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Methods for Assessing the State of Impacted Ecosystems on the Basis of Bioindication Data

V. V. Stolbova and S. V. Mamikhin

Department of Radioecology and Ecotoxicology of Soils, Faculty of Soil Science, Moscow State University

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Abstract—At present, practical application of the method of biological indication for environmental assessment purposes is limited by the poor development of formal procedures for interpreting the results of biological indication in terms of ecosystem quality. Existing approaches to the interpretation of biological indication data on terrestrial, aquatic, and soil ecosystems have been classified with respect to the increasing degree of their formalization into groups of (1) expert estimates, (2) statistical treatment of large data sets, (3) multiple biological indication at different levels of ecosystem organization, (4) analysis of the dose–response relationships, and (5) ecological modeling. For practical reasons, the method of multiple biological indication is considered optimal for unambiguous identification of the state of impacted ecosystems. This method involves appropriate data formalization and consistent rules for their ecological interpretation.

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INTRODUCTION

Increasing anthropogenic loads on the environment induce certain changes in the structure and functioning of natural ecosystems. The state of natural ecosystems is considered the main criterion for assessing the degree of disturbance of the environment. At present, two major approaches are applied to assess the state of natural ecosystems. The first approach can be referred to as the sanitary–hygienic approach; it is based on the analytical determination of concentrations of major pollutants in ecosystem components. The results are compared with the maximum permissible concentrations established for particular environmental media [29]. An advantage of this approach is the simplicity of the interpretation procedure; an unfavorable state of an ecosystem is detected when the measured concentrations of pollutants exceed the maximum permissible concentrations. However, many ecologists argue against the use of the sanitary–hygienic approach for assessing the state of natural ecosystems [1, 4, 6, 10, 14]. The main argument is that the content of various pollutants in natural media is indicative of anthropogenic loads on the ecosystems rather than of their real state. An alternative approach can be referred to as the ecological or biotic approach [14]. According to it, an ecosystem is perceived as a single whole and its state is estimated on the basis of data on the degree of ecosystem disturbances under the impact of technogenic loads. Within the framework of this approach, several stages of the disturbance (degradation) of an ecosystem are distinguished. Sometimes, they are interpreted as the stages of the technogenic succession. The state of ecosystems is judged from the state of its biotic components rather than from the content of pollutants. Various methods of biological indication (bioindication) are applied to study biotic characteristics at different levels: from the molecular level to the biogeocenotic level [35]. Bioindication methods allow us to judge the response of a given biocenosis to multicomponent anthropogenic loads under real conditions in nature; from the methodological point of view, this approach for determining the state of natural ecosystems subjected to anthropogenic loads (including pollution) seems to be more feasible than the sanitary–hygienic approach.

There are many works devoted to deviations of biological indicators of ecosystems under anthropogenic loads from their normal background values. However, in order to transform various quantitative data into qualitative estimates of the state of ecosystems, it is necessary to develop special reference scales characterizing the state of ecosystems at different stages of their degradation. An analysis of published works on this problem shows that there are no universally accepted approaches to the development of such scales. The existing approaches differ significantly from one another in (1) the choice of ecologically meaningful indices (parameters) of the state of ecosystems; (2) the typology of categories used for assessing the state of ecosystems (different categories are used, e.g., the categories of the norm–pathology [23]; crisis–catastrophe–disaster [5]; progress–regress [1]; strong, moderate, and weak disturbance [16]; etc.); (3) the means of grouping of the indices according to the quality scale (e.g., according to the scale from the norm (normal state of an ecosystem) to the pathology (pathological state of an ecosystem); and (4) the number of quality classes (groups) on the scale and the corresponding variations in the selected indices. In this paper, we consider the latter two problems. From our point of view, the absence of unified approaches to judge the quality (state) of ecosystems from the values of indicative characteristics hampers the practical application of the biotic approach for environmental assessment works. Also, in order to obtain unambiguous data, it is necessary to standardize and formalize the interpretation of the results of biological indication.

