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On the Problem of Assessing the Resistance of Planktonic Community to Adverse Influences

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Abstract—An experimental–analytical method for assessing the vulnerability of aquatic ecosystems under conditions of anthropogenic pollution is considered. Such data are very important for estimating economic damage from accidental environmental pollution and determining the seasons in which industrial activities will be less hazardous in ecological terms. A feasible approach to this problem is based on the study of ecosystem behavior under critical conditions. Phytoplankton, being the main primary producer of organic matter in the aquatic ecosystem, is the key element providing for its stability.

Key words: ecosystem, stability, planktonic community, seasonal succession of phytoplankton.

The increasing anthropogenic impact on natural ecosystems makes it necessary to study and forecast the ecological consequences of chemical pollution of the environment, including the hydrosphere. The ability of aquatic ecosystems to maintain homeostasis is limited, and a further increase in anthropogenic load may result in their irreversible transformation and degradation. The state and development of an aquatic ecosystem depend on a combination of different environmental factors, among which a major role belongs to pollution with heavy metals, pesticides, and petroleum products. Exposure to these pollutants may have different consequences, depending on the stage of seasonal succession in the planktonic community (Phillips *et al.*, 1998; Mauser, 1998; Tarkpea *et al.*, 1998). To prevent or reduce ecological damage, it is necessary to determine the periods when ecosystems are most vulnerable. This information is very important for estimating economic damage from accidental environmental pollution and determining the seasons in which industrial activities will be less hazardous in ecological terms. An important task of specialists in ecology, including aquatic toxicology, is to develop the concept of the assessment of critical changes in natural systems under the effects of anthropogenic factors.

PROBLEMS IN ECOLOGICAL TOXICOLOGY

Methods for assessing the vulnerability of biological systems at the ecosystem level have not yet been developed. Traditional toxicological methods based on the responses of individual test organisms to toxic action are not fully applicable to the natural communities of aquatic organisms and whole ecosystems (Wundram *et al.*, 1997; Molchanova *et al.*, 1996; Shadrina, 1997). The responses of different taxonomic groups (species) of planktonic organisms to toxicants differ, and the general stability of the planktonic community varies depending on seasonal changes in both the community structure and the functional activity of different groups of algae.

A feasible experimental approach to this task is to study the functioning of ecosystems under almost critical conditions, i.e., at a concentration of toxicants in an aquatic medium that approaches a certain threshold, but where the changes they cause in the ecosystem are reversible. The concentrations exceeding this threshold cause irreversible changes and degradation of the planktonic community.

Phytoplanktonic organisms, as the main primary producers of organic matter in an aquatic ecosystem, are a key element providing for ecosystem stability. The conditions critical for the phytoplanktonic community are considered to be critical for the ecosystem as a whole. Therefore, it is essential to formulate the principles of assessment of ecosystem resistance to chemical pollution as applied primarily to the phytoplankton.

Seasonal succession in aquatic ecosystems has crucial transitional periods when one community replaces another, which actually determine the subsequent course of succession. If the impact of pollutants exceeds the above threshold at this transitional stage, irreversible changes will occur in the ecosystem structure, and its development will follow a different pathway. For instance, the elimination of usual dominants and their replacement by more resistant forms of algae may take place. Thus, the concept of the critical level of impact should have reference to certain periods in the development of communities and the ecosystem as a whole.

Corresponding ecological changes may upset the balance between the synthesis and decay of organic matter in the planktonic community and organic matter flows. Under certain conditions, a great amount of readily assimilable organic matter released due to the death of planktonic organisms may stimulate an explosive growth of mixotrophic algae and, in some cases, lead to the so-called red tides observed in different areas of the World Ocean.

MAIN APPROACHES

To forecast the ecological consequences of pollution of the aquatic environment, it is necessary to estimate ecosystem resistance to adverse influences during the crucial biological periods. This involves the determination of the critical concentrations of pollutants affecting basic ecological parameters. For the phytoplankton, these parameters include primary organic matter production (P), total biomass (B), species composition, destruction (D), coefficients P/B and P/D, and the abundance and biomass of the main groups of algae.

