Environmental aspects of the integrated development of forest ecosystems: zoning and visualization of multidimensional data

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Abstract. The research is devoted to the development of information and methodological support for assessing the interaction of objects and the degree of impact on the environment within the framework of the concept of sustainable development in relation to enterprises of forest ecosystems. As a computational toolkit of the zoning technique the work uses adapted clustering and visualization methods in the form of constructing a set of Voronoi and elastic maps. The key point in the research is the choice of indicators that take into account the most important features of the process under study. Purpose of the study: revealing hidden patterns in multidimensional data on processes and phenomena that are difficult to formalize. The stages of the proposed computational technique for zoning objects of interest are given on model examples for processing and visualizing the distribution of the selected indicators.

1. Introduction

Intensive development in the region of nature and resource-intensive industries is a real source of increased technogenic loads on the environment and a potential threat of crisis development, social tension and environmental conflicts. The environmental situation and the level of well-being of environmental protection in the region today is a weak competitive position of the region [1].

In general, the situation with the formation of a modern innovative environmentally and socially oriented model in the natural resource sector of the Krasnoyarsk Territory should be considered unsatisfactory. Ensuring sustainable economic and social development of the Krasnoyarsk Territory is largely associated with solving the problems of environmental protection and rationalizing the use of natural resource potential on the basis of an innovative way of development [2-4].

The transition to an innovative environmental and social strategy of the development of the economy of the Krasnoyarsk Territory presupposes strengthen the role of procedures of the investment projects environmental assessment in the process of making economic decisions and management. Such procedures should be aimed at: identifying environmental problems at the early stages of project consideration; inclusion into projects measures aimed at improving the quality of the environment; development of measures to prevent, reduce and compensate environmental damage and risk.

At each stage of the procedure of assessing the impact of a regional program on the environment, indicators, criteria and assessment methods are used within the framework of the concept of sustainable development. This will provide an opportunity for a holistic, interconnected study of all links in the
process of interaction of the regional development program with nature in the chain "source of impact – environmental impact assessment – assessment of consequences in the economic sphere – a system of measures to prevent and eliminate consequences" [1].

2. Setting the zoning problem within a system approach

A holistic systematic approach to the environmental assessment of industrial and other industrial facilities affecting the environment planned for placement is possible on the basis of environmental and economic zoning. Currently, there is no single approach to solving this problem [5].

Therefore, the development of research in these areas seems to be very relevant. There are many qualitative and quantitative indicators for assessing the state of the environment, reflecting the multilateral nature of the problem. Many of them need improvement, and a number of indicators still need to be developed. The natural resource potential acts as the initial base for the formation of the system of indicators.

Six groups of indicators can be distinguished:

- characterizing the current and future state of the natural resource potential (describing certain types of natural resources and giving a comprehensive assessment of the state of the environment);
- reflecting the current state of the economic system and the prospects for its development;
- used as a comparison base for determining the variability of natural systems and acting either in the form of a conditional standard or in the form of a standard (for example, maximum permissible concentration (LOC – level of concern)), maximum permissible emission (MPE), critical load (CL));
- characterizing the degree of variability of systems, obtained by comparing their current state with the standard and reflecting the deviation from these standards, expressed in points, degrees, percentages, levels, etc.;
- reflecting the assessment of the negative consequences of changes in ecosystems in the economic sphere (cost estimates);
- characterizing the effectiveness of the planned environmental protection measures and their effectiveness.

The proposed system of indicators makes it possible to identify links with insufficient information and focus on improving them. At the federal level and in the constituent entities of the Russian Federation, integral indicators (environmental, socio-economic) assessments of the sustainability of the development of territories have not yet been developed and are not used. The mathematical apparatus of the United Nations Development Program, which publishes the Human Development Index (HDI) [5], was adopted as a methodological basis for the resulting indicator developed by the authors and its interpretation. As a mathematical model of the human development index, the geometric mean of the normalized values of each component (environmental, economic, social) is used. With regard to the problem of ecological and economic zoning of the territory of the region, the use of the HDI index as an analogue of the construction is quite justified.

For the interconnection of environmental indicators with indicators of economic and social development of the region, it is proposed to apply the method of environmental and economic zoning based on the integral index of environmental stability (IIES), which takes into account the dynamics of the environmental load on the territory, risks to public health and economic development. This approach was developed in the "Ecological Center for the Rational Development of Natural Resources" and the Department of Forecasting the Economic Development of the Krasnoyarsk Territory [5].

