**Korean J. Limnol. 36 (2): 117~123 (2003)**

# Application of Exergy in Aquatic Ecosystems Health Assessment : Experimental Approach and Field Observations

**Oh, In-Hye* and Eugene A. Silow**

*(Division of Biological Sciences, PaiChai University, Daejeon 302-735, Korea)*

**수계 생태계의 건강성 평가 척도로서의 엑서지 적용성에 관한 연구: 실험 및 야외 관찰.** 오인혜*, 유진 질로브 (배재대학교 생명과학부)

러시아의 바이칼 호수에서의 식물성 플랑크톤을 함유한 mesocosm 실험, 물벼룩(*Daphnia magna*)과 클로렐라(*Chlorella vulgaris*)를 함유한 microcoms 실험 결과에 따르면 펩톤, 디젤오일, o-diphenol 및 $CdCl_2$을 mesocosm에 첨가하였을 때, 또 페놀, $CoCl_2$ 및 $CuSO_4$를 microcosm에 첨가함에 따라 구조 엑서지 (structrural exergy)가 감소하였다. 오염된 지역의 수계 생태계에서는 각 구성성분의 생물량과 총 생물량의 변화 보다는 구조 엑서지의 변화가 훨씬 컸다. 또, 바이칼 호수 주변의 Baikalsk Pulp and Paper Combine으로부터 나오는 배출수의 영향을 받는 지역과 청정지역의 benthos의 엑서지를 비교해 보면, 오염된 지역에서 군집의 구조 엑서지가 급격히 감소하였다. 이러한 결과는 구조 엑서지가 생태계의 건강성을 반영하는 척도로서 이용될 수 있음을 보여주는 것이다.

**Key words : exergy, structural exergy, ecosystem health assemssment, aquatic ecosystem**

## INTRODUCTION

The evidence of the necessity to have measurable parameter reflecting the state of the ecosystem, and allowing to estimate the severity of its anthropogenous damage is clear now (Costanza and Jorgensen, 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. 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 (Jorgensen 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. It demonstrates the amount of work performed to create 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. 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 indicator, demonstrating the level of evolutionary development of organisms the ecosystem consists of. The main features of the changes of exergy in ecological systems under the external perturbations were studied in

* Corresponding Author: Tel: 042) 520-5384, Fax: 042) 520-5854, E-mail: inhyeoh@mail.pcu.ac.kr

the computational experiments with water bodies and flows mathematical models, describing processes of eutrophication and toxification (Patten and Jorgensen, 1995; Silow, 1999; Ray *et al.*, 2001; Jorgensen, 2001).

Previously we have demonstrated the reverse correlation of structural exergy in some Korean reservoirs with the degree of their watershed basin urbanization (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 ecosystem, but when the added substance is too conservative, too toxic or/and is coming 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).

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.

## METHODS

Mesocosm experiments were fulfilled at the Lake Baikal (Fig. 1) from 1986 to 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 publication (Zilow *et al.*, 1989). The water together with the natural plankton was isolated with the use of bags (2.0 $m^3$ in volume) made from polyethylene film (0.050~0.001 mm thick). 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 form 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 bacterioplankon, hydrochemical parameters etc. fulfilled regularly. When the exposition was over the sampling from water of the lake and mesocosms has been fulfilled. The sampling of zooplankton from mesocosms has been fulfilled by filtering the total volume of plastic bag through plankton net. The samples were fixed with standard methods. Temperature and transparency of the water were measured during the exposition. The samples were proceeded as usual. 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 days experiments fulfilled both during open water season (July~September) and under the ice. We have analysed the results of more than 400 series of field experiments we have carried with mesocosms. Additions of non-toxic organic compounds (peptone), phenol compounds (o-diphenol), oil products (diesel fuel), heavy metal ions ($Cd^{2+}$) were tested.

