Math. Model. Nat. Phenom.
Vol. 4, No. 5, 2009, pp. 144-157
DOI: 10.1051/mmnp/20094510

Ecological-Economic Model of the Region: Information Technology, Forecasting and Optimal Control

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Abstract. The paper considers a methodology of mathematical modeling of ecological-economic processes at the regional level. The basis of the model is formed by equations, which describe two interacting blocks: economic and ecological ones. Equations of the economic block are represented by relations of generalized inter-branch balance, while the ecological part is described in terms of differential equations with deviations with respect to some given state of natural resources. Issues of i) information support of the model, ii) techniques used for identification of the coefficients, iii) scenario analysis and iv) forecasting are analyzed.

Key words: ecological-economic processes, mathematical modelling, information support, regional systems, forecasting, optimal control
AMS subject classification: 93A30, 93C95

1. Introduction

There is no need today to persuade anybody of the serious and essential character of ecological problems faced by an individual region or by the humankind on the whole. The impact of people on nature has become compatible, by the scale of its effect, with natural processes. Due to complexity and really urgent character of resource-ecological problems there is the necessity to develop not only traditional methods related to protection of nature against pollution preventing air and water pollutions and/or cleaning-up them completely, but also elaborate low-polluting and non-polluting

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technologies, manufactures and even territorial-industrial systems based on rational placement and organization of the industries.

Problems bound up with control of environmental pollution, rational management of natural resources are stated and are attempted to be solved in the research literature and in everyday life. Attempts are undertaken to find the ways and techniques to determine economic efficiency of nature-protection undertakings. In particular, it was suggested that industrial enterprizes pay for consumption of natural resources and for improper management of natural resources, etc. [29, 31, 32, 38, 41, 45, 49, 50].

In this work we suggest the approach to ecological-economic problems based on modelling and analysis of the scenario of the ecological-economic development. We will discuss the questions of information support, special identification techniques, forecasting and optimal control problems, application of the model to various regions.

2. Ways of Formalization, the Characteristic of the Total Complex of Problems. The Objectives of Modelling

Proceeding from the problem stated above and starting from 1975, scientists of universities and academic institutions of Irkutsk and Ulan-Ude have been conducting complex investigations related to modeling of the Baikal Region natural-economic system. The objective of such investigations implies complex assessment of the regional business activity on account of special requirements related to protection of the natural environment and conservation of Lake Baikal as a unique natural object.

The following definite objectives have been stated:

1. Formulate the conception of reciprocal influence of the economy and the natural environment, which could be represented in terms of a mathematical model, which would be rather simple, easily perceptible and, at the same time, quite pithy and complete.

2. Determine the real potential of information technologies implemented in such a model.

3. Conduct theoretical analysis of the model's applicability for the purpose of making estimates, predictions and planned decisions.

4. Execute a series of experimental computations for the region.

5. Obtain more detailed estimates of the influence of economic activity on water and forestry resources.

6. Conduct qualitative analysis of the condition of Baikal seal population and assess the possibility of its industrial fishing.

7. Develop a technique of economic assessment of the natural resources.

Classical models of economic growth have played an important role in development of the economic theory. The doubtless merit of the models implies their theoretical character, which presumes deep investigation by mathematical methods, while ignoring ecological and social aspects, should be considered as an obvious shortcoming. This shortcoming does not allow one to apply them in solving problems of development in their contemporary, complex problem statement. On the other hand, there exist contemporary models of global dynamics, which are oriented directly to solving ecological and social problems, and which have already played an important role in assessment of the hazard of ecological catastrophe and in defining the paradigm of sustainable development. These models are essentially unique, have quantitative character and may be implemented only in the mode of computer simulation, without assuming any deep qualitative analysis. This is an obvious methodological shortcoming, which does not allow one to use them as a tool for systematic investigations at the level of countries, regions or preserved natural complexes.

In the contemporary literature and practical investigations, special attention is given to constructing ecological models. Such models are mainly used in solving problems of forecasting, assessment of the current state as well as the consequences of some undertakings of economic character. Taking account of potentialities of contemporary computers, which allow the consideration of large number of model's state variables, such models may be improved either at the expense of spatial extension or at the expense of increase of the number of substances or factors taken into account.