INTERPRETATION OF BIOLOGICAL INDICATION DATA: MAJOR APPROACHES

We have analyzed major approaches applied by researchers to interpret the results of bioindication of the state (quality) of ecosystems subjected to anthropogenic pollution. Differences in the theoretical bases of these approaches and in the formal procedures of data handling make it possible to distinguish between five groups of approaches used to transform the values of biotic parameters into the ecosystem assessment categories:

(1) Expert estimates.

(2) Combination of bioindicators.

(3) Formal statistical approaches to analyze large data sets.

(4) Analytic approaches based on the study of relationships between the level of contamination and the ecosystem response to it.

(5) Approaches based on imitation modeling.

To a certain extent, this grouping reflects the level of formalization of the analysis of initial data.

Expert Estimates

The method of expert estimates assumes the establishment of relationships between the bioindication data and the state of ecosystems on the basis of expert judgments with the use of certain classifiers. Different classifiers can be used: (1) phenomenological descriptions of ecosystem disturbances or the lists of criteria used to characterize the degree of disturbances; (2) integral estimates based on certain integral (derived from several indicators) parameters of the state of ecosystems with a corresponding scale making it possible to determine the degree of ecosystem transformation from the values of these parameters; and (3) estimates based on a combination of several essential (according to expert judgment) criteria, whose particular values correlate to the status of the ecosystem's quality [7, 11, 26].

Expert estimates were used to develop a set of criteria for assessing the environmental quality with five quality grades corresponding to different levels of ecosystem disturbance [15]. The degree of ecosystem degradation was considered indicative of the level of anthropogenic loads. The degree and reversibility of ecosystem disturbances were taken into account in another study devoted to terrestrial ecosystems [5]. The authors distinguished between four different states of natural ecosystems and three levels of the natural and anthropogenic ecosystem disturbances. The authors of the biotesting method [13] considered the stability of an organism's development and functioning to be indicative of the state of natural ecosystems. According to this method, the stability of an organism's functioning is judged from the indices characterizing the phenomenon of fluctuating asymmetry, i.e., from the degree of nondirectional differences between the right and the left sides of morphological structures that have bilateral symmetry in a normal state. The correspondence between the degree of these differences and the stability of an organism's functioning is determined by an expert with the use of a five-grade scale. A seven-grade scale characterizing the state of forest ecosystems was developed on the basis of visual characteristics of the state of woody vegetation that can be seen on remote sensing materials [16].

The method of ecological modifications [1] can also be used for expert assessment of the state of biocenoses. In this case, the following grades are used: normal (background) state of a biocenosis, the state of ecological stress, the state of ecological regress, and the state of metabolic regress (destruction) of the biocenosis.

The analysis of the species structure of the amylolytic microbial community of soil made it possible to distinguish four types of changes in the community of actively functioning microorganisms [10]. Upon a gradual increase in technogenic loads on the soil, these types consecutively replace one another; they correspond to four adaptive zones of the microbial community: homeostasis, stress, resistance, and suppression.

The use of several classifiers in the form of a matrix makes the boundaries between different states of a given ecosystem more definite. For example, an area in which a given parameter of ecosystem degradation is manifested can be used as one of the coordinates of a matrix. In this case, the larger the area on which the given parameter of an ecosystem degradation is detected, the more hazardous the ecological situation [5]. Thus, the ecological stress induced by the phytotoxicity of the soil can be judged from the germination capacity of seeds. The larger the area on which the germination capacity (the number of seedlings) is reduced in comparison with the norm, the more dangerous the ecological situation [3]. The same principle of matrix organization of classifiers was used to develop the integral scale for assessing the ecological status of soils with respect to the degree of their disturbance and the degree of their contamination by ecotoxicants. The scale included seven grades; each of them was characterized by the particular time necessary for the self-restoration of the initial soil quality. In turn, the time of soil self-restoration (self-rehabilitation) was estimated by experts on the basis of theoretical concepts about the rate of natural soil development as related to the rate of vegetation successions leading to the restoration of the initial climax ecosystems [24].

