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Aquatic ecosystem assessment using exergy

Eugene A. Silow [a,*], Oh In-Hye [b]

[a] *Scientific Research Institute of Biology, Irkutsk State University, P.O. Box 24, Irkutsk 664003, Russia*
[b] *Division of Life Sciences, PaiChai University, Daejeon 302-735, South Korea*

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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, *o*-biphenyl, $CdCl_2$ 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, $CoCl_2$ and $CuSO_4$) 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.

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 anthropogenous 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, emergy, energy flow maximization, entropy minimization, 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

* Corresponding author. Tel.: +7 395 2334479;
fax: +7 395 2345207.
E-mail address: eugenesilow@hotmail.com (E.A. Silow).

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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).

The main features of the changes of exergy of ecological systems under the external perturbations were studied in the computational experiments with water bodies and flows mathematical models, describing processes of eutrophication and toxification (Patten and Jørgensen, 1995; Silow, 1999; Ray et al., 2001; Jørgensen, 2001).

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., 2002). 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 $2\,m^3$ 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 ($2.0\,m^3$ 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 (Cd^{2+}) were tested.

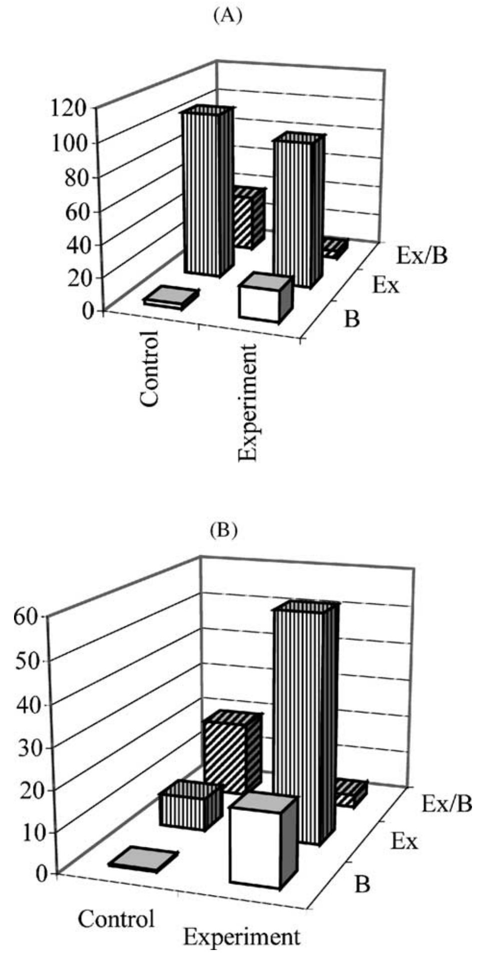

Fig. 1. Effects of addition of diesel oil ($2.5\,mg\,l^{-1}$) in summer (A) and under ice (B) in mesocosms. Total biomass – *B* ($g\,m^{-3}$), exergy – *Ex* (humus equivalent $g\,m^{-3}$), and structural exergy – *Ex/B*.

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 ($CoCl_2$), as representative of non-organic conservative non-degradable toxicants (starting concentrations

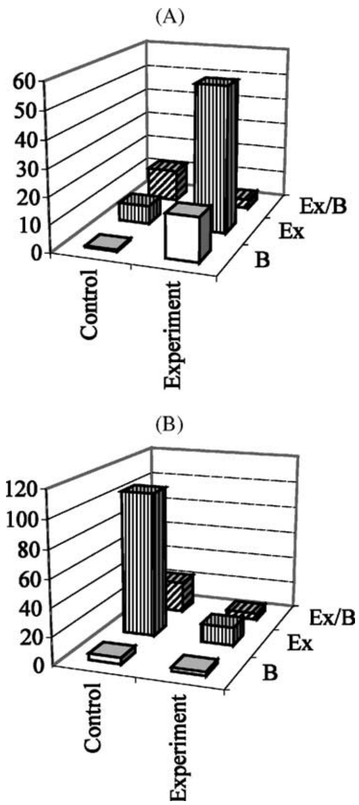

Fig. 2. Effects of addition of peptone ($10\,mg\,l^{-1}$) in summer (A) and under ice (B) in mesocosms. Total biomass – *B* ($g\,m^{-3}$), exergy – *Ex* (humus equivalent $g\,m^{-3}$), and structural exergy – *Ex/B*.