A large number of software systems intended for forecasting meteorological conditions, climate and natural factors have been developed. The set of such systems includes, for example, CRYSYS — CRYosphere SYStem (Canada), which allows the user to construct models of climate and cryosphere for the local, regional and global levels. The Dynamic Global Vegetation Model (DGVM) has been elaborated within the frames of the Project CASA (Carnegie Ames Stanford Approach). DGVM includes seasonal algorithms of phenology, which are calibrated and use interannual global sets of data, including those obtained by satellite measurements. The model allows the user to obtain global estimates of initial production of biomass, gas flows, etc. A global oceanic model OCCAM has been elaborated in the Oceanographic Center of Southampton (U.K.). It consists of a system of equations with partial derivatives and describes variations of water speed, temperature, salinity, etc.

Some global models describing planetary ecological-economic processes are known. Presently such models are under refinement for definite regions of the world. (e.g. for the third-world countries of Asia and Africa). Large-scale models intended for analysis of ecological problems of several industries have been developed. These, for example, include the model known as MARKAL. It has been elaborated and applied in Sweden and Switzerland. The projects related to constructing systems of models, which describe partial ecological processes are developed; project ECOPATH bonds up with modelling water ecosystems for each region of the world; project MEDIAS, etc. Works related to systems analysis and complex mathematical modelling of joint evolution of ecology, economy and social sphere are underway. Meanwhile, there are few works, which are based not on econometric dependencies of variables and finite-dimensional optimization, but rather on dynamic models using the optimal control theory (for example, on models of inter-branch dynamic balance).

Furthermore, there is a tendency of constructing very specialized models, i.e., the ones oriented to deep investigation of some component of natural environment with further possible extension of applicability of such models [8]-[13], [15, 33, 34, 35, 37, 39, 40, 42, 44, 46, 47, 52].

For the first time the models, in which nature and economy were described as equal components of one ecological-economic system, were proposed in [22, 25]. The first experience of their application to modelling a given region was described in [1, 23]. By the present moment, there appeared a series of collective monographs [7, 14, 16, 17, 18, 21, 24, 26, 48, 51], in which various aspects of this direction in modeling ecological-economic systems were enlighten. The same approach has been developed for modelling social processes [20] and public health in the region depending on its economical development and on the state of natural environment [4].

An important role in solving problems of protection of nature and usage of resources is given to creation and analysis of mathematical models, which describe the dynamics of natural processes and economy. Mathematical models represent the tool, which allow the user to integrate and coordinate information of various physical content, what is important in any complex and interdisciplinary investigations. Such investigations need a special universal language, so that a physicist, a biologist, an economist, etc. participating in a joint ecological research could understand each other. A language of mathematical models can be such a language. It is also important that mathematical models allow the user not only to describe the dynamics of ecological-economic systems retrospectively, but also to conduct various machine experiments with models of complex and even unique systems where practical experiments with such systems are hardly possible, to analyze different scenarios of development. The mathematical modelling approach allows one to use at last the total mathematical apparatus developed for complex analysis of the model, for solving the problems of control, normalization (valuation) of the sources, of pollutants discharged, etc. Presently, scientists possess a substantial experience related to application of mathematical models and methods in economic investigations. Different mathematical models, which describe the dynamics of the state of natural environment components, as well as some aspects of influence of the economic state on the state of the environment, have recently been developed.

At the same time, it is worth noting that in the models of territorial-industrial systems, which are presently applied for practical purposes, the natural environment and the resources are introduced only as the constraints, but not as separate subsystems. As shown by the investigation related to planning board's materials, there are almost no systematic data, which characterize the dynamics of natural environment states and resources in interaction with the national economy complex, what inevitably leads to large losses and errors, especially as far as the long-term perspective is concerned. There is only one way to overcome this obvious undesirable tendency — this is efficient and goal-oriented elaboration of scientifically grounded methods of planning and computations, in which these two components of the nature-economic complex are equally represented.