As seen from these examples, different criteria can be used to identify the qualitative state of an ecosystem: the ecosystem stability, the depth and reversibility of ecosystem changes, the time necessary for the ecosystem self-restoration (the relaxation time), the visually seen changes at the levels of a given organism or the entire population, the changes in the species structure of the ecosystem, and the transformation of the ecosystem structure and/or functioning.

The efficiency of expert estimates is related to their low cost and low time expenses. Expert estimates represent an informal way of grouping different parameters of ecosystem quality. The criteria used for such grouping can hardly be strictly formalized. Often, integral concepts of the ecosystem's stability, resilience capacity, self-restoration capacity, reversibility of changes, and sustainability of functioning are used. However, there are no definite approaches to determine these general characteristics. The use of traditional biotic indices does not make it possible to suggest a common scale for assessing the state of different ecosystems [19]. The subjectivity of expert estimates means the potential discrepancy of their results. The results obtained with the use of different criteria may be incompatible with one each other [11, 14]. In other words, informal expert estimates do not guarantee unbiased results, which are necessary for decision-makers.

Combination of Bioindicators

Combination of indicative taxa and their groups. Different states of an ecosystem can be diagnosed by the presence of certain species indicative of the particular levels of ecosystem disturbance. For examples, a six-grade scale for assessing the quality of water bodies (State Standard 17.1.2.04-77) is based on the presence (dominance) or absence of particular indicative taxa. An analogous scale has been developed for terrestrial ecosystems subjected to aerial pollution. In this case, the sensitivity of particular species of lichen to pollutants is taken into account. In other words, the scale is based on the tolerance of different species of lichen to air pollution. The simplest way of using particular combinations of biological indicators for assessing the environmental quality is to develop qualitative scales representing lists of species grouped with respect to their tolerance to the impacts studied.

A common method for revealing different stages of degradation of both aquatic and terrestrial ecosystems is to detect the presence (or absence) of certain groups of indicative organisms arranged according to their tolerance to different levels of pollution. The degree of contamination of water bodies is judged by the presence of certain groups of saprobionts. Lichens are often used to judge the degree of contamination of terrestrial ecosystems. Lichens are arranged into several groups differing in the degree of their tolerance to pollution. An average index of tolerance for a given group can be calculated on the basis of data on the tolerance of particular species of lichen included in this group. Different morphological types of testate amoebas dwelling in soil have proved to be indicative of soil conditions and the character of their anthropogenic disturbances [1, 6, 14, 27]. In all these cases, the biotic indices characterize the distribution of different groups of indicative species by the gradient of ecosystem-disturbing impacts. Expert estimates are used to judge the state of an ecosystem on the basis of data on the presence of particular indicative species and their groups.

Combination of bioindication at different levels of ecosystem organization. Biological indicators can be applied at different levels of ecosystem organization, e.g., at the levels of organisms and populations. A combination of various phyto- and zooindicators applied at these two levels makes it possible to judge the degree and the character of changes in the state of ecosystems [17]. Within the framework of this approach, the authors distinguish between the following states of an ecosystem: (1) the background (normal) state; (2) the state corresponding to the initial disturbances of the ecosystem; (3) the state of considerable disturbances of the ecosystem resulting in certain changes in the ecosystem structure; and (4) the state of functional disturbances of the ecosystem. The larger the difference between the normal value of the index and its value in the disturbed ecosystem, the greater the degree of ecosystem disturbance. It is interesting to combine the results of biological indication at the level of particular organisms with the results obtained at the population and biocenotic levels. This combination allows one to judge the dynamics of ecosystem disturbance. For example, if the physiological indices (at the level of particular organisms) in the given ecosystem differ sharply from their normal values, whereas the population and biocenotic indices remain close to their normal values, we can suppose that we are dealing with an ecosystem at the early stage of disturbances. At the stage of structural changes in the ecosystem, deviations of the physiological and the ecological (population and biocenotic) indices from their norms are approximately similar. At the stage of functional changes in the ecosystem, deviation of the ecological indices from the norm should be greater than that of the physiological indices. At this stage of ecosystem disturbance, the use of physiological indices is insufficient. More reliable estimates of the real state of the ecosystem can be obtained on the basis of ecological (population and biocenotic) indices.