0.05–0.5 mg Co^{2+} l^{-1}), copper sulphate ($CuSO_4$), as algaecide (0.05–0.2 mg Cu^{2+} l^{-1}).

2.2. Field observations

Analysing the exergy content in benthic communities in pure and polluted by "purified" wastewaters of Baikalsk Pulp & Paper Combine we used the data collected by specialists of Institute of Biology at Irkutsk State University. These data were published in available literature (Kozhova and Izmest'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

$$Ex/RT = \sum_{i=1}^{N} c_i f_i, \qquad Ex_{Str} = \left(\sum_{i=1}^{N} c_i f_i\right)\left(\sum_{i=1}^{N} c_i\right)^{-1},$$

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 Ex/RT, expressed in humus equivalent (Jørgensen,

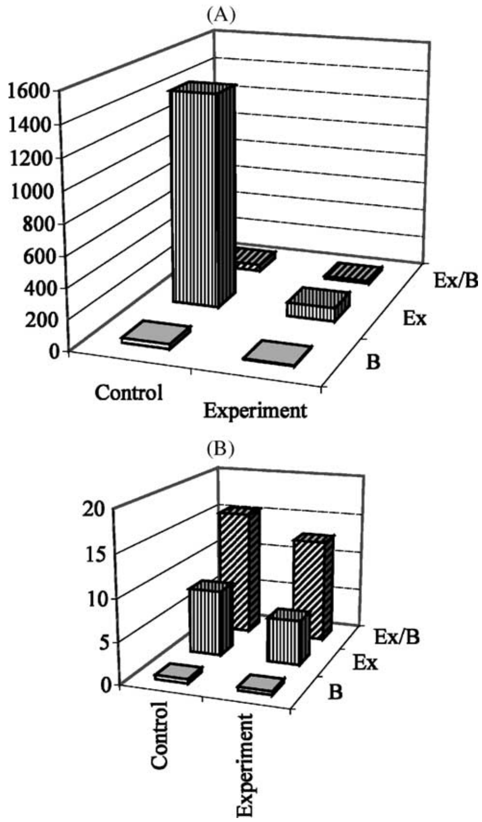

Fig. 3. Effects of addition of *o*-biphenyl (0.5 mg l^{-1}) in summer (A) and under ice (B) in mesocosms. Total biomass – B (g m^{-3}), exergy – Ex (humus equivalent g m^{-3}), and structural exergy – *Ex/B*.

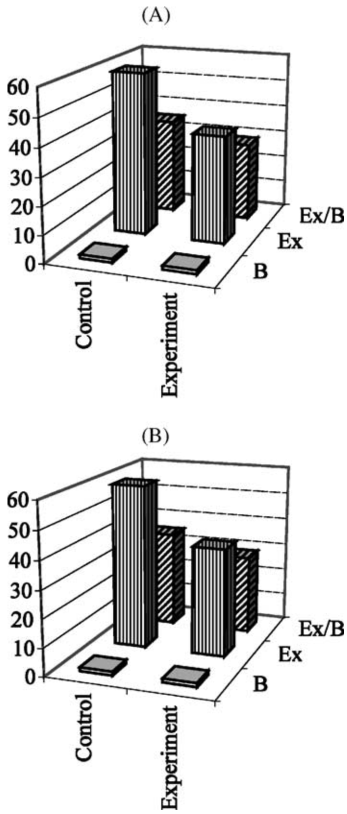

Fig. 4. Effects of addition $CdCl_2$ (10 μg l^{-1}) in summer (A) and under ice (B) in mesocosms. Total biomass – B (g m^{-3}), exergy – Ex (humus equivalent g m^{-3}), and structural exergy – *Ex/B*.

1997), $g\,m^{-3}$ (for mesocosm experiments), $mg\,l^{-1}$ (for microcosm experiments) or $g\,m^{-2}$ (for benthos).

