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Multiparameter ranking of areas based on the analysis of data about the condition of natural and anthropogenic systems

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Zviagintseva A.V. "Multiparameter ranking of areas based on the analysis of data about the condition of natural and anthropogenic systems". Ranking of natural-anthropogenic systems has been fulfilled on the basis of the evaluation of probabilities of complex events associated with simultaneous monitoring of several ecological indicators. The methodology for the evaluation of ecological development is offered. It is based on an algorithmic determination of the statistical probabilities of events that characterize the state of the studied objects. There is an example of the ranking of European countries according to a range of environmental indicators based on the use of existing databases. Evaluation of environmental development of countries is made according to three criteria: total greenhouse gas emissions per capita, the portions of protected areas and the portions of agricultural land in total land area for each country of Europe. This method is objective and doesn't use expert methods for integrated assessment of the state of objects.

Keywords: ecological indicators, integrated assessment, multiparameter ranking, the countries of Europe.

Introduction

In environmental security speaking about the state of natural-anthropogenic systems usually involve the pollution of natural environments, the observed level of anthropogenic impact on nature and humans, as well as anthropogenic features and species biodiversity which is peculiar to such systems.

The natural-anthropogenic system usually means a functioning set of natural and artificial objects, which are formed as a result of building and operation of the various buildings and technical equipment, and interacting with natural objects. In such systems not only natural, but also anthropogenic and technogenic processes play the great role. At any time a natural-anthropogenic system is in a certain state. The state of the system means a set of indicators which characterize the structure and processes of the functioning of systems at any moment of time. Each object in natural, anthropogenic and biological relation can be characterized by many indicators, which are peculiar only to this type of natural-anthropogenic system. To characterize various aspects of the systems in the world practice there are sets of indices and indicators that are adopted for using by the scientific community [1 – 6].

The main directions and trends of research in this area are connected with the accumulation and creation of more extensive databases of indicators of status and change of natural-anthropogenic systems, the use of new visualization techniques and evaluation of data, the use of methods of data analysis, creation of information systems for the storage, presentation and evaluation of data, development of integrated assessment techniques, theories of risk assessment and methods of system dynamics.

Comprehensive assessment of the status and ranking of natural-anthropogenic systems are typically very time-consuming procedures because of the presence of a large number of indicators which reflect various aspects of the systems and require its analysis. In such studies three approaches are usually applied. The first one is connected with the creation of comprehensive analytical reports about the state and expected development of the systems and their mutual comparison. The second approach, in order to simplify the analysis procedure, is based on the indicator method when a variety of indices, which integrate different indicators and rank the systems, are introduced for the assessment of the status and changes of systems. The third theoretical direction of a comprehensive evaluation is associated with the risk assessment methodology and the theory of system dynamics.

The analysis of researches in the field of integrated assessment of natural-anthropogenic systems has been made in the famous works [7 – 11]. The authors observe that in this area there are a number of unresolved methodological problems, namely:

• existing methods of integrated assessment are largely incorrect and subjective, first of all because they use the methodology of the expert methods and don't consider the fundamental regularities of natural-anthropogenic systems. All of them practically reduce to multiple lengthy descriptions of various aspects and components of the systems or to the use of indices, which are built on agreement according to the principle of additivity of indicators and with due regard for the

weights of the indicators and comparison of systems based on these indices;

• the set of complex indices and measures that are built with using hypothetical and expert methods are not adapted to the observed data, have weak resistance to changing data, differ by a strong dependence of indicators used for evaluation;

• models for integrated assessment are based on rather partial and narrow hypotheses and cannot serve as a foundation for formally rigorous theories. In the study of natural-anthropogenic systems a number of fundamental hypotheses, that are widely spread in the natural sciences, practically are not used and are not tested on experimental data. In particular, these are various system-wide principles, the equations of state systems, laws of conservation, assumptions and admissions that would lead to a formalized formulation of problems, etc.;

• we must establish that any rigorous methods of integrated assessment, which would have a high validity of the theory, are not worked out nowadays. Many of the methods when applied to a single object of study can give disparate results, that indicates a violation of the basic principle of science about the reproducibility of the results;

• theoretical works in integrated assessment in the field of environmental Sciences often are reduced to hypotheses and generalizations which are cut off from realistic statistical base and systematic review of the available experimental data.