Microcosms we used contained two trophic levels producers and consumers (green alga *Chlorella vulgaris* and cladoceran *Daphnia magna*, respectively). Each microcosm was an 1 L cylinder, containing 10 mature daphnia specimens and algae in concentration about 0.5 g/L. Microcosms were exposed at constant temperature (20 °C) at 8 hours of darkness, 16 hours of light regime. The exposition was 7 days in each experiment. Direct count of daphnia and algae concentration was fulfilled daily. We have used three model toxicants phenol, as representative of organic non-conservative degradable toxicants (starting concentrations 1~25 mg/L), cobalt chloride ($CoCl_2$), as representative of non-organic conservative non-degradable toxicants (starting concentrations 0.05~0.5 mg $Co^{2+}$/L), copper sulphate ($CuSO_4$), as algicide (0.05~0.2 mg $Cu^{2+}$/L).

Analysing the exergy content in benthic communities in pure and polluted by "purified" was-

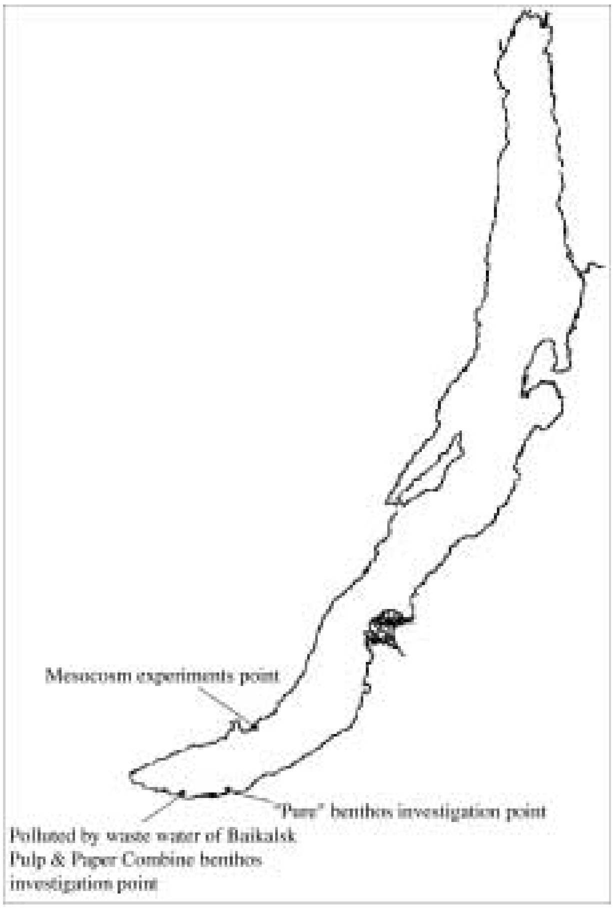


**Fig. 1.** Study sites for mesocosm experiments.

tewaters of Baikalsk Pulp and Paper Combine were used the data collected by specialists of Institute of Biology at Irkutsk State University. These data were published in available literature (Kozhova na Izmest'eva, 1998). We operated with exergy values we have calculated from those primary data [Prior to Exergy was calculated according to Jorgensen and Bendoricchio (2001), structural exergy was determined as relation of total exergy to total biomass]

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

$$Ex/RT = \sum_{i=1}^{N} c_i f_i,$$

$$Ex_{str} = (\sum_{i=1}^{N} c_i f_i)*(\sum_{i=1}^{N} c_i)^{-1}$$

where

$Ex$ : the total exergy of community,
$R$ : gas constant,
$T$ : absolute temperature, K,
$N$ : number of components,
$c_i$ : concentration of component $i$,
$f_i$ : conversion factor for component $i$

## RESULTS AND DISCUSSION

We have selected the most widely spread and important contaminants for lake Baikal. Income of the allochtonous organic matter was simulated by addition of non−toxic organic compound (peptone). Chemically it is similar to organic compounds−products of phyoplankton 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 and Paper Combine). Also they income due to logs rafting in tributaries. Significant amounts of phenol compounds are produced during the dy-

