Aquatic ecosystem assessment using exergy

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Abstract
The recent work is dedicated to the study of behaviour of exergy and structural exergy in physical models of aquatic ecosystems—mesocosms and microcosms and in Lake Baikal. The results of field experiments with mesocosms on Lake Baikal, containing natural plankton assemblage, and laboratory experiments with microcosms containing Daphnia magna and Chlorella vulgaris demonstrated decrease of the structural exergy of the communities after the addition of allochtonous compounds—peptone, diesel oil, α-biphenyl, CdCl₂ to mesocosms assemblage of Lake Baikal and after the addition of toxicants to microcosms. Structural exergy decreased in microcosm experiments proportionally to a value of the added toxicant (phenol, CoCl₂ and CuSO₄) concentration, while other parameters (biomasses of components, total biomass of community, total exergy) fluctuated. Comparison of exergy content for benthos in pure and affected by the discharges of Baikalsk Pulp & Paper Combine also showed significant decrease of structural exergy in polluted area. It points to the possibility of using structural exergy as reflecting ecosystem health.

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Keywords: Exergy; Ecosystem health; Mesocosms; Microcosms; Lake Baikal

1. Introduction
The evidence of the necessity to have a measurable parameter reflecting the state of the ecosystem, and allowing an estimate of the severity of its anthropogenic damage is clear now (Costanza and Jørgensen, 2002). Many authors have proposed various ecosystem goal functions to be used as such ecosystem health indices: ascendancy, energy, entropy, energy flow maximization, etc. (Odum, 1983; Costanza, 1992; Ulanowicz, 1995; Fath et al., 2001). Among them one, namely exergy, is shown to have such advantages as good theoretical basis in thermodynamics, close relation to information theory, rather high correlation with others goal functions and relative easiness of computation (Jørgensen and Bendoricchio, 2001). Exergy is defined as the distance between present state of the system and the state of it in thermodynamic equilibrium with the environment, measured in the units of energy (Jørgensen, 1997). It demonstrates the amount of work performed to create a given system from its primary components (in the case of ecological systems—from primary chemical compounds). Exergy related to the total biomass (structural, specific or normalized exergy) measures the possibility of ecosystem to accept and utilize external fluxes of energy (Jørgensen, 2002). It reflects the degree of ecosystem development or complexity and has such advantages in comparison with the total exergy as independence from the total biomass of the ecosystem.
and possibility to serve as an indicator, demonstrating the level of evolutionary development of organisms the ecosystem consists of (Jørgensen, 1997, 2001).

Now exergy is applied for different problems solving, particularly with the use of mathematical models. Exergy helps to understand and explain fundamental characteristics of ecosystems studied by theoretical ecology (Bastianoni and Marchettini, 1997; Patten et al., 1997; Straškraba et al., 1999; Jørgensen et al., 1999, 2000; Jørgensen, 2002a,b), and to investigate behaviour and interaction of some ecosystem components (Levich, 2000; Park et al., 2001). Exergy seems to be an useful tool for ecological model parameters estimation and calibration of models (Jørgensen, 2001; Jørgensen et al., 2002a,b). Sometimes exergy is applied to analyse the data of field observations and to determine the state of natural ecosystem (Salomonsen, 1992; Xu, 1997; Xu et al., 1999, 2002; Park et al., 2001; Ludovisi and Poletti, 2003; Marques et al., 2003).

Previously we have demonstrated the inverse correlation of structural exergy with the degree of their watershed basin urbanization in some Korean reservoirs (Oh and Silow, 2002). Exergy was also applied to estimate the ecosystem changes under various external influences, mainly chemical intoxication. Some works based on recalculation of results received by other authors appeared (Silow, 1997, 1998; Xu et al., 2000). Analysing the results of 50 experimental works (additions of various chemicals to model aquatic ecosystems) with mesocosms, microcosms, experimental ponds, carried out by different groups of researchers throughout the world we have discovered structural exergy to remain at constant level when the allochtonous compounds can be metabolised by an ecosystem, but when the added substance is non-degradable, too toxic or in too high concentrations, structural exergy is decreasing, demonstrating the inability of the ecosystem to adapt to this influence and, consequently, the irreversibility of changes in the ecosystem (Silow, 1997, 1998).

Until now there is no research, which combines obtaining experimental results under laboratory and field conditions, field observation data and analysis of exergy and structural exergy dynamics on the basis of these data.

The recent work is dedicated to the study of behaviour of exergy and structural exergy in physical models of aquatic ecosystems (mesocosms and microcosms) and in natural water body (Lake Baikal).