We observe that the most significant scientific problems lie in the theory of complex evaluation. Just in the field of theoretical research, there are several problems that don't allow to turn many scientific ideas into the generally accepted theories. As a consequence, on the background of the enormous number of analytical reports widely known theoretical models of natural-anthropogenic systems and science-based integrated assessments of the state of such systems are very limited. Today the scientific direction of comprehensive assessment of systems is being formed to a greater extent as a descriptive science. According to [12] during the last 30 years there wasn't any publication bringing something new to the basic concepts or fundamental laws of environmental Sciences. According to them the environmental world is on the threshold of the scientific revolution associated with the development of the theory, but the new paradigm has not penetrated the naturalists' minds of yet.

However, recent years area of interdisciplinary researches rapidly develops based on the application of natural science methods in biological and ecological Sciences. In this regard it should be noted phenomenological methods of system dynamics [8], which allowed to contribute to a methodology of modeling complex socio-economic systems and the construction of models of biological systems.

We think that this direction of modeling systems is the most relevant as it allows to apply phenomenological methods to describe living systems and social nature.

In the field of monitoring of natural and anthropogenic systems large databases have been accumulated that allow you to talk about the establishment of laws and the development of integrated models of systems and objects. This area of research is already enough developed to put the problem of estimating of the state probabilities of the systems based on complex event simultaneous observation of multiple indicators from existing databases which describe various natural and anthropogenic systems.

Thus, the purpose of this article is to show the possibility of creation on the basis of available statistical information of phenomenological models for integrated assessment of natural and anthropogenic systems, and the ranking of their territories according to environmental indicators.

The basis of this article is the latest developments that are associated with the creation of the theory of system dynamics and the application of algorithmic methods of data analysis about the state of the system [8, 15 – 17].

Methodology of Research, Adopted Methods and Used Data

Models for the environmental assessment can be based on numerical algorithms to determine the statistical probabilities of states of the systems. These probabilities are determined by the amounts of data for complex events of the simultaneous observation of multiple indicators or indicators that characterize the development of countries, regions or territories. These can be some of the most characteristic events, and different combinations of several such events constituting one complex event, for example, a joint event of the observation of the three or four environmental indicators. Such approach allows to take into account the probabilistic patterns of distributing indicative data, which reflect the state of the studied systems.

We illustrate this approach on the example of a methodology for the comparison of European countries according to environmental indicators [6, 16 – 17]. For example we take the following environmental indicators as attribute variables for a comprehensive assessment of countries' development: total emissions of greenhouse gases per capita (p_1), tons CO_2-eq./person.; the part of protected areas in general area of land (p_2), %; the part of agricultural area in general area of land (p_3), %. To solve this problem we can use databases [16, 17].

On the basis of variables p_1, p_2, p_3 form a three-dimensional space of coordinates $\{p_1, p_2, p_3\}$, in which the possible states of the studied system (all European countries) theoretically form a certain area Q_3, covering all the observed points of the database. In this case, the state of each country in three-dimensional space can be represented by three-dimensional point $M(p_1, p_2, p_3)$, and the processes of change of countries' state for a certain period – by multidimensional lines. We assume, as in works [7, 13 – 15], the continuity of the multidimensional area Q_3. It means that in the state space Q_3 there are an infinite set of states for a general set of objects (countries) and point of states $M(p_1, p_2, p_3)$ continuously fill this space. We also assume that the experimental points from the database are limited sample of observations from a given aggregate.

Let's consider a complex joint event of the simultaneous observation of these three indicators and determine that the ecological condition of each country in Europe can be evaluated with this particular observed event. We find the statistical probability of this event according to the basis of experimental data which are in the database [16, 17], using algorithms of selection, grouping, and counting frequencies of favorable events [7, 13, 14]. We think that this statistical probability is a probability of state of the studied system. This statistical probability w is calculated in the whole group of objects (52 European countries). In the process of grouping data the statistical probability of a state is determined by dividing the whole monitored area Q_3 into three-dimensional parallelepipeds based on a specified number (usually equal) intervals of grouping for each variable p_k, and determine the relative frequencies of events. The relative frequencies are the ratio of the number of experimental points that fall into the specified three-dimensional parallelepipeds, the total number of all observed points. Statistical probability is taken as cumulative relative frequencies of given joint events.

