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Review

Exergy as a Tool for Ecosystem Health Assessment

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Abstract: Exergy is demonstrated to be a useful measurable parameter reflecting the state of the ecosystem, and allowing estimation of the severity of its anthropogenous damage. Exergy is shown to have advantages such as good theoretical basis in thermodynamics, close relation to information theory, rather high correlation with others ecosystem goal functions and relative ease of computation. Nowadays exergy is often used in ecological assessment. This paper reviews the application of exergy in ecology in the fields of ecological modeling and natural ecosystem monitoring. Special attention is paid to the use of exergy for aquatic ecosystem studies, particularly, assessment of the lake Baikal ecosystem state.

Key words: exergy; ecosystem health assessment; lake baikal; plankton

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1. Introduction

Evidence of the need to have measurable parameters of ecosystem state has been clear since the middle of the XX century. During this century, many indicators based on various ecosystem parameters (species richness, biomass to production ratio, production to respiration ratio, presence or absence of selected indicator species and many others) were proposed and tested. One of them, namely exergy, was introduced into ecology in the end of the 1970s [1], the theoretical basis for its application as a goal function was developed, and applications of exergy in ecological models were illustrated by several case studies in the beginning of the 1990s [2,3].

Exergy function was basically developed in the field of engineering and is the most useful function to solve problems related to cost-optimization procedures of energy conversion systems and energy policies. Exergy of Sven Jørgensen (Eco-exergy) differs from the classical one. The two main

differences are in the changed reference state, which is more useful for ecological applications, and in the contribution of informational exergy that is taken into account [4]. It will be discussed below.

Early exergy applications caused hot discussions in ecology, and in particular, H.T. Odum [5] defended the energy systems approach and showed limitations of early exergy approaches, though as it is clear now, emergy and exergy application systems are not contradictory, but supplementary. Now exergy theory, together with emergy theory, environ theory, ascendency theory, ecological network analysis and ecological modeling, form the basis of new integrated science–engineering ecology [6].

The application of exergy in ecological, environmental, and related studies are multiple and various. Some researchers try to capture sustainability through exergy analysis [7]. Exergy is used for the analysis of econosystems, where the money is supposed to serve as "social exergy" [8]; for development of an exergy-economic accounting to allow the limits of each analytic discipline to be overcome through its integration in a scheme such as environmental accounting [9]. Different indicators such as system exergy depletion index, cycling ratio of material exergy, *etc.* are used for analysis of eco-industrial systems. Effectiveness of exergy analysis methods and practicability of these exergy estimate indices in industrial ecology is demonstrated [10]. The relations between exergy, sustainability and environmental impact are illustrated to show how improving the performance of the process through exergy efficiency affects the environmental impact and sustainable development [11]. Assessment of the level of resource depletion, environmental impact and local sustainability of the Yellow River basin is fulfilled with the use of emergy, but the authors stress the necessity to develop an improved framework incorporating both quantity and quality contents of the energy and materials from different aspects, including exergy, cumulative exergy consumption, extended exergy, eco-exergy, embodied exergy, ecological cumulative exergy consumption *etc.* [12].

Exergy is used to describe the consequences of Global Change [13].The conceptual model, based on Holling's model [2], has been suggested as a guide for thinking about the impact of climate change on biodiversity. The two-dimensions in this model present connectivity = exergy stored = carbon stored (abscissa) and the amount of capital stored = exergy consumed = nutrients (ordinate). This revision brings Holling's model into agreement with observations and provides insight into the linkages between biodiversity and climate change [14].

There are other exergy applications in environmental and ecological studies. For example, according to [15], most life cycle impact assessment methods have considered freshwater resources to be non-depletable, and therefore are lacking characterization models for freshwater exhaustion, while operational characterization factors for freshwater consumption are given in exergy-based methods, which account for the chemical and potential exergy content of freshwater [16,17]. Exergy is used to describe and imitate the growth of forest [18].

The aim of this study is to provide a brief review of the application of exergy as a tool for ecosystem health assessment in aquatic ecology, especially in the fields of ecological modeling (both mathematical and physical), and natural ecosystem monitoring with special emphasis to lake Baikal.

