forest stands and an equivalence of the species $(a_i = 1)$. The sign $\varphi_i(t)$ changes over time (Fig. 8), generating a network graph of forest management. A network graph is the schedule sequence of execution and interrelationship of operations and is produced to obtain the planned result by the target date. This change of $\varphi_i(t)$ over time (Fig. 8) points to the time of switching the quality (directedness) of management. For instance, the optimal regime of functioning for cowberry-true moss forests implies the promotion of renewal and

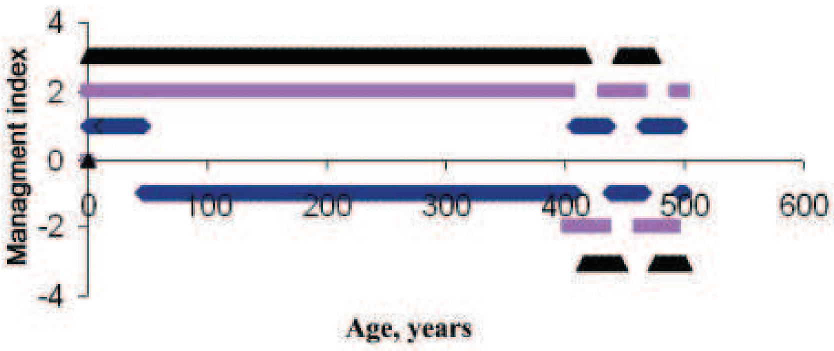

Figure 8: Network graph of resource management of mountainous-taiga cowberry-true moss forests of site class III in forest elements - stands: 1 - small-leaved, 2 - light-coniferous, 3 - dark-coniferous species.

growth of deciduous species to the age of 50 years followed by felling. Dark- and light-coniferous stands are preserved for a long time, to the age of 400 years, whereupon a part of the resources can be exploited.

A change of priorities a_i somehow alters the timeframe for the conduct of economic measures. The network graph for different forest types has an intrinsic structure.

The procedure of calculating the optimization characteristics as realized in Excel permits a prompt change of the various model parameters to obtain results in the form of tables and graphs; for instance, to determine what will occur in the structure of the network graph with a change in the value of the species a_i (the quality (character and degree) of their influence on natural environment or the effectiveness of the economic activities), which makes it possible to use the computational scheme thus developed in decision-making.

The value of categoricity $\varphi_i(t)$ was determined for each forest management unit according to the succession stage of forest development and age. As a result, the map was constructed for the directions and intensity of management of forest stands in terms of the indices $\varphi_i(t)$ (Fig. 9). The categoricity levels are interpreted in terms of landscape planning [33].

The priority of nature conservation protection is established to ensure ecologically sustainable forest management; therefore, the nature conservation goals are put in the forefront. Since group I forests (water-protective and other functions) are dominant in the study area, the preservation is becoming the top priority area of activity: exclusive preservation, the preservation of the current state with abandonment of separate kinds of utilization, and the preservation of the current extensive utilization.

Figure 9 presents the categoricity indices of management of dark-coniferous forests. In most of the territory, it is recommended that the current state of forests be preserved. There are areas of the mountain slopes in need of the promotion of the rehabilitation. Regulated extensive forest exploitation is possible in some scattered areas. Regulated intensive utilization is possible on