3. Results

We have selected the most widely spread and important contaminants for lake Baikal. Input of the allochtonous 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 (Kozhova 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

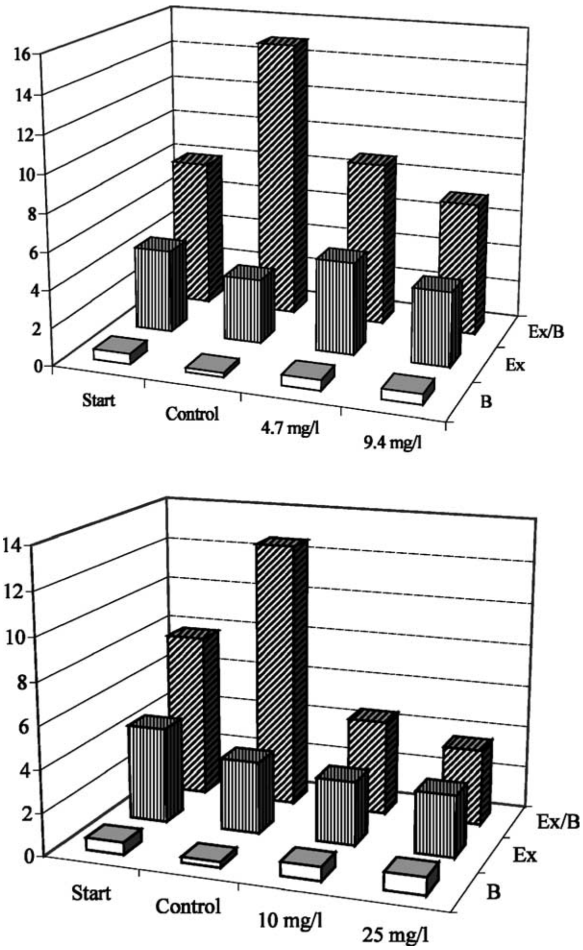

Fig. 5. Changes of total biomass – B ($g\,l^{-1}$), exergy – Ex (humus equivalent $mg\,l^{-1}$), and structural exergy – Ex/B after phenol addition in microcosms.

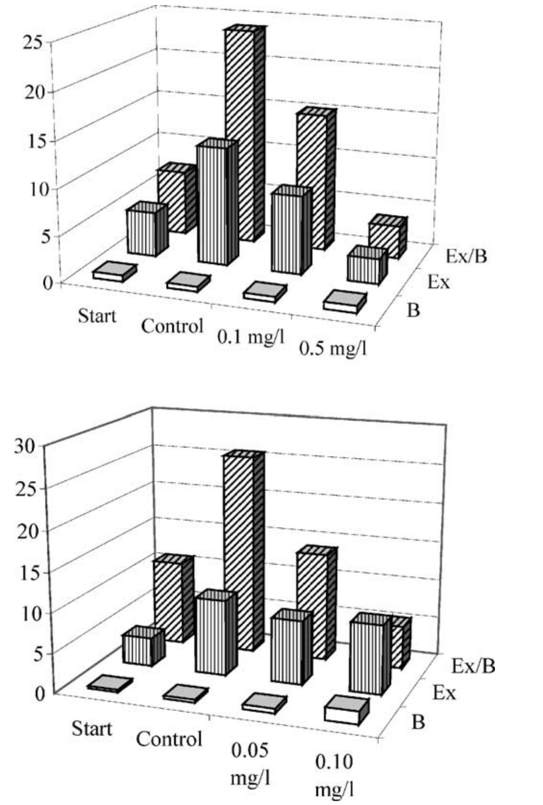

Fig. 6. Changes of total biomass – B ($g\,l^{-1}$), exergy – Ex (humus equivalent $mg\,l^{-1}$), and structural exergy – Ex/B after $CoCl_2$ addition in microcosms.

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 $CdCl_2$ 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