3. Regional Nature-Economic Model

3.1. Description of the Model

All the diverse processes, which take place in the nature-economic system, have been reduced to the following categories: industrial growth, consumption of products, interregional exchange, self-restoration, artificial restoration of natural resources, their reciprocal influence, increase of expenses in case of deterioration of the state of the natural environment and/or the resources. The region is considered as a territory decomposed into sections, which are related by a transport network and by some ways of possible migration of resources. In this case, each section is described by a similar system of equations of generalized dynamic balance

$$Mv = Av + Bu + A^{(z)}z + B^{(z)}w + p + v^i - v^e, \tag{3.1}$$

$$\frac{dX}{dt} = u, \quad \frac{dX^{(z)}}{dt} = w, \tag{3.2}$$

$$\frac{dR}{dt} = Q(R - R^*) - (Cv + Du + Fp + D^{(z)}w + \alpha N) + Jz + r^i - r^e, \tag{3.3}$$

$$0 \leq v \leq V(t, X, R), \quad 0 \leq z \leq Z(t, X^{(z)}, R). \tag{3.4}$$

Here $v,\ p$ — vectors of the outputs and of final nonindustrial consumption of products; $u,\ w$ — rates of capital investments intended for development of the capital and restoration funds; z — intensity of exogenic (with respect to the natural environment) restoration of resources; $X,\ X^{(z)}$ — volume of the capital and restoration funds; R — vector of the indicators, which characterize the natural environment's state; $r^i,\ r^e$ — natural flows of natural resources; $v^i,\ v^e$ — imports and exports of products; $A,\ A^{(z)}$ — matrices of specific direct costs; $B,\ B^{(z)}$ — matrix of fundforming costs; Q — matrix of the coefficients of self-restoration and reciprocal influence of natural resources; C — matrix of specific resource costs; $D,\ D^{(z)}$ — matrices of specific fund-forming costs of resources; F — matrix of resource costs in case of nonindustrial consumption of products; J — diagonal matrix with elements $J_{ii} = +1$, when restoration of resource i leads to the increase of the indicator R_i, otherwise, $J_{ii} = -1$; α — vector of coefficients, which characterize the anthropogenic nonindustrial load on natural resources; N — population of a region; R^* — undisturbed state of natural resources; $V(t, X, R),\ \ Z(t, X^{(z)}, R)$ — production functions of the output power, which are dependent on time, capital funds and the state of natural resources; M — matrix, which takes account of differences in the technologies employed.

In order to take account of labor resources we introduce a restriction of the form

$$\lambda' v + \mu' u + \lambda^{(z)\prime} z + \mu^{(z)\prime} w \leq \beta N, \tag{3.5}$$

where $\lambda,\ \mu,\ \lambda^{(z)},\ \mu^{(z)}$ — vectors of costs of labor resources per unit of output, unit of increase of the main funds, unit of restoration of resources, unit of increase of restoration funds, respectively, β — fraction of labor resources in the total population quantity, "$'$" denotes transposition.

Furthermore, the model has taken into account transport and ecological constraints. The description has been taken to be linear since it necessitates minimum of information. The equation describing the dynamics of indicators of natural environment differs from balance equations of economics. In essence, it describes the regional natural environment in terms of deviation from some undisturbed (natural) state. In case of absence of any influence (impact) from the economic activity via withdrawal and restoration of the resources, the solution of this equation $R(t)$ shall in the limit be tending to R^*. In the general case, R^* is a function of time, and $\frac{dR}{dt}$ in the left-hand side of the equation for the resources has to be replaced with $\frac{d(R - R^*)}{dt}$.

Variations of industrial technological schemes, conditions of production (mining) and prospecting natural resources, increase of labor productivity and other factors, which influence specific costs of products and resources, are taken into account in the model by introduction of dependence of matrices A, B, C, D, $A^{(z)}$, $B^{(z)}$, α, λ, $\lambda^{(z)}$ on time.

In the general case, matrices $A,\ B,\ A^{(z)},\ B^{(z)}$ may be dependent also on R. The dependence $Q(R)$ takes account of the fact that under substantial violations in the natural environment the latter may lose its capacity of self-restoration.

3.2. The information component

The model has been adapted to the water basin of Lake Baikal, Russian territory. Regional differentiation has been conducted along the basins of the main rivers bringing water into the lake: basins of the Verkhniaya Angara, Barguzin, Selenga and the Irkutsk part of the watershed (the run-off part of the south Baikal). The accepted regional differentiation is not the only possible. Furthermore, it has some undesirable traits, one of which implies substantial difference of the districts in their areas and economic potentials. Nevertheless, such a principle gives us the possibility to take account of concentration of river water impurities, and water is considered to be the principal natural resource assessed for the region, right at the mouths of their falling into Lake Baikal.