This qualitative interpretation of quantitative changes in the biological indicators applied at different levels of an ecosystem's organization is based on general regularities of functioning of hierarchically organized biological systems: qualitative changes in the subsystem (of a lower hierarchical level) are indicative of quantitative changes in the system of a higher level [6]. A serious problem related to the use of this method is the choice of normal (background) undisturbed plots. In a number of European regions, it is almost impossible to find undisturbed reference ecosystems.

Formal Statistical Approaches

Formal statistical approaches are based on the methods of mathematical statistics or other mathematical tools that are applied to study the distribution of large sets of ecological data according to the assessment categories (by groups of ecosystems with different degrees of disturbance). It is possible to group these methods into three categories: (a) methods that allow us to distinguish unambiguously between natural (undisturbed) and disturbed ecosystems, (b) methods that are used for subdividing the values of particular indices into those fitting the norm and beyond it, and (c) methods that are used for subdividing ranked data into several grades with specified (desired) criteria.

Unambiguous evaluation of data sets. Ranked distributions of ecological data allow researchers to perform unambiguous evaluation of available data sets and to attribute the studied ecosystem either to the group of natural (undisturbed) ecosystems or to the group of disturbed ecosystems [26, 30, 33, 36]. Thus, the normal distribution pattern is typical of the values characterizing the normal functioning of an ecosystem regulated by homeostatic mechanisms [22, 23]. Ranked distributions can also be used to judge the state of an ecosystem [4, 14]. The biological indicators in this case may be represented by the lists of species with characteristics of their abundance or biomass, or by the set of resources utilized by the community with indication of the intensity of their utilization [31].

Traditionally, estimates based on the indices of species diversity of actively functioning biotic components of ecosystems are used. For example, analysis of ranked distributions of the number of species is widely applied to assess the communities of hydrobionts in the freshwater bodies and seas. In this case, the shape of the ranked distribution curve is analyzed. A linear relationship between the rank of a given species and the logarithm of its total number characterizes an undisturbed community, whereas deviations from the linear relationship are interpreted as a pathological state [14, 23].

To characterize the state of soil microbial communities, indices of the functional diversity determined by the method of multisubstrate testing can be applied. This method is based on the selective capacity of different functional groups of soil microorganisms to utilize a range of substrates. The intensities of utilization of different substrates are ranked; the ranked distribution curves of substrate utilization are described by different models in dependence on the state of the particular microbial cenosis [8]. On this basis, three different states of the soil microbial cenosis that depend on the level of soil pollution with polycyclic aromatic hydrocarbons have been described [9].

An important advantage of this approach is the possibility of assessing the state of the given cenosis on the basis of its internal properties (proportions between different functional groups) without obligatory application of the "control–experiment" methodology of biological indication. In other words, there is no need to search for control (undisturbed) sites and to compare the indices obtained at the experimental sites with those obtained at the control. The conclusions are based on the preliminarily established regularities of the behavior of studied communities.

Alternative distribution of the values of indices. The sample of particular values of biological indicators is subdivided into the groups fitting and beyond the norm. The procedure of biological indication assumes the comparison of measured values with the control value (range of values) characterizing the norm. In dependence on the particular situation, maximum, mean, or minimum measured values may fit the norm [11]. The norm can also be judged from the frequency distribution of measured values. It is important that the normal range of values is established a priori, on the basis of theoretical concepts or previous empirical data; often, it depends on the level of our knowledge about a particular ecosystem [14].