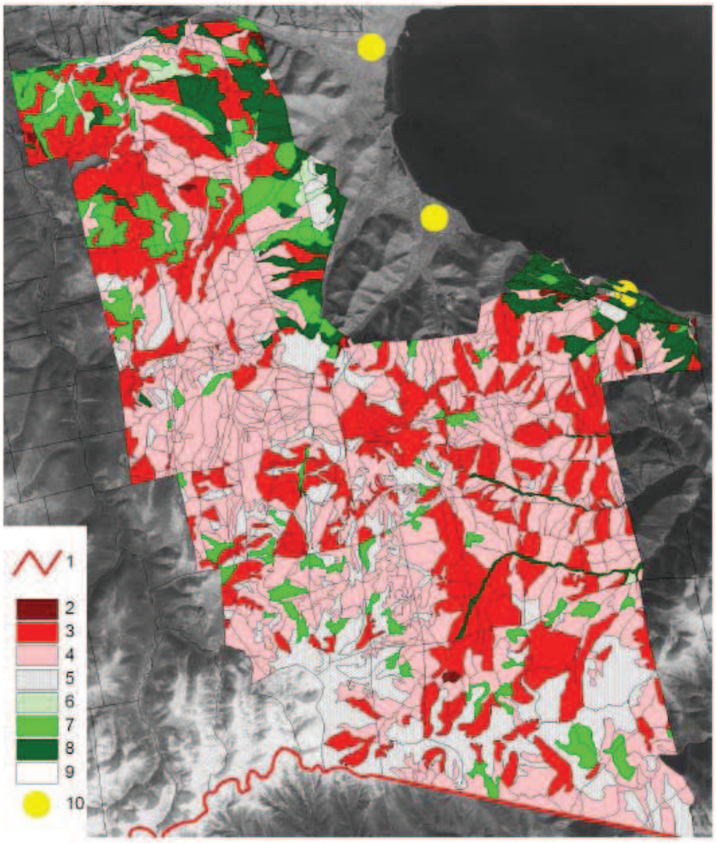

Figure 9: Categoricity indices of management of the timber volume of dark-coniferous forests: 1 – boundary of the Slyudyanka district; categories of management: 2- conservation, reserved modality; 3 – preservation and rehabilitation; 4 – preservation of the current state; 5 – uncertainty in decision-making or no data; 6 – limited utilization; 7 – restricted extensive utilization; 8 – restricted intensive utilization; 9 – compartment network of neighbouring forest districts; 10 – residential centres.

the relatively steep slopes approaching Lake Baikal. This result realistically reflects the present situation in the study area as regards environmental protection [26].

4. Conclusion

Contemporary management of the impact on the environment must switch over from extraction and limitation to rational transformation, and to adaptation of human activities to the peculiarities of natural environment. Organization of purposeful, conscious activity involving the impacts on the environment based on scientific planning of actions, forecasting of the consequences, and search for optimal methods of their management has become an objective necessity. In this case, system approach to the complex set of ecological processes, and system analysis methodology developed on its basis, can provide an integral understanding of the society-nature interaction, and serve a practical tool for optimization of the nature management process, and for the constructive search of techniques of its management.

In particular, practical implementation of the tools and methods of system analysis of GIS data for a territory ensures an enhancement of the capabilities of GIS technologies and system mapping. Mass GIS data are used to provide information support of interaction models of heterogeneous components, which makes it possible to manage the volume stands of different groups of species thus ensuring stability of the natural development processes of forest ecosystems.

The goal of optimal managment is achieved at the final stage of realization of system analysis procedures where the best variant is mathematically selected among a great number of possible variants with due regard for changes in natural environment. The new interpretation of the results from implementing classical mathematical methods in optimal managment by Pontryagin's maximum principle as applied to optimal forest management problems permitted determination of the allowable loads on taiga ecosystems. Managements of different directedness were recommended according to the characteristics of geographical environment and to stages of ecosystem development. The advantage of the suggested approach is the fact that the management strategy is closely associated with local conditions and development stages, which provides a means of calculating for each particular situation the network graph of management for a given criterion of effectiveness and work out the plan of measures.

An important consideration in this case is the implementation of GIS technologies for processing of mass data that are stored in a district's GIS in order to identify all variants of the state of taiga forests of one group of types and site class. As a result, the resource potential of forest stands is estimated in the form of curves of a standard change in volume stands of different groups of species. This allows the interaction models for forest species to be identified, the optimal control problem to be formulated and solved for each forest management unit, and calculation results to be represented as a sequence of optimization maps. Thus, mapping of optimization processes of forest management realizes all the stages of system analysis with geoinformation modelling and mapping.

References

[1] N. Moiseyev. Mathematical problems of system analysis. Moscow, Nauka, 1981.

[2] F. Peregudov, F. Tarasenko. Introduction to system analysis. Moscow, Vysshaya Shkola, 1989.

[3] S. Optner. System analysis for business and industrial problem solving. Moscow, Sovetskoye radio, 1969.

[4] S. Young. System management of organizations. Moscow, Sovetskoye radio, 1973.

[5] J. van Gigch. Applied general system theory. Transl. from English. 2 volumes. Moscow, Mir, 1981.

[6] R. Ackoff, F. Emery. On purposeful systems. Transl. from English. Ed. I. Ushakov. Moscow, Sovetskoye radio, 1974.

[7] W. Ross Ashby. Introduction to cybernetics. Transl. from English. Moscow, Mir, 1959.

[8] S. Beer. Brain of the firm. Transl. from English. Moscow, Radio i svyaz, 1993.

[9] A. Uyemov. System approach and general systems theory. Moscow, Mysl, 1978.

[10] I. Blauberg, E. Yudin. The shaping and essence of system approach. Moscow, Nauka, 1973.