In the proposed theoretical model, the IIES is built through indexes that take into account the levels of economic, social development and environmental state of the Krasnoyarsk Territory. The system of indicators used to build an aggregated integral indicator must meet the following criteria: the ability to use at the regional and federal levels; unambiguous interpretation for decision-makers; presence of the
quantitative expression; support of the existing national statistics system and should not require significant costs for information collection and calculations; provision of temporary monitoring.

3. Methodology of environmental and economic zoning of territories

The specifics of environmental and economic zoning of territories within the framework of the concept of sustainable development should take into account:

- the state of the environmental situation, and this is, first of all, the quality of air, water and waste disposal. At the same time, official statistics provides data in the context of municipalities by the volume of pollutants: emissions (into the air), discharges (into the water environment) and the volume of waste disposal;
- the volumes of emissions, discharges and waste directly depend on the volume of industrial development of the territory, that is, on the level of production of goods and services in the territory, which is also ensured by statistical information. Thus, from the numerous possible economic factors, the main one (production of goods and services) is selected, which is directly related to the ecological state of the territory;
- the health of the population is the main social factor associated with the state of the environment. Over the past 10 years, Rospotrebnadzor has annually assessed and published statistics on carcinogenic and non-carcinogenic risks. Carcinogenic and non-carcinogenic risks are directly related to the quality of the environment (air, water, waste).

The above-described factors were selected as the basic indicators for the construction of the IIIES of the territory. For a correct comparison of factors of various nature (environmental, economic, social), normalization is proposed on an accessible (provided by reliable statistics) time interval (recommended at least 5 years).

Normalization:

\[
I_i = \frac{A_i - A_{\text{min}}}{A_{\text{max}} - A_{\text{min}}}
\]  

(1)

in fact, it transforms a time series of any nature into an informational one, varying from 0 to 1.

Thus, all the components included in the index are preliminarily normalized, which ultimately makes it possible to assess the stability of the territory with respect to environmental, social (risk of disease) and economic factors in units from 0 to 1.

Using the methodology for constructing the IIIES based on statistics on municipalities, a comparative assessment was made, which satisfactorily characterizes the real state of the territory of the region. Based on the IPES gradation, which is presented below, it is advisable to carry out an ecological and economic zoning by identifying three corresponding gradations on the territory of the Krasnoyarsk Territory according to the integral indicator proposed for use:

- 0.0 < Y ≤ 0.25 – sustainable ecological situation. The ecological (assimilation) potential of the environment provides favorable conditions for life and conservation of biological diversity. The development of economic activities is possible on the territory provided Y ≤ 0.25.
- 0.25 < Y ≤ 0.75 – the state of the natural system is in stable-dynamic equilibrium. The development of industrial production is possible subject to the transition to the best available technologies (BAT), and / or modernization of old environmentally dirty industries.
- 0.75 < Y ≤ 1.0 – the ecological assimilation potential of the territory has been exhausted; critical situation. The economic development of the territory is possible only if the industrial load is reduced, i.e. a ban on the construction of new environmentally harmful production facilities or technological modernization of existing production facilities.
Thus, it is proposed to use the following approach to determining the criteria for the need to establish restrictions on economic and other activities within the framework of the concept of sustainable development (table 1).

**Table 1.** Criteria for the ecological and economic zoning of the territory of the region according to the integral indicator of environmental stability, taking into account economic and social factors

| The value of the calculated IIES indicator (Y) | The need to establish restrictions |
|------------------------------------------------|----------------------------------|
| 0.0 < Y ≤ 0.25 | Establishment of direct restrictions is not required, annual monitoring of the sustainability of socio-environmental and economic development based on the calculation of IIES is required, with values of 0.0 < Y ≤ 0.25, economic activity is not limited. |
| 0.25 < Y ≤ 0.75 | It is possible to locate industrial facilities provided that the calculated IIES value (0.75) is not exceeded, taking into account the effects of the new facility in the system of already operating industries, i.e. restrictive administrative measures are introduced. |
| 0.75 < Y ≤ 1.00 | Prohibitive measures are established for the location of economic activities that exert an additional burden on the environment, since the assimilation capacity of the environment in this area has been exhausted, social risks (risks to public health) are high. |

The development of proposals for limiting economic and other activities is necessary for the territories of municipalities, the estimated IIES for which today is within the range of values 0.25 < Y ≤ 0.75. With values of 0.0 < Y ≤ 0.25, economic activity is not limited. Provided 0.75 < Y ≤ 1.00, making decisions on starting a new economic activity is not allowed without using the best available technologies.

The implementation of the above procedure will lead to the need to impose restrictions on the type of economic and other activities when making investment decisions, including when allocating a land plot for placement, construction of industrial enterprises and facilities.