2. Other Goal Functions

As highlighted above, thereare many goal functions that have been proposed for dynamic system analysis (Table 1).

Most of these disparate extrema are mutually consistent, suggesting a common pattern for system development. This pattern unfolds in the network organization of systems. [19]. The most well known and widely used parameters are emergy and ascendancy.

Emergy analysis provides a means of evaluating all inputs and outputs of a system in common units (solar energy) [20]. Emergy, formally defined as the energy of one form required through all processes and transformations to make a product or flow, provides a numeric framework for comparison of species contributions to ecosystem organization. Emergy is often referred to as energy memory, reflecting that this system synthesis approach is effectively a form of accounting that traces energy flow and dissipation back through all necessary transformations [21]. For example, sunlight, fuel, electricity, and human service can be put on a common basis by expressing them all in the emjoules of solar energy that is required to produce each. [22].

The ascendancy concept aims at quantitatively describing the growth and development of an ecosystem as whole. Growth is an increase in the total system throughflow, while development is taken to be a rise in the average mutual information inherent in the network flow structure. As an ecosystem matures and goes through a series of successing stages, its ascendancy exhibits a propensity to increase [23]. e.g., system ascendency analyses were applied to eutrophication of aquatic ecosystem study and demonstrated that ascendency was clearly higher in the non-eutrophic area [24].

Table 1. Proposed Goal Functions for dynamic systems (after [25] with additions from [19])

Goal Functions	References
Multiple systems	
Maximum useful power or energy flow	[26,27]
Minimum specific dissipation	[28,29]
Minimum entropy	[30]
Maximum retention time	[31]
Ecological systems	
Maximum ascendency	[32]
Maximum cycling	[33]
Maximum biomass	[34]
Maximum persistent organic matter	[35,36]
Maximum emergy	[37]
Maximum exergy stored	[1]
Maximum exergy dissipation	[38]
Maximum indirect effects	[40]
Minimum empower to exergy ratio	[41]
Minimum specific dissipation (or minimum specific entropy production)	[62, 100]
Maximum Structural Information	[44]
Economic systems	
Maximum profit	Various authors

3. Definition

The term "exergy" denotes the measure of the quality of energy; as energy is used in any process, it loses quality and decreases in exergy [42]. It is hard to not agree with scientists who find this definition of exergy ambiguous. Basically, the exergy is a measure of the thermodynamic distance of a system from the equilibrium with the surrounding environment, and therefore, it is both a quantitative and qualitative measure of the energy (mostly free energy in the context of ecological systems) incorporated into a system.

The exergy of a system is a measure of its deviation from thermodynamic equilibrium with the environment, and represents the maximum capacity of energy to perform useful work as the system proceeds to equilibrium, with irreversibility increasing its entropy at the expense of exergy [43]. Taken by itself, the total exergy of an ecosystem is a measure of the change in entropy content from the equilibrium and the actual state [44].

Considering systems far from thermodynamic equilibrium, it was proved that the exergy is a functional of a dissipative function, which is undertaken along the trajectory from a thermodynamic equilibrium to a dynamic one. A close connection between the measure of additional information (Kullback's measure) and exergy was shown [45].

If the vegetation is regarded as an active surface, which is interacting with solar radiation, absorption, reflection and emission of radiation are consequences of this interaction, resulting in a new composition of the spectrum of outgoing radiation. This is equivalent to the exchange of energy and information. The difference between incoming and outgoing radiation is not only defined by the properties of these radiation fluxes, but also the properties (state) of the active surface (vegetation). Measuring the change of energy by the radiation balance and the increment of information by the Kullback measure Svirezhev and Steinborn defined exergy as a function of these variables [46].

The development and maintenance of the far-from-equilibrium condition of ecosystems is due to the steady storage of free energy into complex organic structures, biosynthesized from simple inorganic compounds. Accordingly, the total exergy of an ecosystem actually reflects the accumulation of biomass into the system, irrespective of the distribution of biogenic matter among ecosystem components [44]. Exergy is a measure of the free energy of a system with contributions from all components including the energy of organisms [47]. The measure for exergy in ecology also includes a factor to weigh the "complexity" of the ecological species [48]. Moving from macroscopic to microscopic information storage, the exergetic contribution due to information grows and becomes even three orders of magnitude higher than the physical one in the more complex living systems. The capacity of packaging information at the molecular level (DNA) that differs from one organism to another can be taken into account using eco-exergy function [4].