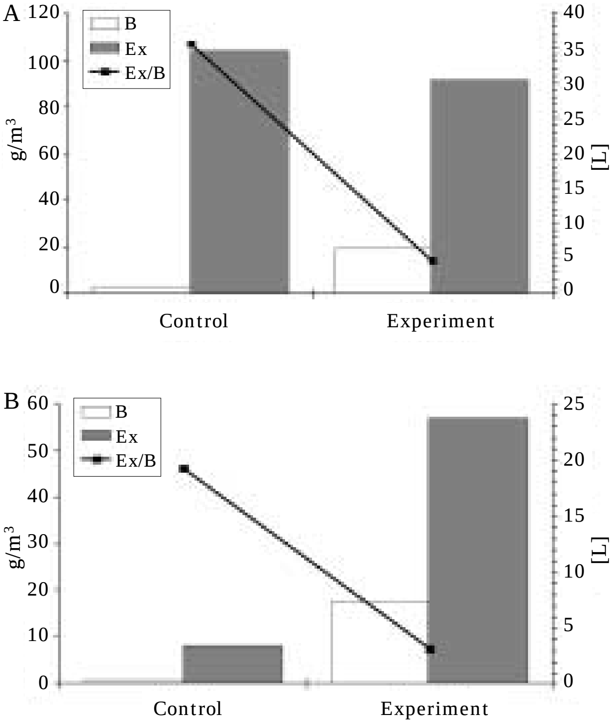


**Fig. 2.** Effects of addition of diesel oil (2.5 mg/L) in summer (A) and under ice (B) in mesocosms. B: Biomass, Ex: Exergy, Ex/B: structural Exergy.