For effective visualization of the spatial location (and interaction) of the objects under study, taking into account the "physical" properties of spatio-temporal data, algorithms for constructing a Voronoi set and an elastic grid are proposed as a computational tool for the zoning technique [6-8].

### 4. Computational zoning technique toolkit

Let us consider the possibilities of applying relatively new approaches to the analysis of random spatial fields of observational data (location of objects and their interactions). Algorithms are proposed for their quantitative analysis and visualization based on the theory of quantization (construction of Voronoi sets) [6] and the method of "elastic grids" [7, 8].

Consider \( T \) – some connected subset of some space. Points \( t_i \in T \) – represent observation data of a natural process (for example, an earthquake catalog). We cover the original set of points with a lattice at the nodes of which auxiliary points \( \{t^k_i\}_{i=1}^N \) are located. The problem is to reduce a continuous set of points to Voronoi sets that meet the following condition [6]:

\[
\mathcal{E}_N[T] = \sum_{k=1}^N \int_{\Delta_k} p(t_i, t^k_i) dt \rightarrow \min, \quad p(t_i, t^k_i) \rightarrow \min, \tag{2}
\]
where \( p(t_i, t^k_i) \) is some non-negative function equal to the distance from point \( t_i \) to point \( t^k_i \). The task is also to find a set of points \( \{t_i\} \) and corresponding partition \( \{\Delta_k\}_{k=1}^N \) such that error \( \varepsilon_N[T] \) is as small as possible. Error \( \varepsilon \) of given point \( t_i \in T \) to point \( t^k_i \) is measured by integral:

\[
\varepsilon = \int_{\Delta_k} p(t_i, t^k_i) dt, \quad k=1,\ldots,N. \tag{3}
\]

The total error for all points \( \{t_i\} \) of the subset \( T \) up to points \( \{t^k_i\}_{i=1}^N \) is measured by the sum of these integrals. The area in which points \( t_i \) and the set of points \( \{t^k_i\}_{i=1}^N \) lie will be denoted by \( \Delta_k \). As a result, we get a collection of sets \( \{\Delta_k\}_{k=1}^N \) that form a partition \( T \), these partitions are called Voronoi sets.

Further, a design scheme for constructing Voronoi sets is proposed for analyzing spatio-temporal observational data. With the help of the developed algorithm, in particular, the properties of a set of points are studied in relation to the studied subject area.

Consider [7, 8] the spatial data associated with the above-described meaningful problem. Let the analyzed object be a bounded two-dimensional manifold embedded in the set of observational data under study in such a way that the shape and location of the manifold reflect the main features of the distribution of the initial data points.

In order to describe this two-dimensional manifold, you can use the vector function \( r = r(x, y) \) from two coordinates \( x \) and \( y \), which are called internal coordinates (parameters). Thus, any point on the surface is specified by only two internal coordinates (the dimension of the manifold given by the formula \( r = r(x, y) \) is equal to two), and on the other hand, being a point in \( m \)-dimensional space, it has \( m \) coordinate values.

When constructing computational procedures, operations are performed not with the manifold itself, but with its point approximation, specified using a grid of nodes. To describe the position of a rectangular grid of nodes, \( m*p*q \) numbers are enough, where \( m \) is the dimension of space, and \( p \) and \( q \) are the number of nodes of the rectangular grid horizontally and vertically. After the map is built and the data points are transferred from the feature space to the surface of the map, we will use its two-dimensionality.

The set of data is located on the surface of the grid so that the square of the distance from the points (data) to the nearest node is minimal. Following [8], we formulate an optimality criterion, which would include not the initial and final positions of points (before and after projection onto the map), but the positions of the map nodes relative to the initial data. Then the dimension of the optimization problem will be significantly reduced to \( mpq \), where \( p, q \) is the number of nodes of the rectangular grid horizontally and vertically, and \( m \) is the dimension of space.

Consider a two-dimensional rectangular grid of nodes, in which \( p \) nodes are horizontal, \( q \) nodes are vertical. Let us enumerate the nodes of this grid using two indices \( y_{ij}, i = 1\ldots p, j = 1\ldots q \). The generated mesh is positioned at the set of data points so that each data point is mapped to the nearest grid node.