A hypothesis on the normal frequency distribution of the values of biological indicators makes it possible to substantiate the range typical of the undisturbed state of an ecosystem. In the case of a small number of observations, this range can be defined as the mean ± variability. For biomonitoring purposes, the variability characterizes the limits of the natural variation of the studied index in an undisturbed ecosystem. The anthropogenic disturbance of the ecosystem is judged from the "statistically significant overrun of the studied index beyond the limits of natural variability" [21, p. 193].

In ecology, the state of ecosystems is traditionally judged from the values of the main biotic parameters. If they overrun the normal range, an anthropogenic anomaly is detected. There are certain numerical constants allowing us to estimate the reversibility–irreversibility of ecosystem transformation [18]. Though the values of these constants have been obtained by the method of expert estimates [6], their application for determining permissible (recoverable) deviations from the normal state is feasible, as it makes the assessment procedure better formalized.

The normal state of the community can be characterized by the long-term averages of certain biotic characteristics. The use of mean annual data is particularly efficient for some utilitarian biotic indices. For example, long-term data on commercial fish catches in the lower Don River were used to judge the state of aquatic ecosystems [14]. In the case of deviation of the distribution of some biological indicators from the normal law, the normal range was found with the use of binary estimates of the "well-being–ill-being" type. The numbers of each of the indicative groups of plankton and benthos were subdivided into approximately equal categories of the low and high population densities. The favorable or unfavorable state of the ecosystem was judged from the abundance of the given indicative groups of organisms [14].

Desirability functions. Detailed qualitative estimates can be obtained with the use of the so-called desirability functions. These functions make it possible to show natural values of the selected indices on the dimensionless scale ranging from 0 to 1. The correspondence between the particular values of the index and its place on this scale is established by experts with the use of the so-called significance functions [7] or with the use of definite rules in dependence on the range of the normal values [11, 14]. The desirability function method is based on a priory notion about "desirability" of the particular values of the studied index for the given ecosystem. Thus, it is possible that maximum, mean, or minimum values become desirable. If there are no adequate data on the object, the desirability function can be built of the basis of the distribution curve for the values of the particular index. The concept of statistical norm [3] suggesting that the most frequently found values in an undisturbed ecosystem are the desired values is taken into account [14]. As the desired values of an index are usually set up a priori and the desirability function is built by subjective means, some researchers argue that this approach cannot be qualified as objective. However, it makes the procedure of expert estimates more transparent [6].

In general, it should be noted that the application of statistical methods in applied ecological studies may be limited by the (a) deviations of the distribution of particular values from the normal law, (b) insufficient volume of data, and (c) heterogeneity of statistical samples [14, 26].

Analytical Approaches

Analytical approaches are possible if we know the relationship between the intensity of the impact and the dynamics of the indices characterizing an ecosystem state [28, 32].

Analysis of the dose-and-effect relationships. The curves showing the relationships between the impact and the ecosystem response to it can be referred to as the dose-and-effect curves. They make it possible to distinguish between several qualitatively different states of an ecosystem related to the intensity of external loads on it. These curves can be obtained during the study of impacted territories, where ecosystems are subjected to the impact from point-size pollution sources [6]. They can also be obtained in the course of long-term stationary monitoring studies and regular measurements of the particular indices at different stages of the anthropogenic transformation of an ecosystem. This approach has been used to study degradation of pastures in the semidesert and desert zones [5].

It is supposed that the response of an ecosystem to pollution should have a nonlinear character, i.e., there should be two different levels (states) of the studied biotic parameter with a sharp transition between them. Thus, the analysis of the $y(x)$ relationships (where y is a biological indicator of an ecosystem, and x is the load on the ecosystem) make it possible to diagnose different stages of the ecosystem degradation. Variable y is considered an indicator of ecosystem quality. The analysis of differential derivatives of the $y(x)$ function is used to distinguish between different qualitative states of the ecosystem [5, 15]. It is assumed that the maximum of the first derivative corresponds to the transfer of the ecosystem into the critical state. The first maximum of the second derivative indicates the transition to the catastrophic state. However, the interpretation of this formal procedure requires special substantiation, because, strictly speaking, the passing through the critical point only means that variable y in this area changes much faster than in neighboring areas [6]. For an unambiguous estimate, it is necessary to choose such an indicator whose changes in the critical points actually correspond to significant changes in the ecosystem functioning and structure.