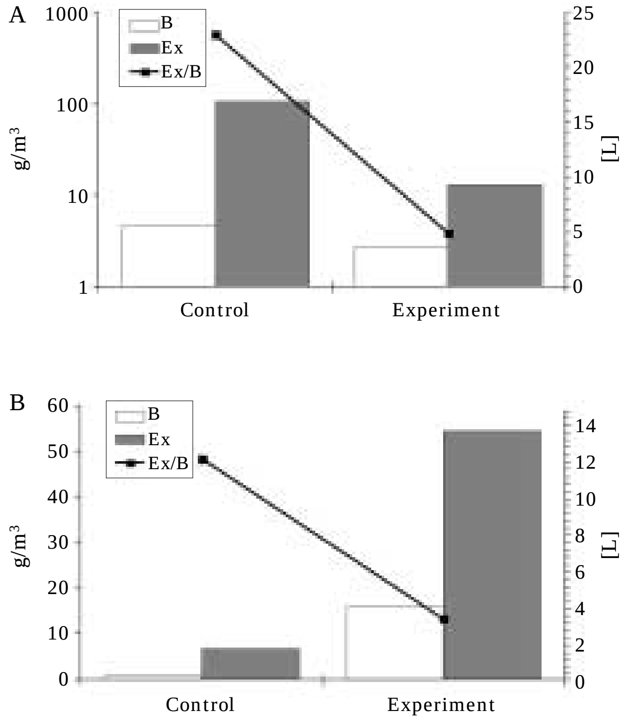


**Fig. 3.** Effects of addition of peptone (10 mg/L) in summer (A) and under ice (B) in mesocosms.

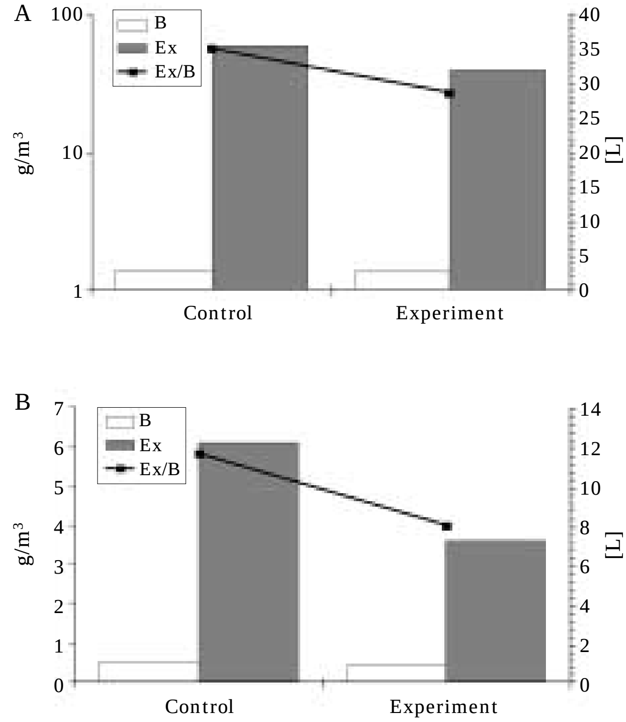


**Fig. 5.** Effects of addition $CdCl_2$ (10 g/L) in summer (A) and under ice (B) in mesocosms.

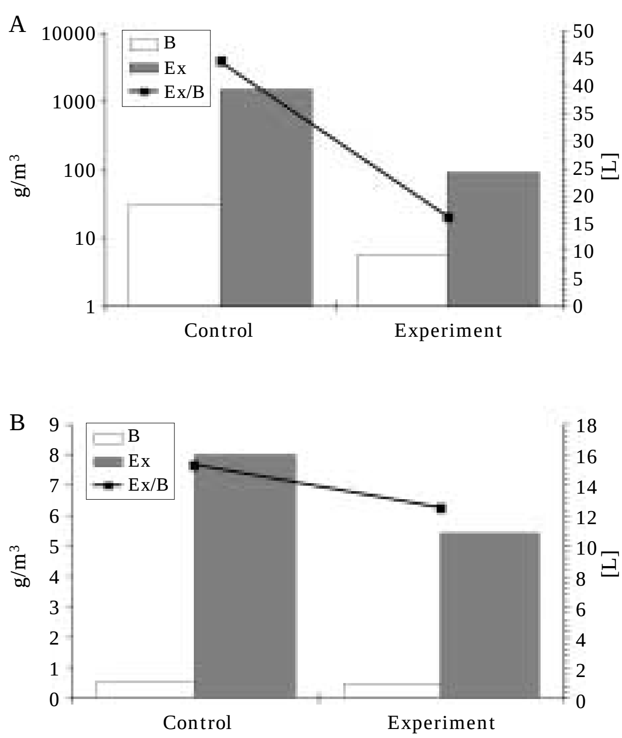


**Fig. 4.** Effects of addition of o-diphenol (0.5 mg/L) in summer (A) and under ice (B) in mesocosms.

ing off the algae after phytoplankton blooms. Oil products income the water of the lake from shoreline (in the regions of railroads in the Southern and Northern parts of the lake). Fair 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).

Additions of non-toxic organic compounds (peptone), phenol compounds, oil products, in low concentrations are shown 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 $CdCl_2$ and relatively high concentrations of o-diphenol (0.5 mg/L), diesel fuel (2.5 mg/L), even non-toxic peptone (10 mg/L) caused sufficient decrease of structural exergy and irreversible degradation of ecosystem structure (Figs. 2-5). Under ice community was remarkably more sensitive to additions than summer one. It can be related to the fact of higher percentage of endemic forms both