In the present paper, we accept the following definition of exergy (according to [3,49–52]): Exergy is the distance between the 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 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 the ecosystem to accept and utilize external fluxes of energy. It reflects the degree of ecosystem development or complexity, and has advantages in comparison with

the total exergy such as independence from the total biomass of the ecosystem and possibility to serve as an indicator, demonstrating the level of evolutionary development of organisms in the ecosystem.

4. Natural History of Exergy

The biosystems, including ecosystems, are able to maintain local order (low entropy) within their system boundaries. This organization is observed in the thermodynamic parameters that describe ecosystem, such that these parameters can be used to track ecosystem growth and development during succession. Thermodynamically, ecosystem growth is the increase of energy throughflow and stored biomass, and ecosystem development is the internal reorganization of these energy mass stores, which affect transfers, transformations, and time lags within the system [53]. All these processes are reflected in the growth of exergy. H. T. Odum [5] proposes that in a self-organizing adaptive system, exergy, requiring larger investment per unit available energy, must provide commensurate higher quality cybernetic work in the form of feedback control.

The ecosystems follow five tendencies during succession: minimize specific entropy production, maximize dissipation, maximize exergy storage (includes biomass and information), maximize energy throughflow, and maximize retention time. Fath and collaborators investigated ecosystem succession as a series of four growth and development stages: boundary, structural, network, and informational. They demonstrated how each of these ecological thermodynamic orientors behave during the different growth and development stages, and show that while all apply during some stages, only maximizing energy throughflow and maximizing exergy storage are applicable during all four stages. Therefore, they concluded that the movement away from thermodynamic equilibrium, and the subsequent increase in organization during ecosystem growth and development, is a result of system components and configurations that maximize the flux of useful energy and the amount of stored exergy. Empirical data and theoretical models support these conclusions [53].

The growth of environmental exergy during geological time was demonstrated with the use of the thermodynamic model, representing the Earth as chemical reactor. The same model shows its decrease since the start of industrial activity two century ago [13].

5. Exergy Calculations

Exergy in ecological research is calculated according to S. E. Jørgensen and G. Bendoricchio [54], structural exergy is determined as relation of total exergy to total biomass:

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

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

where

Ex – the total exergy of community,

$\boldsymbol{Ex_{Str}}$ – the structural exergy of community,

N – number of components,

ci – concentration of component i,

fi – conversion factor for component i.

The most important stage of exergy calculations is the assessment of conversion factor fi, often designated as вi. This factor is determined by the degree of given species organism complexity, depending on its evolutionary development and calculated based on the number of informative genes and number of cell kinds of a given organism. These factors are estimated for many groups of organisms (Table 2). Since until now only few general values of в have been published, many authors extend their list. For example, original в-values for 244 seaweed and seagrass species that are common in Mediterranean coastal lagoons were estimated [55]. However, the calculation shown in this section actually pertains to "Eco-exergy" or "exergy index", which were later proposed by Jørgensen and Bendoriccio. These latter quantities have two main drawbacks:

- They break away from the "classical" exergy function, losing, in particular, the property of being pure thermodynamic measures of work and energy (they do not reflect the real capacity of work)
- The calculation of the weighting factors is highly speculative and it is not universally accepted, particularly by biologists.

Table 2. Exergy/Biomass Conversion factors for different groups of organisms, based on [4,25,55–64]

Group	Exergy conversion factor	Group	Exergy conversion factor
Minimal cell	5.8	Brachiopoda	109
Bacteria	8.5–12	Seedless vascular plants	158
Archaea	13.8	Rotifera	163
Yeasts	18	Insecta	167–446
Alga	15–298	Chironomida	300
Cyanobacteria	15	Moss	174
Dynophyta	18	Crustaceans	230–300
Green microalgae	20	Cladocera	232
Diatoms	66	Copepoda	240
Macrophyta (alga)	67–298	Amphipoda	290
Rhodophyta	92	Mollusca	297–450
Protozoa	31-97	Bivalves	297
Amoeba	38	Gastropoda	312–450
Gastrotricha	97	Gymnosperm	314
Fungi	61	Macrophytes (Phanerogam)	356–520
Nemertina	76	Flowering plants	393–543
Worms	91–133	Fish	499–800
Cnidaria	91	Amphibia	688
Plathelminthes	120	Reptilia	833
Oligochaeta	130	Aves	980
Nematoda	133	Mammalia	2127
Sponges	98	Homo sapiens	2173