Analysis of response surface. The study of self-regulation processes in an ecosystem upon increasing rates of pollution makes it possible to distinguish between several phases of an ecosystem's response to the pollutants: (a) the phase of nonspecific physiological and biochemical reactions similar to those in an ecosystem composed of a single species, (b) the phase of mutual action of physiological and ecological compensatory mechanisms with a more complex response, and (c) the phase of irreversible changes and degradation of the ecosystem with switched-off ecological compensatory mechanisms [12]. The creators of this method experimentally determined critical loads of toxicants on the biotic indices of hydrocenoses. Then, they analyzed response surfaces for the cenoses of different complexities. The response of a single-species system to the increasing concentration of the toxicants was relatively simple and monotonous. The response of multispecies systems was more complex, which was due to the action of specific ecological compensatory mechanisms. The deviation from the monotonous response was interpreted as the transition of the ecosystem to the second phase. Loads corresponding to this phase were considered critical loads; the transition to the third phase was considered an irreversible degradation of the structure and functioning of the ecosystem [12].

This method is based on the study of the response of natural ecosystems to external impacts. It is analogous to the method of ecotoxicological laboratory experiments. However, in this case, increasing doses of toxicants are applied to natural ecosystems to test their tolerance. Thus, the problem of inadequacy of the experimental conditions to those in nature can be ignored. A similar approach of the initiated response was applied to study soil microbial communities [10]. The species composition of the community changed significantly upon the doubling of the concentration of toxicants. This state of the community was referred to as the stress state. Upon a further rise in the concentration of the toxicants, the species composition of the community remained stable, which attested to a certain tolerance of this new transformed community to the toxicants.

It is important that the responses of communities to certain loads can be preliminarily studied. As well as in the case of formal statistical methods, this circumstance eliminates the problem of choosing the control plots in nature. The subdivision of the responses of biotic communities to artificially introduced external loads (e.g., contaminants) into the phases of physiological and ecological responses is similar to that applied in the method of multiple biological indication of natural objects [17].

In general, the ecological value of the results of analytical approaches depends on the adequacy of the response of the selected biological indicator to the response of the entire system. Extrapolation of data on separate indicative species over the entire system is open to argument [6, 26]. An unambiguous decision can only be made if the detected changes in the selected biological indicators do correspond to functional changes in the entire ecosystem. Some researchers argue that indicators adequately describing quantitative changes in the ecosystem can be chosen with the help of expert estimates or mathematical modeling [6, 22].

Modeling of the Process

The development of a model of an ecosystem behavior under external impacts (including technogenic pollution) makes it possible to perform numerical experiments, to predict ecotoxicological disasters, to reveal the most sensitive ecosystem components, and to establish relationships between the values of biological indicators and the functional properties of ecosystems. This method allows us to register the transition from quantitative to qualitative changes and to suggest control measures in advance. Two major types of mathematical models are used in ecology: analytical (empirical) models and imitation models. Analytical models allow us to trace the relationships between separate characteristics of the biotic and abiotic components of an ecosystem [22, 34]. However, extrapolation of data obtained on the separate components of an ecosystem over the entire ecosystem is not always correct. Many researchers believe that the method of imitation modeling is more adequate in order to distinguish between different qualitative states of an ecosystem [6, 22].