Data points have form \( t_{ij}(x, y, I) \), where \( (x, y) \) are its coordinates, \( I \) is the corresponding indicator. This method splits the entire data set into \( p*q \) subsets \( K_{ij} \) – taxa, within each of which the points of the subset will be closer to the grid node \( y_{ij} \) than to any other node. Let us designate this circumstance as follows [8]:

\[
K_{ij} = \left\{ t \in P \mid \| y_{ij} - t \| ^2 \leq \varepsilon \right\}. \tag{4}
\]

The grid must have the following properties: stretching property (this property ensures the uniformity of the mesh); smoothness property; property of proximity to data points. For a mesh to have both of
these properties, it is necessary to add a measure of total mesh stretching, a measure of total bend, and a measure of total proximity to the criterion to be minimized.

Adding all three of these measures together, we get a general criterion due to which the mesh will be attracted to the data points and strive to minimize its stretching, assuming the smoothest possible shape (to become more regular). We get the following quality functional:

$$D = \frac{D_1}{|P_s|} + \lambda \frac{D_2}{pq} + \mu \frac{D_3}{pq} \rightarrow \min,$$

where $|P_s|$ – the number of points in $X$; $\lambda$, $\mu$ – elastic coefficients responsible for stretching and curvature of the grid, respectively; $\lambda$ – the number of iterations made, $D_1$, $D_2$, $D_3$ – terms responsible for the properties of the grid. As a measure of the proximity of the grid to the data points, we take the value of the square of the distance from the points to the nearest grid node.

The property of a measure of proximity of a grid to data points is represented as:

$$D_1 = \sum_{i,j} \sum_{t \in K_{ij}} \| y_t - y^{ij} \|^2.$$

The longer the edge length, the more the mesh is "stretched"; the minimized functional includes the differences between the positions of neighboring nodes:

$$D_2 = \sum_{i,j} \sum_{t \in K_{ij}} \| y^{i,j} - y^{i+1,j} \|^2 + \sum_{i,j} \sum_{t \in K_{ij}} \| y^{i,j} - y^{i+1,j} \|^2.$$

- a measure of the stretch of the grid. The degree of curvature is determined by estimating the magnitude of the second derivative, using the second differences. As a result, we get the following functional:

$$D_3 = \sum_{i,j} \sum_{t \in K_{ij}} \| 2y^{i,j} - y^{i+1,j} - y^{i-1,j} \|^2 + \sum_{i,j} \sum_{t \in K_{ij}} \| 2y^{i,j} - y^{i+1,j} - y^{i+1,j} \|^2.$$  

- a measure of the smoothness of the grid.

Further, on the basis of the stated formulation of the problem, an algorithm for constructing an "elastic mesh" is developed, taking into account the values of the introduced "physical" feature for the data under study, which characterizes the process under study.

5. Construction algorithms of Voronoi set and "Elastic Grids"

Following [6] we consider $T$ – some connected subset of some space. Points $t_i \in T$ are model data of the studied process. We cover the original data set with a lattice, at the nodes of which auxiliary points $\{t^k_{ij}\}_{k=1}^N$ are located (figure 1). The task is to reduce a continuous set of points to Voronoi sets that satisfy condition (2). The challenge is also to find a set of points $\{t^k_{ij}\}$ and corresponding partition $\{\Delta_k\}_{k=1}^W$ which provide the smallest error $\varepsilon_N[T]$. Error $\varepsilon$ of a given point $t_i \in T$ to point $t^k_{ij}$ is measured by the integral (3). The total error for points $t_i$ lie of the subset $T$ to points $\{t^k_{ij}\}_{i,j=1}^N$ is measured by the sum of these integrals. The area where points $t_i$ and the set of points $\{t^k_{ij}\}_{i,j=1}^N$, will be denoted by $\Delta_k$. 

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Figure 1. An example of a set of observational data covered by a grid

Consider some set $T$. Points $t_i \in T$ are observation data. Each data point $t_i$ has some properties: $(x, y, I(R))$, where $(x, y)$ are its coordinates (of the object), $I$ is the value of the corresponding indicator. For each value $I$, a domain of influence is determined, i.e. radius $R$ – of the domain of attraction to point $t_i$ with indicator $I$. These properties, as applied to a real problem, make it possible to find the central point from set $T$ (figure 2).

We split the set of starting points into some Voronoi subsets to make error $\epsilon_N[T]$ minimal. To do this, from the set of points in $T$, we select the point that, by its property (value of the indicator), is the main (central) one. Let us fix this point and find the distance between it and all other points by the ratio.

$$p^0(t_i, t_j) = \frac{\| t_i - t_j \|_2}{\| v - t_j \|_2} \rightarrow \min,$$

where $v$ is the midpoint of segment $(t_i, t_j)$.