For construction models of quantitative data we also accept the hypothesis about continuity of the probability distribution of the system state in the area Q_3. In other words, we assume the existence of a scalar field of statistical probability w in the area Q_3 in the form $w = w(M)$, which can be estimated from experimental data.

Let's suppose that in the area Q_3 you can set continuous analytical function $T(p_1, p_2, p_3)$, on the basis of which a mathematical model of the probabilistic space will be formed. For a known function $T(p_1, p_2, p_3)$ and the values of the variables p_1, p_2, p_3 in the area Q_3 you can construct one more scalar field, which is taken as the simulation environment.

In this variant of the construction of theories about the creation of data models the most important thing is the choice of simulation environment T. In [7], for example, this environment was described by relationships which belong to homogeneous classes or multiplicative functions relative to the attribute variables. It was established that under these conditions during modeling you can use multidimensional quasi-linear partial differential equations of the first order, which are closely related to Pfaff's equations. For modeling it is assumed that in the space of states Q_3 scalar field of values w and T are definitely related with each other. This relationship is represented in the form of phenomenological ratios $dw = c_l \cdot dT$, where c_l – empirical quantities which are the functions of the development process.

If these hypotheses are true phenomenological descriptions of the data, presented in tabular and temporal arrays of information are closely related with Pfaff's equations of the form [7]:

$$dw = c_1 \cdot \frac{\partial T}{\partial p_1} dp_1 + c_2 \cdot \frac{\partial T}{\partial p_2} dp_2 + c_3 \cdot \frac{\partial T}{\partial p_3} dp_3. \quad (1)$$

Introduction of the function $T(p_1, p_2, p_3)$ is necessary for construction of theoretical models describing the data (states of European countries). The solution of the Pfaff's equation with constant values c_k depends on the type of the function $T(p_1, p_2, p_3)$. As we study the distribution of statistical probability, we can represent this function in the form of geometric probability of the state space Q_3

$$T = \frac{p_1 \cdot p_2 \cdot p_3}{p_{1,\max} \cdot p_{2,\max} \cdot p_{3,\max}} \quad (2)$$

or as a measure of relative changes

$$T = \frac{p_1 \cdot p_2 \cdot p_3}{p_{10} \cdot p_{20} \cdot p_{30}}, \quad (3)$$

where $p_{k,\max}$, p_{k0} – the maximum value or some reference values of ecological indices, accordingly.

In the case (3), in particular, for data analysis we should provide a reference point $M_0(p_{10}, p_{20}, p_{30})$ and the states of all other countries to connect with this point. With considering (3) equation (1) can be presented then in the form:

$$dw = T \cdot ds = T \cdot \left(c_1 \cdot \frac{dp_1}{p_1} + c_2 \cdot \frac{dp_2}{p_2} + c_3 \cdot \frac{dp_3}{p_3} \right). \quad (4)$$

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And after integration of this equation the function of the state can be represented in the form

$$s = c_1 \cdot \ln\left(\frac{p_1}{p_{10}}\right) + c_2 \cdot \ln\left(\frac{p_2}{p_{20}}\right) + c_3 \cdot \ln\left(\frac{p_3}{p_{30}}\right). \quad (5)$$

This state function is usually called entropy. Thus, according to [7] for this Pfaff's equation (1) in the area Q_3 there is a field of directions, which is generated by the scalar field of statistical probability w and which is characterized by the vector lines of this field – lines of entropy. In addition for this equation in a multidimensional space Q_3 there is a total potential of the form $P(p_1, p_2, p_3) = C$, that is a surface orthogonal to the vector lines of the field [7]:

$$P = \frac{p_1^2 - p_{10}^2}{c_1} + \frac{p_2^2 - p_{20}^2}{c_2} + \frac{p_3^2 - p_{30}^2}{c_3}. \quad (6)$$

Potential P can be adopted as a generalized criterion for an integrated assessment of the European countries' states in a multidimensional area Q_4 for selected environmental indicators. This value is a function of the state under true conditions for the existence of scalar field of statistical probability w. The change of the potential depends only on the initial and final state of the country in the process of its ecological change and does not depend on the way of transition between these states.

An Example for Ecological Assessment of Natural and Anthropogenic Systems

The obtained results allow to assess objectively the ecological state of European countries and to construct a system of their ranking according to ecological indicators, which is not based on expert methods.