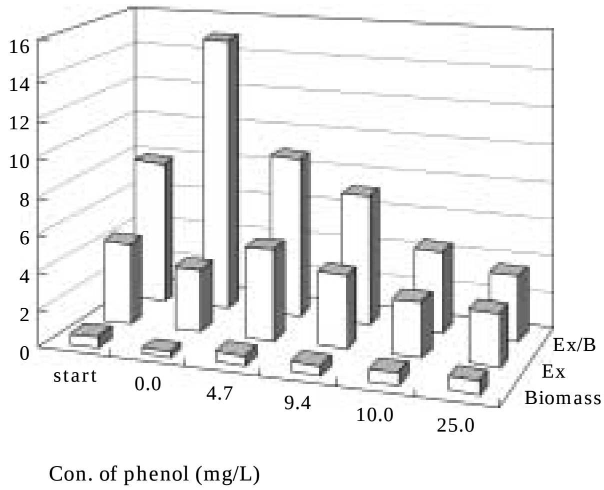


**Fig. 6.** Changes of total biomass (g/L), exergy (humus equivalent mg/L), and structural exergy after phenol addition in microcosms.

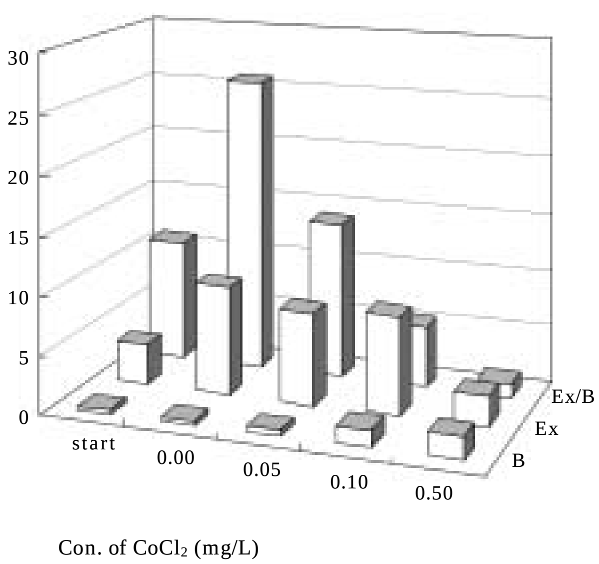


**Fig. 7.** Changes of total biomass (g/L), exergy (humus equivalent mg/L), and structural exergy after $CoCl_2$ addition in microcosms.

in phyto− and zooplankton under ice cover (Kozhova and Izmest'eva, 1998).

Results obtained with microcosms (some are presented in Figs. 6−8) 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.

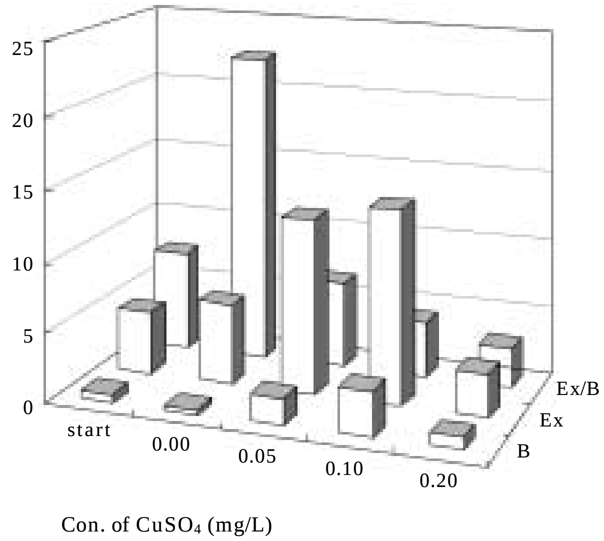


**Fig. 8.** Changes of total biomass (g/L), exergy (humus equivalent mg/L), and structural exergy after $CuSO_4$ addition in microcosms.

It is necessary to point on the fact that, according to our previous results, when added substances where very toxic or non−metabolized, *e.g.* Kepone (pesticide), cadmium ions, mercury ions, inorganic acids, or the substances were introduced in high concentrations (copper ions, bifenthrin (pesticide), chlorinated organic compounds, benzene, oil) the decrease of structural exergy was observed. Often it indicated the sufficient degradation of ecosystem, elimination of its component or even entire trophic levels. Sometimes it was observed when the toxicant was added in sub−lethal concentrations, *e.g.* low concentrations of mercury inhibited the crustacean zooplankton development rate and the growth of fishes (Silow, 1998).