The economy of each of the studied districts has been subdivided in our model into 13 aggregated industries, each being characterized by the total gross output (computed in thousands of roubles). The natural complex on the whole has been characterized by 10 indicators (see Table 1).

Table 1. Economic branches and indicators of natural environment

Economic branches	Indicators of natural environment
1. Extracting	1. Reduced concentration of impurities in the water*
2. Chemical-metallurgy complex	2. Concentration of the typical impurity in the water (mg/l)
3. Agriculture	3. Reduced concentration of impurities in the air*
4. Transport	4. Concentration of the typical impurities in the air (mg/m^3)
5. Construction engineering	5. Estimated productivity of the soil (units)
6. Energetics	6. Area of agricultural lands (hectares)
7. Food industry	7. Stock of mechantable wood (m^3/hectare)
8. Mechanical engineering	8. Area covered with forests (thous. hectares)
9. Light industry	9. Reduce reserves of mineral resources (thous. roubles)
10. Wood processing and pulp and paper industry	10. Reduced reserve of biological biological resources (thous. roubles)
11. Construction material industry	
12. Other industries	
13. Recreation and nonindustrial sphere	

* — total concentration of impurities in fractions of the limit admissible concentration (LAC).

The concrete set of indicators unequivocally determines also the pithiness of all the model's coefficients. Furthermore, some part of the coefficients of the economic block, i.e. the matrices of direct and fund-forming costs, have been obtained by recomputation of statistical data of the 1985 interindustry balance for Buryat Republic, Irkutsk Region and Chita Region. However it is not possible to obtain the remaining part of the coefficients from any official statistical data. It has necessitated elaboration of special techniques of observations and experiments, which presumed both separating some objects of economy and natural environment and the accumulation of various information. For example, coefficients of matrices $A^{(z)},\ B^{(z)}$ may be assessed via the indicators of activity of certain nature-restoring enterprizes, which usually specialize their activity on some resources (soils, forests (wood resources), etc.) according to the following scheme:

1) The calculation of current and capital annual costs of nature restoration are computed on the basis of the documents of the enterprize, and the respective results (e.g. the area of recultivated lands during a year, etc.) are assessed.

2) On the basis of the table containing descriptions of the accepted structure of industrial branches, the items of costs (expenses) are related to the respective industries; furthermore, the capital investments are related to only two fund-forming branches: construction engineering and mechanical engineering. The respective results are recomputed according to the units of measurement accepted for the model. For example, growing trees on the area of 1 hectare implies some increase in the rate of restoration of forestry reserves per year.

3) The desired coefficients are computed as a ratio of the cost corresponding to certain industrial branch to the result defined in item 2). So, we obtain columns of matrices $A^{(z)},\ B^{(z)}$ for the indicators related to resources.

Another example. The computation of parameters, which characterize the influence of economy on the state of the air environment — elements of matrix C — has been based on the data related to the atmospheric discharges and to industrial capacities of some enterprizes. A list of large enterprizes and typical small ones has been identified for each of the industrial branches. Next, a relation between the discharged substance m (mg per year) and the LAC (mg/m^3) has been determined for each enterprize and each substance, as well as their relation to the volume w (m^3) of the lower layer of the atmosphere in the district, where the enterprize is situated, and the cost v (thous. roubles) of the products annually issued by the enterprize: m/(LAC$\cdot w\cdot v$). This relation has proved the average increase of the weighted (i.e. represented in fractions of LAC) concentration of the pollutant (m/w), discharged by the enterprize per a unit of manufactured production (per 1 thous. roubles of produce). The values obtained were summed up for the substances forming R_3. When a branch j is represented by one enterprize, the desired elements of matrix C — $c_{3,j}$ and $c_{4,j}$ are determined by the formulas

$$c_{3,j} = \sum_{i=1}^{n} \frac{m_i}{\mathrm{LAC}_i \cdot w \cdot v}, \quad c_{4,j} = \sum_{i=1}^{n} \frac{m_{SO_2}}{\mathrm{LAC}_{SO_2} \cdot w \cdot v}. \tag{3.6}$$

We have taken gaseous sulphur dioxide as a typical regional pollutant. When several enterprizes (k_j) of an industrial branch j were considered, the values of coefficients representing the influence of the branch on the air were determined by averaging of the respective coefficients $c^r_{3,j}$ and