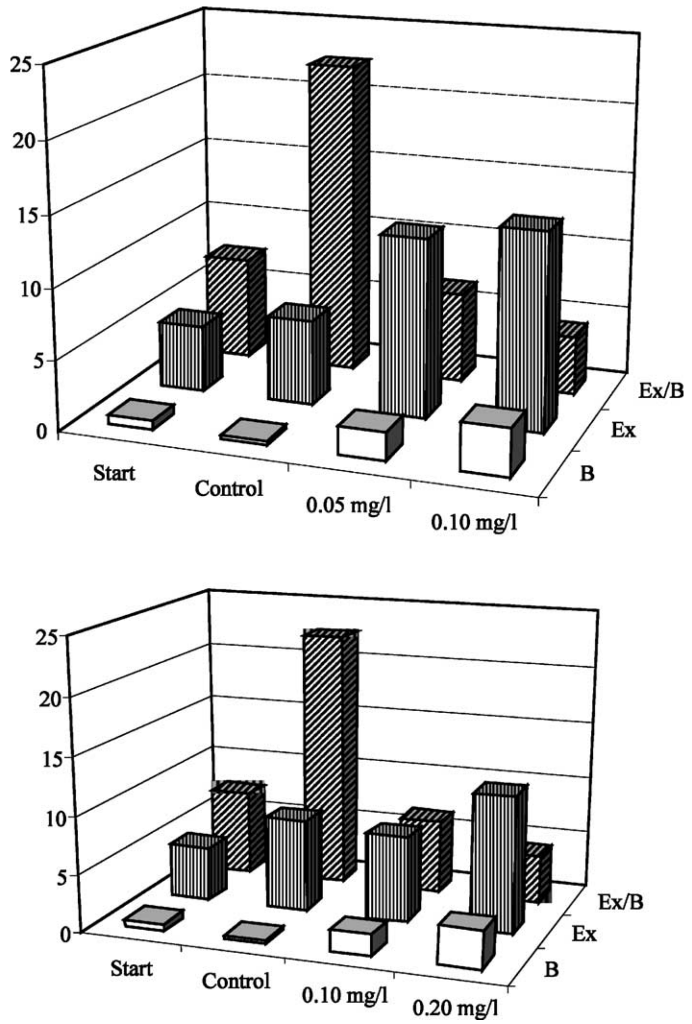

Fig. 7. Changes of total biomass – *B* ($g\,l^{-1}$), exergy – *Ex* (humus equivalent $mg\,l^{-1}$), and structural exergy – *Ex/B* after $CuSO_4$ addition in microcosms.

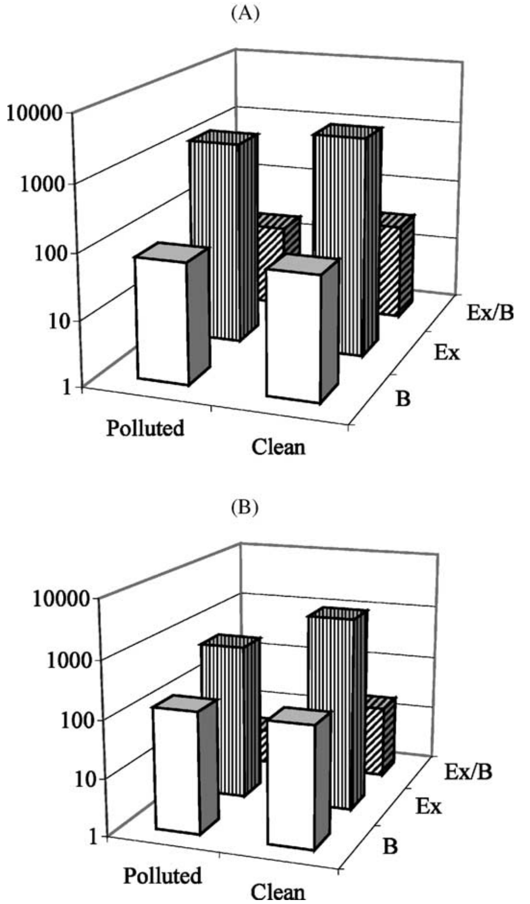

Fig. 8. Exergy of benthos in polluted and clean regions of Baikal. (A) Silt, (B) sand, depth 0–20 m. Total biomass – B (g m^{-2}), exergy – Ex (humus equivalent g m^{-2}), and structural exergy – Ex/B.