For the search of nonlinear relationships between the statistical probability of the system state and ecological indicators we will use the method of regression for determination of the relation (5).

Choose reference values of ecological indicators. Thus, total emission of greenhouse gases per capita (p_1) in European countries changes in enough wide range from 0,85 to 28,1 ton CO_2-eq./person. We will take as the base value of this index the average value for European countries $p_{10} = 8,8$ ton CO_2-eq./person. Similarly, we take the reference value for the protected areas $p_{30} = 10,9$ % (the range of variation from 0,5 to 40,1 %) and a part of agricultural land in the total area of the land, – $p_{40} = 48,8$ % (the range of variation from 3,0 to 77,0 %). According to these data we'll get the control point $M_0(p_{10}, p_{20}, p_{30})$.

We connect the probability w with the values of the variables in the array of experimental data, as the result of which we will have the following regression dependence of w from the entropy of the system state:

$$\ln(w) = -1{,}804 + s \, ; \quad (7)$$

$$s = 0{,}466 \cdot \ln\left(\frac{p_1}{p_{10}}\right) + 0{,}495 \cdot \ln\left(\frac{p_2}{p_{20}}\right) + 1{,}041 \cdot \ln\left(\frac{p_3}{p_{30}}\right)$$

The correlation coefficient of relationship (7) is 0,91 and the results of data processing are given in Figure 1. The original variables were related to values p_{10}, p_{20}, p_{30}, which correspond to a selected reference state. The data show that the phenomenological constants c_k for the studied case are respectively equal to: $c_1 = 0{,}466$, $c_2 = 0{,}495$, $c_3 = 1{,}041$. The algorithm for calculating probability of the system state is quite definite, so there is always a dependence of the probability w from the original variables, which is presented in tabular form. As shown in Figure 1, by converting the coordinates this nonlinear dependence can be represented approximately as linear one.
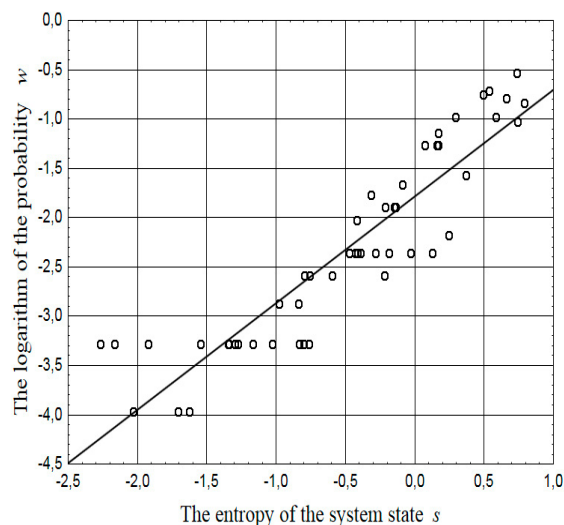

Figure 1. –The dependence of the statistical probability w from the entropy s indicators p_1, p_2, p_3

Thus, in the space of observable states of the system Q_3 we can built curvilinear coordinates that specify a certain field of directions that reflects average trends associated with ecological changes throughout the studied class of objects (among European countries).

The corresponding vector lines and the potential of this field P determine the natural curvilinear coordinates in the area Q_3, in this case. The point $M(p_1, p_2, p_3)$, which characterizes the state of each country in the process of its ecological

change, will take a position in accordance with these coordinates. This allows us to determine objectively the rank of the country in the hierarchical set of other objects on the basis of simultaneous observations of the three ecological indicators p_1, p_2, p_3. The potential is the most convenient tool for ranking objects.

According to the obtained data, based on the probabilistic evaluation of complex joint events, the potential of the state is identified for each country in Europe. The results of the ranking are given in Table 1.