Comparison of exergy content of benthic communities for pure region of Baikal and for the region of "purified" wastewaters of Baikalian Pulp and Paper Combine (calculations are fulfilled basing 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. 9−11). As it was stressed above, Jorgensen (2001) connects the value of normalized 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

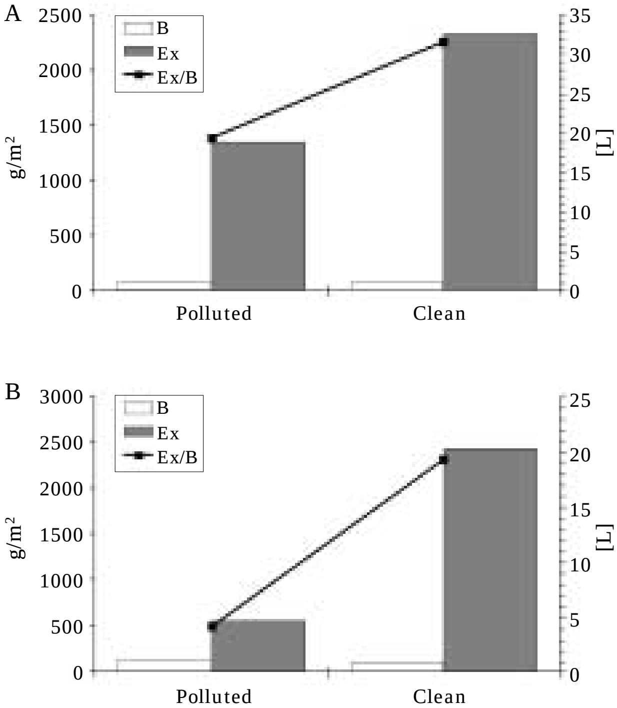


**Fig. 9.** Exergy of benthos in polluted and clean regions of Baikal. A silt, B sand, depth 0～20 m.

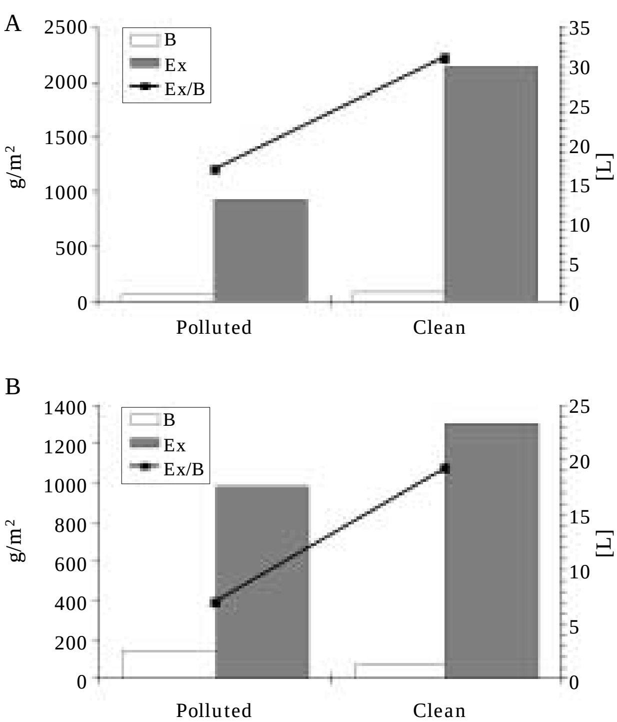


**Fig. 10.** Exergy of benthos in polluted and clean regions of Baikal. A silt, B sand, depth 20～50 m.

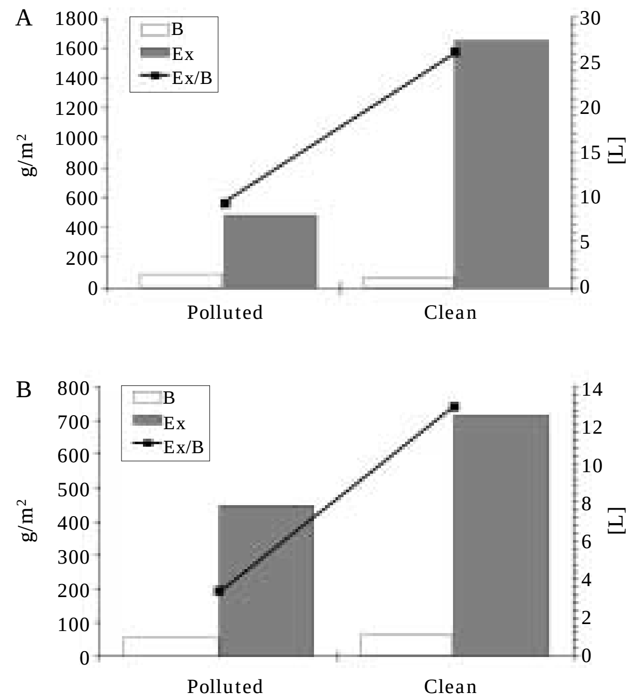


**Fig. 11.** Exergy of benthos in polluted and clean regions of Baikal. A silt, B sand, depth 50～70 m.

this case destructive). The remaining of structural exergy at the level, equal to initial or control, 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 (Oh and Silow, 2002).

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

## ABSTRACT

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-diphenol, $CdCl_2$ to mesocosms assemblage, phenol, $CoCl_2$ and $CuSO_4$ to microcosms. Structural exergy changes were more expressed than changes of components biomasses and total biomass of the community. Comparison of exergy content for benthos in clean and affected by the discharges of Baikalsk Pulp and Paper Combine also showed sufficient decrease of structural exergy in polluted area. It points to the possibility of the use of structural exergy as ecosystem health reflecting parameter.

## ACKNOWLEDGEMENT

This work was financially supported by a Research Fund in 2002 from PaChai University. The authors are thankful to Song-Il Park and Si-Jin Oh, the students taking an active participation in the recent investigation.