$c^r_{4,j}$, $r = \overline{1,k_j}$ computed for the enterprizes by formulas (3.6) proportionally to the cost of the issued product and the typical character of the enterprize having the number r. Hence

$$c_{3,j} = \sum_{r=1}^{k_j} a^j_r \cdot b^j_r \cdot c^r_{3,j} / \sum_{r=1}^{k_j} a^j_r \cdot b^j_r,$$

$$c_{4,j} = \sum_{r=1}^{k_j} a^j_r \cdot b^j_r \cdot c^r_{4,j} / \sum_{r=1}^{k_j} a^j_r \cdot b^j_r,$$

where j is the number of the branch in model (3.1)–(3.5), k_j the number of enterprizes in the j-th branch, which have been identified as typical in the process of computing the coefficients; c^r the value of the respective coefficient of air impact, which is determined for the r-th enterprize by formulas (3.6); a_r characterizes the typical character of the r-th enterprize, i.e. the number of similar enterprizes in the district; b_r the contribution of the enterprize in the total branch output, i.e. the cost of the products manufactured by this enterprize.

Totally, we have computed over two thousand coefficients. Detailed description of the techniques and some previous results of our investigation can be found in [1, 26].

3.3. Problems of optimal control

Consider the following problem:

$$\dot{X} = u - \Delta X, \quad \dot{X}^{(z)} = w, \tag{3.7}$$

$$\dot{R} = Q(R - R_*) - (cv + Du + Fp + \alpha N + D^{(z)}w) + Jz, \tag{3.8}$$

$$p = (E - A)v - Bu - A^{(z)}z - B^{(z)}w, \tag{3.9}$$

$$0 \le v \le V(X), \tag{3.10}$$

$$u \ge 0, \quad w \ge 0, \tag{3.11}$$

$$X_{\min} \le X \le X_{\max}, \tag{3.12}$$

$$R_{\min} \le R \le R_{\max}, \tag{3.13}$$

$$I = \int_0^T [l'p - l^0(R - R_*)^2]dt \to \max, \tag{3.14}$$

where $X(t)$ is an n-dimensional vector, Δ is a diagonal matrix, whose elements are depreciation coefficients, $X^{(z)}(t)$ m, R, w, z are m-dimensional vectors, v, u, p n-dimensional vectors. Equation (3.7) describes the dynamics of funds, equation (3.8) the dynamics of natural resources, relation (3.9) defines the profit, (3.10) constraints imposed on the production output, (3.11) on investments, (3.12) on capital funds, (3.13) on the state of natural resources. Functional (3.14) is called the use functional, $I = \int_0^T l^0(R - R_*)^2 dt$ characterizes the value of the fine for violation of the ecological equilibrium. Therefore, the problem implies maximization of the profit under the conditions of small impact on the state of the natural environment. Note that there is no constraint imposed on the intensity of artificial restoration of natural resources.

For the purpose of qualitative investigation of such a problem we have applied methods of optimal control [27, 28, 36, 43], which have given the possibility to analytically find a so called main-stream mode widely used in investigations related to mathematical economics. In order to find numerically optimal plans, we used the algorithms described in [3], and the main-stream mode was employed as an initial approximation.

Suppose now that the restoring branch operates with its full power $z = X^{(z)}$, which is linearly dependent on the funds. Let us write down the form of the main-stream mode. Let $V = \gamma X^{\alpha},\ A,\ C,\ Q$ be constant matrices, $0 < \alpha < 1$. Introduce the notation

$$\psi_R = (J + FA^{(z)})^{-1}A^{(z)}l, \quad \psi_X = B'l + (D' - B'F')\psi_R,$$

$$\psi_z = B^{(z)\prime}l + (D^{(z)\prime} - B^{(z)\prime}F')\psi_R.$$

Hence the main-stream mode writes

$$\tilde{v}_i = \begin{cases} V_i(X), & \kappa_i > 0, \\ 0, & \kappa_i < 0, \\ \text{any}, & \kappa_i = 0, \end{cases}$$

$\kappa = \begin{pmatrix} \kappa_1 \\ \dots \\ \kappa_n \end{pmatrix} = (E - A)(l + F'\psi_R) - C'\psi_R$. When $\kappa > 0$ we have

$$\tilde{X}_i = \left(\frac{\kappa_i \gamma_i \alpha}{\Delta_{ii}\psi_{x_i}}\right)^{1/(1-\alpha)}, \quad \tilde{R} = R_* + \frac{Q'\psi_R}{2l^0}.$$

When $\tilde{R},\ \tilde{\Phi}$ lie within some given boundaries, they will give the desired main-stream modes. When $\kappa_i \leq 0$ we have $\tilde{\Phi} = \tilde{\Phi}_{\min}$.