Imitation modeling. This method is particularly efficient for solving applied problems of ecology when the "final goal is to find those conditions under which the desired state of particular (important for humans) parameters of an ecosystem is achieved" [22, p. 328]. As we consider ecosystems in the critical state, relatively simple models can be applied [25]. For example, such a model was applied to study degradation of a desert ecosystem under the impact of grazing loads and global warming [20]. This model described hourly dynamics of weather parameters, the soil temperature and water content, and the reserves of organic matter in the plant cover. The ecosystem state was judged from the productivity of its phytocenosis. Numerical experiments with this model made it possible to asses the existing grazing pressure for desert ecosystems under conditions of their agricultural use and in the reserved territories.

Combination of Approaches

Different approaches described in this paper can be combined with one another. For example, the method of expert estimates and the method of imitation modeling were combined to study the anthropogenic transformation of tundra landscapes [2]. The values of selected parameters of a given type of tundra landscape were determined by an expert. Then, the mathematical formalization of existing concepts about the natural and anthropogenic dynamics of landscapes (i.e., about natural successions and successions initiated by external impacts) was performed, and a formal description of the impacts was made. As a result, every type of landscape was described by a set a parameters (vector of parameters). In the model, the impacts were characterized by the difference in the values of these parameters before and after the impact. First, isolated areas with an assumed similarity of an ecosystem's response to particular impacts were described. The rules of transition from the given state of the ecosystem to another state were formulated. Then, the matrix of such areas was modeled. It was taken into account that some ecosystems could be transformed into other ecosystems under the impact of anthropogenic loads. The types of ecosystems and their parameters were determined with the help of experts.

The use of imitation modeling for distinguishing between quantitatively different states of different ecosystems poses the problem of unification of the initial data sampling. Extensive and costly field and laboratory studies should be preliminarily performed. The methodology of computer-based modeling suggests that the requirements for unification of the initial data should be worked out before the stage of field studies [20].

CONCLUSIONS

Evaluation of the state of natural ecosystems under technogenic loads assumes that several qualitative states of an ecosystem corresponding to different stages of its technogenic transformation should be distinguished and diagnosed. In comparison with a combined and unambiguous estimate on the basis of the criteria of maximum permissible concentrations (MPCs) of the pollutants, the method of biological indication of the state of natural ecosystems involves certain objective difficulties in the interpretation of the results. These difficulties, together with insufficient standardization of the methods of biological indication, hamper the practical application of these methods, though the use of the biological indicators for judging the state of impacted ecosystems seems to be more promising than the use of the MPC concept.

We have analyzed different approaches to the development of the "norm–pathology" scales for aquatic and terrestrial ecosystems with the use of biological indicators. All these approaches make it possible to distinguish between separate stages of the technogenic degradation of natural ecosystems from the corresponding values (ranges of values) of the selected biological indicators. Most often, the correspondence between particular values of the selected biological indicators and the state of the ecosystem is established on the basis of expert estimates. The separation of discrete states of an ecosystem by the method of expert judgment is always somewhat subjective; as a result, ambiguous estimates are possible. At the same time, the method of expert estimates is the only method to qualify characteristics of an ecosystem that are difficult to measure but which are very important, such as the depth and reversibility of transformation changes, the relaxation period, the loss of tolerance, etc. More objective estimates require costly and laborious investigations. The results obtained by the formal statistical methods cannot be correctly interpreted without the preliminary testing of the corresponding statistical hypotheses. Analysis of the dose-and-effect relationships poses the problem of transfer from the state of particular biological indicators (for which these relationships have been established) to the state of the entire ecosystem. Promising methods of imitation modeling are not always provided with sufficient amounts of the initially unified data.

It is necessary to maintain an optimal balance between objectivity and unambiguity of ecosystem assessment, which is ensured by the accepted formal rules and by the ecological significance of the results. From our point of view, an approach based on multiple biological indication of a studied object at different levels ensures both the required formalization of the assessment procedure and the ecological significance of the obtained results. Within the framework of this approach, changes at the higher level are interpreted as the next stage of the technogenic transformation of the ecosystem. Biological indication of ecosystem disturbances under natural conditions and the method of laboratory testing of the response of native communities to different concentrations of toxicants serve as the methodological base for interpreting the results of multiple biological indication.

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