Table 1. – Potential values for the European countries

European Countries	Potential of the country , P	European Countries	Potential of the country, P
Albania	-4,01	Liechtenstein	25,15
Andorra	-3,02	Lithuania	-1,41
Armenia	-2,36	Luxembourg	22,64
Austria	12,29	Macedonia	-2,32
Azerbaijan	-2,26	Malta	-2,91
Belarus	-2,11	Republic of Moldova	-2,37
Belgium	1,51	Monaco	6,24
Romania	-1,68	the Netherlands	4,62
Bulgaria	-0,56	Norway	-0,77
Croatia	-2,30	Poland	11,34
Cyprus	-1,52	Portugal	-2,21
Czech Republic	6,09	Bosnia and Herzegovina	-4,25
Serbia and Montenegro	-3,26	the Russian Federation	1,90
Estonia	18,23	San Marino	-5,01
Finland	2,65	Denmark	2,07
France	0,81	Slovakia	8,79
Georgia	-4,01	Slovenia	-1,17
Germany	15,28	Spain	0,04
Greece	0,97	Sweden	-2,01
Hungary	-0,20	Switzerland	10,88
Iceland	-1,24	Tajikistan	0,88
Ireland	4,23	Turkey	-3,22
Italy	1,38	Turkmenistan	-0,99
Kazakhstan	1,60	Ukraine	-0,80
Kyrgyzstan	-3,56	Great Britain	5,89
Latvia	-1,01	Uzbekistan	-2,44

From the data of Table 1 it is obvious that the European countries can be ranked according to several environmental indicators by determining the potential of each country in the space of variables $\{p_1, p_2, p_3\}$. A comprehensive assessment is carried out by determining the position of each country in curvilinear coordinates in this space taking into account the average trends in the development of all countries. The estimation is performed with respect to the average values of ecological indicators in relation to the reference point $M_0(p_{10}, p_{20}, p_{30})$. Thus, taking into account probabilistic assessment of joint events associated with simultaneous monitoring of ecological indicators, it is possible to have a mutual comparison of different natural and anthropogenic systems based on state data and environmental development of these systems.

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Conclusions

This method of complex assessment can be applied to various natural and anthropogenic systems, such as countries, regions, cities, natural and industrial complexes and enterprises, as well as to any set of initial ecological indicators. However, we should note that when increasing number of indicators more than 3 or 4 it's necessary to have a sufficiently large amount of data. The number of data is commensurate with the value $N = d \cdot f^{p}$, where f – the number of intervals, grouping data for one indicator (from 7 to 10); d – the number of experimental data in the same interval of grouping $(d = 5 - 7)$; p – the number of indicators, which form a joint event. The proposed method of evaluation is based on the probabilistic approach and doesn't use expert methods of data analysis.

Thus, a database of ecological indicators in combination with methods of comprehensive evaluation, based on the determination of the probabilities of events, allow you to set the patterns of ecological development of natural-anthropogenic systems.

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Звягінцева Г.В. «Багатопараметричне ранжування територій на основі аналізу даних про стан природно-антропогенних систем». Ранжування природно-антропогенних систем виконано на основі оцінки ймовірностей спільних складних подій, пов'язаних з одночасним спостереженням декількох екологічних показників. Запропоновано методику оцінки екологічного розвитку, яка заснована на алгоритмічному визначенні статистичних ймовірностей подій, що характеризують стан досліджуваних об'єктів. Наведено приклад ранжирування країн Європи за комплексом екологічних показників на основі використання існуючих баз даних. Виконано оцінку екологічного розвитку країн за трьома показниками: сумарними викидами парникових газів на душу населення, часткою територій, що охороняються, та часткою сільськогосподарських земель у загальній площі землі для кожної країни Європи. Дана методика є об'єктивною та не використовує експертні методи при комплексній оцінці стану об'єктів.

Ключові слова: екологічні показники, комплексна оцінка, багатопараметричне ранжування, країни Європи.

Звягинцева А.В. «Многопараметрическое ранжирование территорий на основе анализа данных о состоянии природно-антропогенных систем». Ранжирование природно-антропогенных систем выполнено на основе оценки вероятностей совместных сложных событий, связанных с одновременным наблюдением нескольких экологических показателей. Предложена методика оценки экологического развития, которая основана на алгоритмическом определении статистических вероятностей событий, характеризующих состояния изучаемых объектов. Дан пример ранжирования стран Европы по комплексу экологических показателей на основе использования существующих баз данных. Выполнена оценка экологического развития стран по трем показателям: суммарным выбросам парниковых газов на душу населения, доли охраняемых территорий и доли сельскохозяйственных земель в общей площади земли для каждой страны Европы. Данная методика является объективной и не использует экспертные методы при комплексной оценке состояния объектов.

Ключевые слова: экологические показатели, комплексная оценка, многопараметрическое ранжирование, страны Европы.

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