The ecosystem responds differently to adverse environmental influences in different periods (seasons of the year), depending on the state of ecosystem components (the concentration of biogenic elements, the species structure of communities, conditions of illumination, etc.). The pattern and geographic features of seasonal changes in the degree of ecosystem stability are virtually unknown. The experimental–analytical approach to the assessment of stability of freshwater planktonic communities under stress is as follows.

In the course of seasonal succession in the phytoplankton, there are periods characterized by different degrees of its resistance to a certain adverse external influence. This is explained primarily by differences in the resistance of individual structural components of the phytoplanktonic community in a given period of time. To determine the most vulnerable periods in the development of the planktonic community, it is necessary to perform simultaneous observations providing data on the stage of seasonal succession, dominant algal species in the community, and the responses of phytoplankton to standard influences (for instance, pollutants added at certain doses). In addition, model ecotoxicological experiments are necessary for determining the range of concentrations and combinations of pollutants that are critical for the given community. Only the sum of these data can provide a reliable basis for analyzing the dynamics of resistance of the planktonic community to adverse influences and predicting its behavior in stress situations taking place in different periods of the biological season.

Special attention should be paid to the response of the phytoplanktonic community to the anthropogenic impact in the aforementioned crucial periods that determine the subsequent stages of succession. To identify such periods, it is necessary to analyze natural seasonal changes in aquatic ecosystems and distinguish the phases of community development differing in the structure and composition of dominant species, the content of biogenic elements, and the background concentrations of pollutants.

The vulnerability of the phytoplankton in the crucial periods identified in this way may be estimated in an ecotoxicological experiment. In such experiments, the response of phytoplankton to different concentrations of toxic agents is evaluated by parameters such as primary production, live release of organic matter, species composition, and biomass. They are performed with natural species complexes (in microcosms) under quasi-in situ conditions. Comparison of phytoplankton responses to the impact of toxic concentrations of pollutants at different stages of succession makes in possible to reveal the most vulnerable periods (Dallakyan *et al.*, 1999). In these experiments, toxicants are added only as standardized adverse factors causing certain community responses. The response of the phytoplanktonic community to concrete concentrations of pollutants are not considered in this case. Along with experimental studies, field observations on the current state of ecosystems, including hydrological, hydrochemical, and biological parameters, are performed.

When short-term experiments based on the dose–effect principle are aimed at comparing the responses of different communities to the same factor, rather than estimating the toxicity of a certain substance, it is only important to perform all series under the same conditions, whereas the requirement for their correspondence to natural conditions loses its validity (Lifshits and Korsak, 1988). Such experiments provide the possibility of ecotoxicological sounding of aquatic ecosystems with the purpose of revealing differences in the adaptation potentials of different communities (on a geographic or temporal scale). This approach implies the careful selection of biological indices responding to toxic exposure, which must satisfy the following requirements: (1) the index must be integrated, i.e., reflect the state of the entire ecosystem or of its most important part; and (2) its changes under the effect of toxic agents must be rapid and consistent.

Comparing the results obtained in different areas, it is possible to estimate the sensitivity of ecosystems and trends in its changes in the crucial periods of plankton succession.

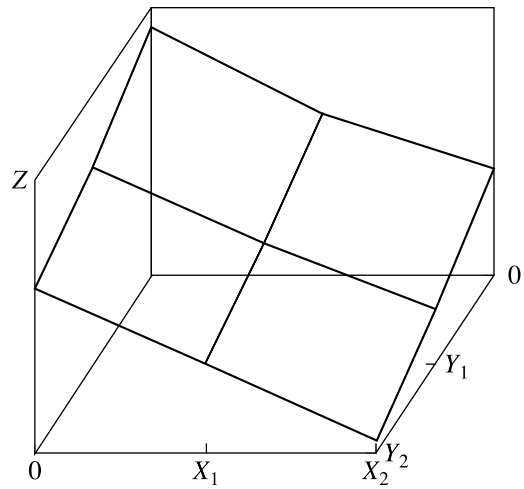

Fig. 1. Response surface reflecting unspecific (physiological) reaction of the community in a factor experiment: *Z*, test parameter (e.g., primary production); *X* and *Y*, factors (e.g., concentrations of toxicants).