2. Mesocosm experiments

Mesocosm experiments were conducted at Lake Baikal (1986–1990). Mesocosms used were 2m³ plastic bags containing natural plankton community of Lake Baikal. Methods of operation with mesocosms are described in details in previous publications (e.g. Silow et al., 1989, 1991). The water together with the natural plankton was isolated with the use of bags (2.0 m³ in volume) made from polyethylene film (0.05 ± 0.001 mm thick). Polyethylene tube (1 m in diameter) attached to the plastic ring was put on the water column and isolated from both ends. A weight was attached to the lower end, while the upper end was provided with the float and the plastic tube (7.5 cm in diameter) for sampling. During the summer–fall experiments the bags were fastened to a rope with floats. Both ends of the rope were anchored in the bottom. During the under ice experiments bags were established through ice-holes and fastened to ice. The bags were filled at the same place they were exposed later at the depth of 2–2.5 m. The number of replicates varied from 2 to 5. One experiment usually included 8–10 mesocosms. The sampling of plankton has been carried out simultaneously with the bags filling. Then samples of water from lake and each mesocosms for phyto- and bacterioplankton, hydrochemical parameters, etc. were taken regularly. When the exposition was over, water sampling from the lake and mesocosms was completed. The sampling of zooplankton from mesocosms was conducted by filtering the total volume of plastic bag through plankton net. The samples were fixed and processed using standard methods. Temperature and transparency of the water were measured during the exposition.
The duration of experiments varied. During the experiments phytoplankton composition and biomass, bacterial colony forming units on fish-peptone agar number were registered daily, zooplankton composition and biomass—in the start and the end of experiment. Here, we used the data of 10-day experiments completed both during open water season (July–September) and under the ice. We have analysed the results of more than 400 series of mesocosms field experiments. Additions of non-toxic organic compounds (peptone), phenol compounds (o-biphenyl), oil products (diesel fuel), heavy metal ions (Cd²⁺) were tested.

2.1. Microcosm experiments

The microcosms we used contained two trophic levels—producers and consumers (green algae *Chlorella vulgaris* and cladoceran *Daphnia magna*, respectively). Each microcosm was a 1 l cylinder, containing 10 mature daphnia specimens and algae in concentration about 0.5 g l⁻¹. Microcosms were exposed at constant temperature (20°C) at 8 h of darkness, 16 h of light regime. The exposition was 7 days in each experiment. Direct counts of daphnia and algae concentration were taken daily. We used three model toxicants—phenol, as representative of organic non-conservative degradable toxicants (starting concentrations 1–25 mg l⁻¹), cobalt chloride (CoCl₂), as representative of non-organic conservative non-degradable toxicants (starting concentrations...
0.05–0.5 mg Co^{2+} \cdot l^{-1}), copper sulphate (CuSO_4), as algaeicide (0.05–0.2 mg Cu^{2+} \cdot l^{-1}).

2.2. Field observations

Analysing the exergy content in benthic communities in pure and polluted by “purified” wastewaters of Baikal Pulp & Paper Combine we used the data collected by specialists of Institute of Biology at Irkustk State University. These data were published in available literature (Kozhova and Izmost’eva, 1998). We operated with exergy values that we have calculated from those primary data.

2.3. Exergy calculations

Exergy was calculated according to Jørgensen and Bendoricchio (2001), structural exergy was determined as relation of total exergy to total biomass

\[ \frac{Ex}{RT} = \frac{\sum \text{Ex}_{i}}{N} \]

where \( Ex \) is the total exergy of community, \( R \) is gas constant, \( T \) is absolute temperature (K), \( N \) is number of components, \( c_i \) is concentration of component \( i \), biomass per unit of volume, or per unite of area, wet weight, g m\(^{-3}\) (for mesocosm experiments), mg l\(^{-1}\) (for microcosm experiments) or g m\(^{-2}\) (for benthos), \( f_i \) is conversion factor for component \( i \) relative to humus (according to Jørgensen, 1997; Jørgensen and Bendoricchio, 2001; Park et al., 2001; Ludovisi and Poletti, 2003).

The “exergy” we refer to in the paper below is actually \( \frac{Ex}{RT} \), expressed in humus equivalent (Jørgensen,
3. Results

We have selected the most widely spread and important contaminants for lake Baikal. Input of the allochthonous organic matter was simulated by the addition of a non-toxic organic compound (peptone). Chemically, it is similar to organic compounds—products of phytoplankton activity in the River Selenga (the main tributary of the lake supplying half of the all water input to Baikal). Phenol compounds enter the lake as a result of human industrial activity (Baikalsk Pulp & Paper Combine). Also, the compounds enter due to logs rafting in tributaries. Significant amounts of phenol compounds are produced during the dying off of the algae after phytoplankton blooms. Oil products enter the water of the lake from shoreline (in the regions of railroads in the southern and northern parts of the lake). Some quantities of oil products come to the lake due to water transport activity (multiple cargo and passenger ships, motor boats, etc.). Heavy metal ions enter the lake both with precipitations and with water of tributaries being the waste products of industry of the region (Korshova and Izmest’eva, 1998).

We show that additions of non-toxic organic compounds (peptone), phenol compounds, oil products, in low concentrations to do not affect structural...
Exergy and the changes in ecosystem structure were reversible. Biomass responses varied (no changes, increase or decrease), as well as total exergy content. The additions of CdCl2 and relatively high concentrations of o-biphenyl (0.5 mg l\(^{-1}\)), diesel fuel (2.5 mg l\(^{-1}\)), even non-toxic peptone (10 mg l\(^{-1}\)) caused decrease of structural exergy and degradation of ecosystem structure (Figs. 1–4). Under ice community was remarkably more sensitive to additions than summer one.