6. Applications of Exergy to Specific Problems of Theoretical Ecology

Exergy approach was demonstrated to be very fruitful during the analysis of the application of thermodynamic principles and laws to the main fundamental concepts of ecology at the end of the XX century. The analysis of three thermodynamic laws expressions in ecological rules together with exergy analysis led to formulation of the Fourth (Ecological) Law of Thermodynamics, describing - as an ecosystem, in addition to the growth of biomass, also can develop by increasing the ecological network and the information content of the ecosystem, it is possible for ecosystems to move further away from thermodynamic equilibrium – increase the content of eco-exergy, even the maximum respiration rate has been achieved [3,49,51,65–69]. This exergy maximization principle applicability to ecosystems was proven by series of model researches [70–72]. The rules were in all cases in accordance with the principle that an ecosystem strives toward highest possible exergy at the prevailing conditions [73].

Many interesting results were received in the field of mathematical theoretical modeling. The idea of using exergy as a goal function in ecological modeling was shown to be applicable to explain ecosystem reactions [74], and to facilitate the estimation of parameters of models [50]. The introduction of eco-exergy has enabled models to deal with ecosystems that can show major structural changes resulting from adaptation and shifts in species composition [65].

Non-equilibrium thermodynamics models based on the concept of exergy provided a common basis for representing many aspects of ecosystem development and response to environmental impacts as a single measure [75]. The use of exergy made possible the investigation of the flows of an ecosystem in terms of exergy and to arrange the system as a hierarchically ordered sequence of systems, thermodynamically embedded in each other [76]. Experiments with mathematical models supported the hypothesis that the ecosystem can coordinate the most complex behavior in the case of high level of exergy of the systems at the edge of oscillation before entering into the chaotic situation [77]. The thermodynamic notion of exergy was shown to give better insight both to the patterns of nonlinear ecosystem behavior and to comparison of the patterns in ecological modeling [45].

The objective of one interesting study was to focus on the spatial patterns of an ecosystem and to show their impacts on two common extremal principle estimations, namely the maximum exergy and entropy productions. For this purpose, two similar Daisy worlds differing only by their spatial description were developed. The dynamics of daisies and of the planet parameters differed when random (non-spatial) or local (spatial) interactions were assumed. Results indicated that neglecting these spatial patterns in the ecosystem organization led to drastic differences in the maximum exergy/entropy values [78].

The following six rules regarding network effects on exergy and power were discovered with the use of models [41]:

1. Increased input gives proportional increase of exergy and power;
2. Additional links only affect power and exergy when they increase the overall network throughflow, thus the connection placement is important;
3. Food chain prolongation has a positive effect on the power and exergy of the network;
4. Reduction of loss of exergy to the environment or as detritus yields a higher power and exergy of the network;

5. Faster cycling—detritus is decomposed faster or the transfer rates between two tropic levels are increased—implies higher power and exergy;
6. Input of additional exergy or energy recycling flows has more effect the earlier in the food chain the addition takes place.

Exergy was used to model the selective changes observed in a population of Darwin's Finches [79], exergy density and exergy flow rate were shown to be excellent descriptors for the evolution [80].

7. Applications of Exergy to Specific Problems of Aquatic Ecology

It is strange that there are very few works devoted to analysis of plankton communities with the aid of exergy.

The implications of body sizes of phytoplankton and zooplankton for total system dynamics by optimizing exergy as a goal function for system performance indicator with mathematical models have been analyzed [81]. A structurally dynamic model based on phosphorus nutrient limitation has been developed for Lake Mogan located nearby Ankara, Turkey. Exergy was applied as a goal function to consider the dynamic adaptation and the seasonality of plankton species (e.g., size shifts) [82,83].