ANALYSIS OF THE COMBINED EFFECT OF ADVERSE FACTORS

At the next stage, experiments are performed to study the combined effects of environmental factors. It is known that pollutants in water can interact in a complex way with different abiotic components, and their toxic effect in each particular case depends on a variety of conditions (water temperature, its chemical composition, etc.). Therefore, these model experiments should be performed under conditions close to those in a natural water body and according to a certain plan that involves a quantitative assessment of the interaction of factors under study.

The purpose of complete factor experiments (CFEs) in ecotoxicology is a quantitative analysis of the combined and independent effects of toxic agents at several concentrations and in different combinations on biological objects (Maksimov *et al.*, 1969). As a rule, CFEs are performed with two or three agents (factors) at three concentrations (CFE 3^2 or CFE 3^3, respectively), with each combination studied in an individual experimental series. The correct range of factor values (e.g., effective concentrations of a toxicant) for CFE is determined in preliminary dose–effect experiments. It is convenient to represent the results of CFEs as diagrams of response surfaces that reflect changes in the test parameter (e.g., primary production or biomass of the phytoplankton) depending on the combination of factors (Fig.1).

Regardless of the extreme diversity of biological objects, the strength of response observed in dose–effect experiments with a single species directly depends on the strength of impact: the more toxic the environment created in the experiment, the more severe the disturbances in biological processes. Conversely, such a trend is usually not observed in experiments with multispecific systems or in the course of observations on the pattern of responses in nature (Korsak and Nakani, 1976). This can only be attributed to the effect of the compensatory resources of ecosystems.

Observations of the ecological state of water bodies and the results of biocybernetic investigations provide evidence that the response of an ecosystem to toxic exposure has two phases. At the first phase, when the toxic impact is not very strong, unspecific physiological–biochemical compensatory mechanisms begin to operate. No profound rearrangement of the species structure of the ecosystem (such as the extinction of individual species or the change of dominants) takes place, and adverse effects on the ecosystem as a whole or on any process occurring in it are compensated due to the quantitative changes in the rate of metabolic processes in individual groups of organisms (in phytoplankters, for instance, exposure to pollutants leads to changes in the rate of photosynthesis, the amount and pattern of excretions, membrane permeability, etc.). In general, the unspecific response of the ecosystem to the inhibition of individual biological processes has the same pattern as in the case of experiments with groups of conspecific organisms.

At the next phase, as the concentration of pollutants or the period of exposure increase, the species structure of the ecosystem begins to change. The species less sensitive (more resistant) to the corresponding influence gain dominance in individual components of the ecosystem, and its total species diversity decreases. Both physiological and ecological compensatory mechanisms operate in this period, and the ecosystem response has a more complex and diverse pattern. When the impact becomes still stronger, it overpowers the resistance of the ecosystem and causes irreversible changes in it, which are so profound that they may lead to its degradation and eventual destruction. The species composition at this phase is impoverished, and interspecific compensatory rearrangements are insignificant (Korsak *et al.*, 1976; Maksimov *et al.*, 1985).

Thus, the level of toxic exposure that causes the second phase of response involving specific ecological compensatory mechanisms is critical for the ecosystem. The monotonic pattern of ecosystem response is disturbed, with the points of inflection of one-dimensional and multidimensional response surfaces corresponding to the critical concentrations of toxicants. Their range can be determined by comparing the standard (reference) and the experimental response surfaces and identifying the zone in which they do not coincide. These concentrations are indeed critical, since they indicate the limit of toxic exposure that cannot be exceeded without causing irreversible disturbances in the structure and functioning of the ecosystem.