As a result, we get a set in which all the considered data points lie. Let's compare the obtained values and exclude the points from the constructed set, the distance from which to the fixed point is greatest. For the remaining points, the central point is selected in the same way, and the steps described above are performed. The set under consideration will be divided into several domains $\{\Delta_k\}_{k=1}^N$ (figure 2).

Figure 2. An example of dividing a set into domains (zones)
In order to check which of the constructed domains (zones) is asymptotically optimal, we use formula (9). To find error $\varepsilon_{N}[T]$ it is necessary for all points to find corresponding points $t^k_i$. We get a segment, which is the radius - the vector of the circle. Error $\varepsilon$ of each segment length is determined by formula (3). Total error $\varepsilon_{N}[T]$ of all points $t^i_i$ of the considered Voronoi set is found by formula (2). For all other domains, calculations are carried out in the same way.

Thus, the following block diagram is proposed, which describes the actions of the proposed algorithm:

- by value $I$ ("physical" property of the initial data) we determine the central point for the analyzed data set;
- we build on this basis the Voronoi set;
- we determine the location of points $t^k_i$ for each starting point;
- we calculate error $\varepsilon$ for each data point, then using these estimates we calculate total error $\varepsilon_{N}[T]$;
- we exclude the most distant points from the selected central point; we compare the received errors and find the optimal one, zoning is done.

An algorithm for visualizing model data on the location of objects based on the method of elastic grids is proposed [7, 8]. The peculiarity of this method of visualizing the indicated data is that the system of nodes obtained during its application turns out to be ordered. As a result of the algorithm's action, the neighboring nodes on this grid turn out to be adjacent in the data space, which makes it possible to visualize them after placing the data points on the nearest nodes of the two-dimensional grid.

In this case, the projections of the data are shown in the original internal coordinates, the nodes of which are represented in the form of a rectangular grid. The grid constructed in this way is located at the set of original data points so that each data point $t^j_i$ is associated with the closest grid node $y^i_j$. Given the positions of the grid nodes and placing data points in it, the set of model data is divided into taxa $K^j_i$ (figure 3).

![Figure 3. An example of splitting data points into taxa](image)

After this partition, functional $D$ is minimized according to formula (5). First, values $D_1$ from (6) are calculated. Each grid node has four neighbors with which it is connected by an "edge". The greater the average length of the edge, the more the mesh is "stretched"; therefore, it is necessary to minimize this value using $D_2$ from (7).
This space is metric, so measure of smoothness $D_3$ is not used. The steps are repeated until functional $D$ stops changing. The iterative process converges, since at each stage of minimization the value $D$ will decrease; at the same time, it is bounded from below ($D$ is non-negative).

At the final stage, the initial data is visualized (zoning). To determine which feature or subset they belong to, the following technique is used: a coloring is applied that reflects the distribution of both the entire data cloud and any of its subsets (division into taxa). The block diagram of the described algorithm is implemented in the computing environment MathCAD 2000.

1. Input of initial data. The distribution of the objects contained in the data table has the form shown in figure 4. Constraints are introduced on the minimum grid step in $X$ and $Y$ ($\text{setka\_min\_x, setka\_min\_y}$) and the criterion for dividing into subsets ($\text{ALFA}$).

![Figure 4. An example of source data (location of objects)](

2. We calculate the step and the number of grid nodes in $X$ and $Y$. We calculate the grid nodes and search for the nearest grid nodes to the coordinates of the objects.

3. Perform division into subsets (taxa).

4. Building a data model (zoning) and analyzing the results using the appropriate coloring of points and selected taxa (figure 5).

![Figure 5. An example of a map built for this subset](

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As a result, we get a visual image (map) of the "interaction of model objects", for each of which the nearest grid node is indicated, and the number of the subset to which it belongs. Figure 5 shows an example of a model data map with a two-dimensional color spectrum. The light parts in the figure show the values of the indicator characterizing the acceptable level of anthropogenic load on the ecosystem for the location of production facilities, the dark ones refer to the territories where making decisions about starting a new economic activity is not allowed without using the best available technologies.

6. Conclusion
The use of the integral indicator of environmental and economic zoning of territories allows to objectively rank the interaction and impact on the nature of enterprises of the forest ecosystems of the region. This approach allows us to take into account the difference in the sustainability of individual territories, primarily when forming long-term development programs for the region, as well as to introduce restrictive measures in relation to those investment projects that can worsen the state of the environmental situation. The proposed computational toolkit within the framework of the proposed zoning technique is an important element of a comprehensive analysis of multidimensional data for revealing hidden patterns in complex processes and phenomena that are difficult to formalize.

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