Interesting work was fulfilled for the North Sea ecosystem model. The ecosystem integrity was approved to be reflected in exergy capture, storage capacity, cycling, matter losses, and heterogeneity (the diatom/non-diatom ratio of planktonic algae was used). Its feasibility was assessed as an ecosystem model of the North Sea, for the Elbe plume, after prior satisfactory calibration. The modeling effort suggested that drastic nutrient load reduction from the Elbe alone would have a limited effect on the larger German Bight: even a 60% reduction scenario would only lead to moderate changes in all five indicators [84].

Multiple and more representative are applications of exergy to benthos communities. Thus, exergy was used in optimization models of phytobenthos [85]. The use of the exergy concept allowed the finding of the best adapted macroalgae and seagrass species in a given environmental condition and to explain in a satisfactory way the observed distributions of both macroalgae and seagrass in the Lagoon of Venice, Italy [48].

Exergy storage was estimated for benthic communities of sandy and muddy bottoms of the North Adriatic Sea subjected to experimental disturbance, induced by means of a controlled trawl fishing haul. The control area was proposed as a dynamic reference for estimating local exergy storage of the benthic community. The results showed a decrease of local exergy content in the disturbed area, with the minimum, both in sandy and muddy bottom, one month after the experimental disturbance. Subsequently, the exergy of the benthic community increased to the reference level, *i.e.,* the surrounding control area, in accordance with the proposed hypothesis on the dynamics of exergy storage during a systems' development [63].

The changes of exergy and specific exergy were studied with data of benthic macrofauna communities, periodically sampled along an estuarine gradient of eutrophication in the Mondego estuary (Western Portugal). Estimates for the exergy indices provided useful indications for the evaluation of environmental impact due to the eutrophication process [60].

Export of exergy was estimated for benthic communities of Aiguillon Cove and Brouage Mudflat, on the South-Western Atlantic Coast of France. This export was mainly composed of first, the

migration of grazing fish during the warm season, and second, of cultivated bivalves during the cold season [86].

In the following study, the authors implemented a self-organizing map for patterning exergy of benthic macroinvertebrate communities of 650 sampling sites in the Netherlands, including 855 species. Using these datasets, exergy of five trophic functional groups (carnivores, detritivores, detritivore–herbivores, herbivores, and omnivores) were calculated for each sampling site on the basis of the biomass data. Exergy of different trophic groups responded differently to different water types displaying characteristics of target ecosystems [47].

Succession plots (west end of Chongming Island, Yangtze River, China) were disturbed by ecological engineering, which also led to the damage of the benthic communities. Eco-Exergy and Specific Eco-Exergy were used to characterize the state of the community during the recovery process [87].

The analysis of available data about the macro-benthic community (Venice lagoon, Italy) from 1935 to 2004, allowed description of changes of the community structure over almost 70 years, showing a sharp decrease in its diversity. The results obtained highlight the presence of an idiosyncratic relationship between diversity and system efficiency, estimated with the use of exergy [88].

8. Exergy as Indicator of Ecosystem Health

The idea to use exergy as an indicator of ecosystem health was proposed by S.E. Jørgensen [3,49,51,95], but the first applications of exergy as an ecosystem health indicator were fulfilled with mathematical models. The first pioneer papers describing the application of exergy indicators for natural aquatic ecosystems were published in 1997. There were investigations of Lake Chaohu (China) ecosystem development state [56] and the Mondego estuary (Portugal) benthic community eutrophication study [57].

1998 was the year the first application of exergy analysis to the results of field and laboratory experiments with real aquatic ecosystem was published. The changes of biomass, exergy and structural exergy under the action of various chemical pollution (nutrients, pesticides, chlorinated phenols, oil, heavy metal ions, acidification) were analyzed for 50 experimental works with model aquatic ecosystems - microcosms, mesocosms and experimental ponds. The difference in total and structural exergy was demonstrated. Structural exergy was shown to remain at a constant level or to increase when the allochtonous compounds could be metabolized by the ecosystem, or when the ecosystem could adapt itself to the input of toxicant by structural changes. When the substance was too conservative, too toxic or/and was in too high concentrations, structural exergy was decreasing, demonstrating the inability of ecosystem to adapt to this influence and irreversibility of changes in ecosystem [89].