Consider the economic interpretation of the condition $\kappa_i > 0$. For the purpose of simplicity consider the case of one-product model. The expression for κ is assumed in the form

$$\kappa(A, A^{(z)}, F, C) = l[(1 - A) + A^{(z)}(1 + FA^{(z)})^{-1}[(1 - A)F - C]].$$

Note for comparison that in V. Leontyev's model of interbranch balance $\kappa = 1 - A$, and the profitability threshold is defined by the inequality $1 - A \geq 0$. When ecological-economic interactions are taken into account, this threshold is reduced by the value of $A^{(z)}(1 + FA^{(z)})^{-1}[(1 - A)F - C]]$, for example, when $F = 0$ the profitability threshold is $1 - A - A^{(z)}C$.

It is also possible to state the problem of normalization for the given model: determination of maximum boundaries of the anthropogenic impact on natural resources under the condition that the state of natural resources will lie within given limits [30].

3.4. Practical application of the model

We have used model (3.1)–(3.5) to conduct systemic analysis of several variants of development of the Baikal region. Over 10 scenarios have been considered. The list of scenarios included: the scenarios reflecting existing tendencies; the scenarios taking account of transition to progressive technologies and forms of organization of manufacturing processes; scenarios oriented to predominant development of only some of the industrial branches (e.g. the extractive industry, the recreation complex, etc.); scenarios, which imply a detailed analysis of local regional problems (development of the Baikal-Amur Railway zone; reorientation of the Baikalsk pulp and paper plant etc.). Furthermore, applying special methods of optimal control (main-stream regimes) we have obtained optimal scenarios providing the desired high-standard ecological indicators and their maintenance with a maximum economic efficiency. On the basis of (i) special criteria, (ii) the normative-goal basis, which implies comparison of scenarios participating in the analysis, and (iii) detailed investigations and estimates, we have obtained recommendations for the development of certain industrial branches and resource complexes, recommendations related to planning and management of the territory, recommendations related to normalization of external sources of influence, and also the recommendations on the issues of the respective international cooperation. These recommendations have laid the basis of the Project of the General Conception of Development of Industrial Potential in the Lake Baikal Area submitted in 1988 to Siberian Branch of the Soviet Academy of Sciences.

Some additional investigations and computations were conducted in the process of preparation of the Territorial Complex Scheme of Protection of the Lake Baikal (TCSPLB). The materials obtained were reflected in this document. On the basis of the materials related to the development of the General Conception we have published a monograph in “Nauka Publ. Sibrian Branch” [7]. Some of the results of these investigations can be found in [19].

The proposed methodology of analysis of interdependence of nature and national economy, the developed models, the algorithms proposed and the software elaborated for computations may be useful in ecological-economic expertise of similar projects in other regions of the country.

In 1994–1995, the methodology was applied in the Conception of Sustainable Development of the Baikal Region, for the purpose of development of the Ecological Program of Irkutsk Region. In 2001, it was employed in ecological-economic assessment of the state of the Baikal region after the reformation of Russian economic system. Our ecological-economic model has been successfully applied in investigations of other regions of the world: Pereslavl-Zalessky region (Russia), Heiludzyan Province (China) [2, 5, 6, 19, 48].

4. Conclusion

The paper has described the experience of mathematical modeling of regional ecological-economic processes. A technology of constructing such models, the experience of information support, scenario analysis and application of the models and the methodology in different regions of Russia have been discussed. Note, the methodology proposed has been elaborated for medical-ecological-economic processes on account of social factors and innovation processes.

Acknowledgements

The work has been supported by Russian Foundation for Basic Research (Grant 08-01-00156), RF President Grant (NS-1676.2008.1), Interdisciplinary integration project 79 of Siberian Branch RAS, Russian Foundation for Humanities (Grant 09-02-00650).

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