Results obtained with microcosms (some are presented in Figs. 5–7) demonstrate structural exergy decrease in microcosm experiments proportionally to a value of the added toxicant concentration, while other parameters (biomasses of components, total biomass of community, total exergy) fluctuated.

Observations on the structure of benthic community in the region of the discharge of Baikalsk Pulp & Paper Combine waste waters are available since 1960s. From the same time these data are compared with the results of the investigation of physically similar region of the lake bottom where benthos initially was practically identical to now polluted region. We have calculated exergy content of benthic communities for both pure and “dirty” locations, using data collected by

![Graph](image)

**Fig. 7.** Changes of total biomass – \(B\) (g l\(^{-1}\)), exergy – \(Ex\) (humus equivalent mg l\(^{-1}\)), and structural exergy – \(Ex/B\) after CuSO\(_4\) addition in microcosms.
the specialists of Institute of Biology at Irkutsk State University. Comparison of exergy content of benthic communities for pure region of Baikal and for the region of “purified” wastewaters of Baikalsk Pulp & Paper Combine (calculations are made based on the data published by Kozhova and Izmest'eva (1998)) input has shown that structural exergy in pure region is significantly higher than in polluted one, while biomass can be lower or higher (Figs. 8–10).

4. Discussion

Higher sensitivity of under-ice community of Baikalian plankton in comparison with summer community can be related to the fact of higher percentage of endemic forms both in phyto- and zooplankton under ice cover, because endemic diatom species develop mainly during spring bloom as well as endemic rotifers species are practically absent in summer zooplankton (Kozhova and Izmest’eva, 1998).

The region of Baikalsk Pulp & Paper Combine wastewaters discharge is characterised by presence of thick layer of lignin, high biomass of some molluscs and oligochaetae, but low biodiversity, pure aquatic flora and is characterised by various coefficients like species diversity index, etc. (Kozhova and Izmest’eva, 1998) as “degrading” region of the lake bottom. Exergy calculations presented here are in good accordance with these data.
It is necessary to point on the fact that, according to our previous results, when added substances were very toxic or non-metabolised, e.g. Kepone (pesticide), cadmium ions, mercury ions, inorganic acids, or the substances (copper ions, bifenthrin (pesticide), chlorinated organic compounds, benzene, oil) were introduced in high concentrations, a decrease of structural exergy was observed. Often it indicated the sufficient degradation of ecosystem, elimination of its component (severe decrease or even disappearing of some species) or sometimes entire trophic levels, e.g. cladocerans were replaced with copepods after addition of carbaryl, and with ostracods after addition of streptomycin, crustaceans, worms and insects were replaced with rotifers and fishes under the action of esfenvalerate, insects and crustaceans were replaced with molluscs and worms in the presence of trichloroguainicol (Silow, 1998). The addition of Kepone in high concentration, which caused complete elimination of zooplankton and fishes and decrease of phytoplankton biomass resulted in sharp fall down of structural exergy (Silow, 1998). Sometimes it was observed when the toxicant was added in sublethal concentrations, e.g. low concentrations of mercury inhibited the crustacean zooplankton development rate and the growth of fishes (Silow, 1998).

According to Schaeffer et al. (1988) ecosystem health criteria: (1) should not depend on the presence, absence, or conditions of single species, (2) should be numerical and dimensionless, (3) should reflect our knowledge of ecosystem. Structural exergy seems to suit these demands. Additionally exergy is relatively easy to calculate, the data collected during ordinary monitoring are quite sufficient for its calculation, and it reflects the condition of of an ecosystem as whole (Jørgensen, 1997; Jørgensen et al., 2002a,b). As it was stressed above, Jørgensen (2001) connects the value of normalised or structural exergy with the possibility of ecosystem to accept and utilize external fluxes of energy. The addition of toxicant can be accepted as external flux of energy and information (in this case—destructive). If the structural exergy is equal to the initial or control level, then this demonstrates the stability of ecosystem and its ability to withstand this external influence. The decrease of it shows degradation of ecosystem and its disability to support its structure at given level of external influence. These conclusions are in good accordance with results of mathematical modelling experiments (Silow, 1999) and calculations based on the results of the field observations and experiments (Jørgensen et al., 2002a,b; Oh and Silow, 2002; Marques et al., 2003).

5. Conclusion
Of course, our results are preliminary and are far from being an ultimate truth, but they may be accepted as fact. We can see structural exergy decrease when ecosystem suffers from chemical pollution. Taking into account the data presented here and discussed above, we now can recommend to use structural exergy goal function in environmental monitoring as
a holistic and quantitative parameter, reflecting the ecosystem state and its anthropogenic changes. Certainly, additional investigations are necessary.

Acknowledgements

The authors are grateful to Prof. Dr. S.E. Jørgensen, the initiator of this research and direct teacher of one of them. The authors are also thankful to the students taking an active participation in the recent investigation. Students of Irkutsk State University took part in the mesocosm experiments, PaiChai University—in microcosm experiment. The current work is partly supported by RFBR grant no. 02-04-49362.

References