The geometric analysis of response surfaces obtained in the course of factor experiments makes it possible to analyze the complex processes involved in the reactions of planktonic communities to the anthro-

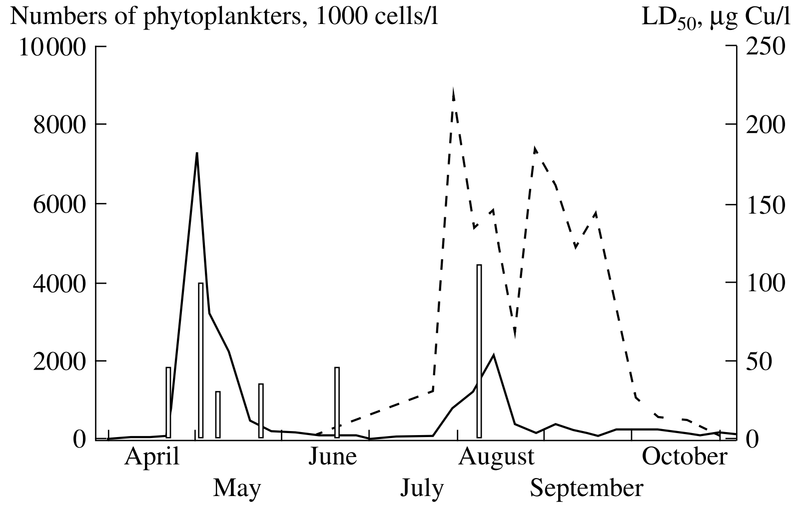

Fig. 2. Results of ecotoxicological experiments performed in different periods of the seasonal population dynamics of groups dominating in phytoplankton of the Ucha Reservoir: columns show copper concentration causing a 50% decrease in the primary production (LD_{50}); solid line, numbers of diatoms; broken line, numbers of blue-green algae.

pogenic impact. The ecological–analytical comparison of the response surfaces of natural communities with a standard (reference) surface may be instrumental in determining the resistance of the planktonic community to an adverse impact and estimating potential critical changes in the ecosystem structure (Maksimov *et al.*, 1989). In practice, to determine the degree of correspondence between the experimental and standardized surfaces, it is necessary to calculate the coefficient of orderliness of the response surface (CORS), i.e., the ratio of the number of cases deviating from the standard to the total number of concentrations compared. This index characterizes the ecological profundity of the community response and allows specialists to supplement a purely descriptive analysis of the results of a factor experiment with quantitative data. In the case of purely physiological, unspecific responses, CORS = 0; if all possible combinations of concentrations induce only ecological responses, CORS = 1 (Maksimov *et al.*, 1989).

Thus, we can determine the limits of the critical concentrations of pollutants (or other adverse factors) by comparing the response surface obtained in experiments with a true multispecific system and the response surface characterizing a monospecific system in which only unspecific, physiological compensatory mechanisms operate. For the standard response surface, the following trend was revealed in numerous experiments (Nosov *et al.*, 1981; Dallakyan *et al.*, 2002): the stronger the impact, the more intense the adverse response of the system (mortality increases, and biological processes are inhibited to a greater extent).

We used the dose–effect approach in studies on the toxic influence of copper on primary phytoplankton production in the Ucha Reservoir, which included several series of ecotoxicological experiments with the natural phytoplanktonic community performed in different periods of its seasonal development. The results of one series are presented in Fig. 2. They show variation in the sensitivity of production capacities of the phytoplankton in the course of seasonal succession, when considerable changes in abundance and the replacement of main dominant groups (diatoms and blue-green algae) took place. It is apparent that the phytoplankton was most resistant to the toxic effect of copper in the periods of its greatest abundance and highest total primary production. However, note that specific production (i.e., primary production related to the total phytoplankton abundance) was minimal in these periods.

These results provide a basis for the conclusion that transitional periods in the seasonal phytoplankton succession may be the most sensitive to adverse factors. However, basic trends in the effects of certain factors (for instance, heavy metals) on the structural and functional characteristics of phytoplankton require further investigation, namely, into their combined action, using the principles of the factor experiment.

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