This work was continued by F.L. Xu and coauthors [90]. They presented the structural, functional and system-level symptoms of four chemical stresses, acidification, copper, oil and pesticide contamination in freshwater model ecosystems. Exergy, structural exergy and zooplankton buffer capacity were used as Ecological indicators for the measurement of ecosystem-level responses to the four chemical stresses. The results show that the changes in ecosystem level is highly related to the changes in structure and function of the studied ecosystems and these changes indicate the effects of

chemical stress on freshwater ecosystem health. The results led to a set of comprehensive Ecological indicators for assessing the impacts of chemical stress on freshwater ecosystem health, including structural, functional and system-level indicators. These indicators were successfully applied to assess the health of a lake ecosystem [91].

In any case, the numerous works to estimate the applicability of exergy as an ecosystem health indicator were performed with both mathematical models as well as with data sets for natural aquatic systems. Only one other work was performed to prove the applicability of structural exergy, unlike total exergy, as an ecosystem health indicator, in experiments with mesocosms and microcosms under the influence of chemical stressors [92].

Therefore, the possibility to use such parameters as structural exergy and exergy for estimation of ecosystem state and its changes under various external influences was demonstrated for real natural and experimental ecosystems. These parameters were shown to reflect the state of ecosystem and can indicate the degree of ecosystem adaptation, decreasing when important for ecosystem functioning components were eliminated. The resulting paper by S.E. Jørgensen proposed to use eco-exergy, specific eco-exergy = eco-exergy/biomass and ecological buffer capacities as Ecological indicators for ecosystem development and health [93].

Exergy is now often used for eutrophication assessment. Exergy and structural exergy as ecosystem health indicators were applied for the estimation of Lake Taihu (China) eutrophication [94], and for eutrophication processes in other aquatic ecosystems [91,95]. Different average values for the indices of exergy and specific exergy were estimated relatively to areas with different levels of eutrophication, in the 'spatial' gradient of eutrophication in the Mondego estuary (Western Portugal). Higher exergy levels and lower exergy content per unit of biomass (specific exergy) were associated to populations more stabilized or areas less perturbed. Additionally, the index of specific exergy seemed capable of providing indications for the qualitative alterations in the communities (in temporal and spatial terms) that go in the direction of the observations made in this ecosystem [60]. The recent biological changes in the Mondego estuarine ecosystem were found to comply with the framework of the theories considered, while both Exergy-based indices were able to capture the state of the system and distinguish between different scenarios [96].

Exergy indices for health assessment are used for ecological engineering purposes. The analysis of ecological changes during construction of offshore wind farms was performed with the use of several ecosystem integrity indicators, including exergy capture as indicator of ecosystem health (*i.e.,* the use of available nutrients and light for building of organic material) [97]. Eco-Exergy and Specific Eco-Exergy provided useful information about the structural development of the riverine benthic community (the west end of Chongming Island, Yangtze River, China) during recovery after ecological engineering work [87].

Many applications of exergy health indices are connected with benthic studies. A thermodynamic and network analysis on the micro and meio-benthic community in a wide coastal area of the southern Adriatic Sea was applied in order to assess ecosystem [64]. Exergy revealed to be a useful indicator that integrates the processes underlying the recovery of the benthic community after disturbance [63]. The application of Specific exergy of macrophytes as an integrated index was aimed to assess ecosystem health in coastal lagoons [18]. The assessment results of the Tolo Harbour ecosystem health showed the decrease of ecosystem health state from good to bad both in space and time. Some

recommendations to improve further the marine coastal ecosystem health in the Tolo Harbour were developed [98].

The effectiveness of exergy and specific exergy indices as Ecological indicators of the trophic state of lake ecosystems was tested on a set of lakes [99]. The ecosystem maturity was estimated for Lake Trasimeno (Umbria, Italy). The results support the hypothesis that the minimization of specific dissipation is a primary criterion of evolution of ecological systems and also sustain the use of specific dissipation as an indicator of ecological maturity [100].