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

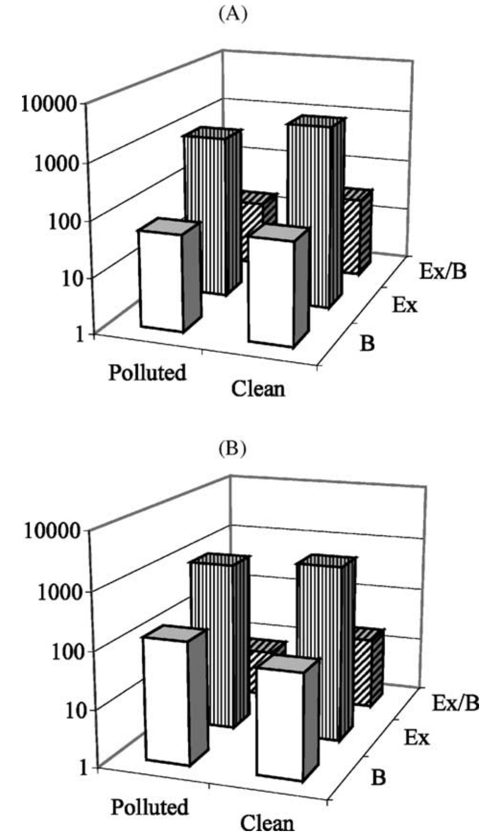

Fig. 9. Exergy of benthos in polluted and clean regions of Baikal. (A) Silt, (B) sand, depth 20–50 m. Total biomass – B (g m^{-2}), exergy – Ex (humus equivalent g m^{-2}), and structural exergy – Ex/B.

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.

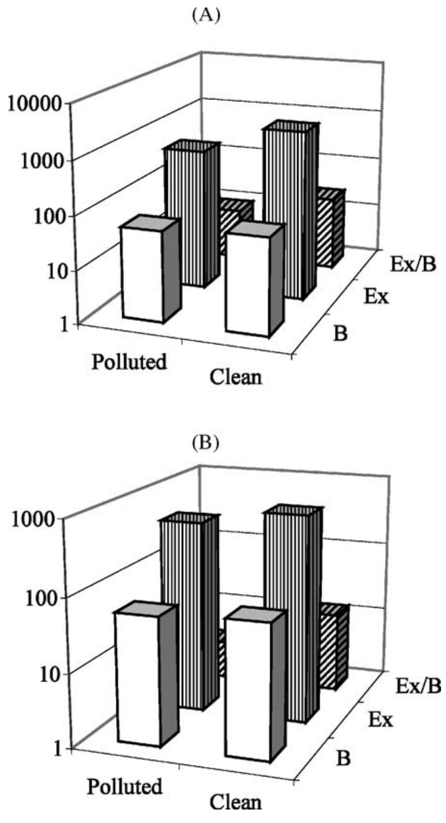

Fig. 10. Exergy of benthos in polluted and clean regions of Baikal. (A) Silt, (B) sand, depth 50–70 m. Total biomass – *B* ($g\,m^{-2}$), exergy – *Ex* (humus equivalent $g\,m^{-2}$), and structural exergy – *Ex/B*.

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 trichloroguaiacol (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.

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References

Bastianoni, S., Marchettini, N., 1997. Emergy/exergy ratio as a measure of the level of organization of systems. Ecol. Modell. 99, 33–40.

Costanza, R., 1992. Toward an operational definition of ecosystem health. In: Ecosystem Health. Washington, pp. 239–256.

Costanza, R., Jørgensen, S.E. (Eds.), 2002. Understanding and Solving Environmental Problems in the 21st Century. Elsevier, Amsterdam.

Fath, B.D., Patten, B.C., Choi, J.S., 2001. Complementarity of ecological goal functions. J. Theor. Biol. 208, 493–506.

Jørgensen, S.E., 1997. Integration of Ecosystem Theories: a Pattern, second ed. Kluwer Academic Publishers, Doedrecht/Boston/London.

Jørgensen, S.E., 2001. Parameter calibration and estimation by the use of exergy. Ecol. Modell. 146, 299–302.

Jørgensen, S.E., 2002. Explanation of ecological rules and observation by application of ecosystem theory and ecological models. Ecol. Modell. 158, 241–248.

Jørgensen, S.E., Bendoricchio, G., 2001. Fundamentals of Ecological Modelling. Elsevier, Amsterdam.

Jørgensen, S.E., Patten, B.C., Straškraba, M., 1999. Ecosystem emerging: 3. Openness. Ecol. Modell. 117, 41–64.

Jørgensen, S.E., Patten, B.C., Straškraba, M., 2000. Ecosystem emerging: 4. Growth. Ecol. Modell. 126, 249–284.

Jørgensen, S.E., Ray, S., Berec, L., Straškraba, M., 2002a. Improved calibration of a eutrophic model by use of the size variation due to succession. Ecol. Modell. 153, 269–277.