## REFERENCES

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

Jorgensen, S.E. and G. Bendoricchio. 2001. Fundamentals of Ecological Modelling. Amsterdam: Elsevier.

Jorgensen, S.E. 2001. Parameter Calibration and Estimation by the Use of Exergy. *Ecological Modelling* **146**: 299-302.

Kozhova, O.M. and L.R. Izmest'eva. (Eds.) 1998. Lake Baikal Evolution and Biodiversity. 2nd completely rev. & enlarged ed., Backhuys Publishers.

Oh, I.H. and E.A. Silow. 2002. Comparative Study of Exergy Characteristics of 3 Korean Reservoirs and Their Connections with Environmental Factors. In: *Ecology in a Changing World*. Seoul, p. 204.

Patten, B.C. and S.E. Jorgensen (Eds.). 1995. Complex ecology: the part-whole relation in ecosystem. Prentice Hall PTR, Englewood Cliffs.

Ray, S., L. Berec, M. Straskraba, and S.E. Jorgensen. 2001. Optimisation of exergy and implications of body sizes of phytoplankton and zooplankton in an aquatic ecosystem model. *Ecological Modelling* **140**: 219-234.

Salomonsen, J. 1992. Examination of properties of exergy, power and ascendancy along an eutrophication gradient. *Ecological Modelling* **62**: 171-181.

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

Silow, E.A. 1998 The changes of ecosystem goal functions in stressed aquatic communities. *The Journal of Lake Science*. **10**: 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. *Ecological Modelling* **121**: 103-113.

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

Zilow, Ye. A., A.R. Rudykh, and D.I. Stom. 1989. An Ecotoxicological Experiment under the ice in lake Baikal. *Hydrobiological Journal* **25**: 98-100.

(Received 23 Mar. 2003, Manuscript accepted 25 May 2003)