[11] Yu. Urmantsev. General system theory: present state, applications and development prospects. System, symmetry, harmony. Moscow, Mysl, 1988.

[12] Iu. S. Nikulnikov (ed.) Geographical examination of economic development of a territory. Novosibirsk, Nauka, 1992.

[13] A.K. Cherkashin (ed.). Landscape-interpretative mapping. Novosibirsk, Nauka, 2005.

[14] S. Kamionsky. Management in a Russian bank: experience in system analysis and management.Ed. and preface by D.Gvishiani. Moscow, Business Library "Omskpromstroibank", 1998.

[15] Yu. Kolesov. Modelling of systems. Object-oriented approach. A textbook. Yu. Kolesov, Yu. Senichenkov. St. Peteresburg, BkHV-Petersburg, 2006.

[16] E. Yourdon, C. Agila. Case studies in object-oriented analysis and design. Moscow, Izd-vo "Lori", 2007.

[17] S. Loiselle, C. Rossi, G. Sabio, G. Canziani. *The use of systems analysis methods in the sustainable management of wetlands*. Hydrobiologia, 458 (2001), No. 1–3, 191–200.

[18] Yu. Pykh, E. Kennedy, W. Grant. *An overview of systems analysis methods in delineating environmental quality indices.* Ecological Modelling, 130 (2000), No. 1–3, 25–38.

[19] A. Cherkashin. Polysystem modelling. Novosibirsk, Nauka, 2004.

[20] S. Vasiliev. Ed. Modelling and management of regional development processes. Moscow, FIZMATLIT, 2001.

[21] V.I. Gurman (ed.) Models of natural resource management. Moscow, Nauka, 1981.

[22] V. V. Bufal, V. I. Gurman (eds.) Ecologo-economic strategy of a regions devel-opment: mathematical modelling and system analysis exemplified by the Baikal region. No-vosibirsk, Nauka, 1990.

[23] S. Myasnikova, A. Cherkashin. *Development of mechanisms and geoinformation technologies of territorial nature management (legal and organizational issues)*. The geography of Asian Russia. Proc. 11th Scientific Conference of Geographers of Siberia and the Far East. Irkutsk: Institute of Geography SB RAS, 2001, 214–215.

[24] L. Pontryagin. Mathematical theory of optimal processes. Moscow, Nauka, 1976.

[25] G. Khilmi. Fundamentals of biosphere physics. Leningrad, Nauka, 1966.

[26] S. Myasnikova, A. Cherkashin. *Geoinformation systems in implementation of the sequence of system analysis procedures*. InterCarto/InterGIS 10: Sustainable development of territories: geoinformation support and practical experience. International Cartographic Association, Vladivostok, 2004, 36–43.

[27] S. Myasnikova. *Expanding the possible uses of GIS technologies in territory management*. Geography: novel methods and development prospects. Irkutsk: Institute of Geography SB RAS, 2003, 184–185.

[28] S. Myasnikova, A. Cherkashin. *Geoinformation systems and mathematical technologies in implementation of system analysis procedures*. Landscape interpretation mapping. T. Konovalova, S. Myasnikova et al. Novosibirsk: Nauka, 2005, 315–324.

[29] L. Elsgolts. Differential equations and calculus of variations. Moscow, Nauka, 1969.

[30] S. Myasnikova, A. Cherkashin. *Optimizational geoinformation mapping*. Geodeziya i kartografiya, 4 (2007), 38–42.

[31] A.K. Cherkashin (eds.) The geoinformation system of territory management. Irkutsk, Institute of Geography SB RAS, 2002.

[32] S. Myasnikova, A. Cherkashin. *Forecasting the dynamics, and optimal management of taiga ecosystems of the Khamar-Daban in terms of modelling of interaction mechanisms of their components.* Modelling of geographical systems. Irkutsk: Institute of Geography SB RAS, 2004, 73–77.

[33] A.N.Antipov (ed.) Ecologically oriented land use planning in the Baikal region. The Goloustnaya river basin. Irkutsk, Institute of Geography SB RAS, 1997.

[34] S. Myasnikova, A. Cherkashin. *Spatial behaviour patterns of game animals in disturbed mountain-taiga landscapes*. Proc. School-Seminar "Mathematical methods in ecology". Petrozavodsk, 2001, 166–168.

[35] S. Myasnikova. *Information support of modelling of the budgetary process of municipal education.* Transformation of socio-economic space and prospects of sustainable development of Russia. Barnaul, 2006, 178–181.