Jørgensen, S.E., Marques, J., Nielsen, S.N., 2002b. Structural changes in an estuary, described by models and using exergy as orientor. Ecol. Modell. 158, 233–240.

Kozhova, O.M., Izmest'eva, L.R. (Eds.), 1998. Lake Baikal—Evolution and Biodiversity, second completely revised and enlarged ed. Backhuys Publishers.

Levich, A.P., 2000. Variational modelling theorems and algocoenoses functioning principles. Ecol. Modell. 131, 207–227.

Ludovisi, A., Poletti, A., 2003. Use of thermodynamic indices as ecological indicators of the development state of lake ecosystems: 2. Exergy and specific exergy indices. Ecol. Modell. 159, 223–238.

Marques, J., Nielsen, S.N., Pardal, M.A., Jørgensen, S.E., 2003. Impact of eutrophication and river management within a framework of ecosystem theories. Ecol. Modell. 166, 147–168.

Odum, H.T., 1983. System Ecology. Wiley Interscience, New York.

Oh, I.H., Silow, E.A., 2002. Comparative study of exergy characteristics of 3 Korean reservoirs and their connections with environmental factors. Ecology in a Changing World. Seoul, p. 204.

Park, Y.S., Kwak, I.S., Chon, T.S., Kim, J.K., Jørgensen, S.E., 2001. Implementation of artificial neural networks in patterning and prediction of exergy in response to temporal dynamics of benthic macroinvertebrate communities in streams. Ecol. Modell. 146, 143–157.

Patten, B.C., Jørgensen, S.E. (Eds.), 1995. Complex Ecology: the Part-Whole Relation in Ecosystem. Prentice Hall PTR, Englewood Cliffs.

Patten, B.C., Straškraba, M., Jørgensen, S.E., 1997. Ecosystems emerging: 1. Conservation. Ecol. Modell. 96, 221–284.

Ray, S., Berec, L., Straškraba, M., Jørgensen, S.E., 2001. Optimisation of exergy and implications of body sizes of phytoplankton and zooplankton in an aquatic ecosystem model. Ecol. Modell. 140, 219–234.

Salomonsen, J., 1992. Examination of properties of exergy, power and ascendancy along an eutrophication gradient. Ecol. Modell. 62, 171–181.

Schaeffer, D.J., Herricks, E.E., Kerster, H.W., 1988. Ecosystem health. I. Measuring ecosystem health. Environ. Manage. 12, 445–455.

Silow, E.A., 1997. The possibility of use of structural exergy for ecosystem state assessment. ANSWER. Nanjing.

Silow, E.A., 1998. The changes of ecosystem goal functions in stressed aquatic communities. J. Lake Sci. 10 (Suppl), 435–450.

Silow, E.A., 1999. The use of two lumped models for the analysis of consequences of external influences on the lake Baikal ecosystem. Ecol. Modell. 121, 103–113.

Silow, E.A., Rudykh, A.R., Stom, D.J., 1989. An ecotoxicological experiment under the ice in lake Baikal. Hydrobiol. J. 25 (4), 98–100.

Silow, E.A., Stom, D.J., Basharova, N.I., et al., 1991. Influence of biogenous elements on the lake Baikal plankton community. Acta Hydrochim. Hydrobiol. 19 (6), 629–634.

Straškraba, M., Jørgensen, S.E., Patten, B.C., 1999. Ecosystems emerging: 2. Dissipation. Ecol. Modell. 117, 3–39.

Ulanowicz, R.E., 1995. Network growth and development: ascendancy. Complex Ecology. NJ, pp. 643–655.

Xu, F.L., 1997. Exergy and structural exergy as ecological indicators for the development state of the Lake Chaohu ecosystem. Ecol. Modell. 99, 41–49.

Xu, F.L., Jørgensen, S.E., Tao, S., Li, B.G., 1999. Modeling the effects of ecological engineering on ecosystem health of a shallow eutrophic Chinese lake (Lake Chao). Ecol. Modell. 117, 239–260.

Xu, F.L., Dawson, R.W., Tao, S., Li, B.G., Cao, J., 2002. System-level responses of lake ecosystems to chemical stresses: exergy and structural exergy as ecological indicators. Chemosphere 46, 173–185.