9. Exergy and Other Indices and Goal Functions Relations

The relations of exergy indices with other ecological indicators are presented in Table 3. Correlation of many of them is obvious and is based on their fundamental properties.

Table 3. Correlation of various exergy based indicators with other indicators of ecosystem state.

Parameter	Exergy, Eco-Exergy, Exergy Index	Structural exergy, Specific Eco-Exergy, Specific Exergy Index	Reference
Total Biomass	Positive		[89,58,92,105,56]
Phytoplankton biomass	Negative	Negative	[99,58,92,105,56]
Zooplankton biomass	Positive	Positive	[58,92,105,90]
Secchi Disk Transparency	Positive	Positive	[99,91]
Bacterial biomass	Positive	Negative	[92,105]
Fish biomass		Positive	[58,91]
Benthic biomass	Positive		[60,92,105]
Biodiversity as species richness	Positive	Positive	[57,88,92,105,90]
Biodiversity as heterogeneity	Positive		[57,88,92,105]
Shannon–Wiener Index	Positive	Positive	[24,87]
Margalef Index	Positive	Positive	[24]
Pielou evenness	Positive	Positive	[24]
Ratio of zooplankton biomass to phytoplankton biomass	Positive	Positive	[92,105,90,91]
Trophic State	Positive	Negative	[89,56,90]
Carlson's Trophic State Index	Negative	Negative	[99]
Zooplankton buffer capacity	Positive		[58,90]
Ecological Evaluation Index	Positive	Positive	[18]
Fisher Information	Negative		[106]
Emergy	Positive	Positive	[56,107,108]
Ascendancy	Positive	Positive	[77,23,109,110,64]

10. Development of New Ecosystem Health Indices on The Basis of Exergy

Exergy is actively used for the development of new indices for ecological assessment. On the basis of exergy and emergy, a new index (the ratio of emergy flow to exergy) has been developed [40]. The proposed index is related to the efficiency with which a system organizes itself, or if steady, maintains its complexity. Their experimental results show that the emergy/exergy ratio was the lowest for the

ecosystem of Caprolace lagoon (Italy), a 'natural' system placed in a national park, and the highest for waste pond, fed with estuarine water mixed with more 'polluted' (*i.e.*, richer in nutrients) effluent. Control pond fed with estuarine water had the intermediate emergy/exergy ratio value .

The beginning of the XXI century is very fruitful in the sense of creation of new methods based on joining several indices to form more or less complex systems. It is necessary to mention here F.L. Xu and collaborators (China) among the most active groups in the development of complex ecological assessment methods based on exergy applications. The Ecological Modeling Method (EMM), including the use of eco-exergy indices, was applied to the ecosystem health assessment of a eutrophic Chinese lake (Lake Chao) as a case study. The results compared quite favorably with the actual current conditions at Lake Chao. The EMM was therefore suitable for assessing lake ecosystem health [95]. An ecosystem health index methodology (EHIM) was developed for assessing lake ecosystem health. Phytoplankton biomass was selected to serve as a basic indicator, while exergy and structural exergy were used as additional indicators, among others. The results suggest that the EHIM is a valuable and relatively uncomplicated methodology - with simple principles, ease of calculation, reliable and intuitive results. As a practical planning tool, it can be widely used for the quantitative assessment and comparison of ecosystem health states for a single lake, a series of different lakes, or more complicated lake systems [101]. Procedures for assessing a marine coastal ecosystem health were presented. The assessment consisted of the following five steps: (1) review of human activities; (2) identification of human-induced stresses; (3) analysis of ecosystem responses to the stresses; (4) development of ecosystem health indicators (including exergy); and (5) assessment of ecosystem health [98].

Another active and successful group in this field is the research team led by A. Ludovisi (Italy). They propose that the specific entropy production or the specific dissipation of a community index as the ratio between the entropy produced and the exergy stored by the biological component of an ecosystem, as a tool for understanding the evolution and state assessment of ecological systems. Specific dissipation could serve as an indicator of ecosystems maturity as well as an ecological orientor whose minimization is expected throughout ecosystem development, as it could be considered as an indicator of the ability of a self-organizing dissipative system to maintain itself far from equilibrium by pumping out entropy. It has been applied to the characterization of the development state of the communities of a set of shallow lakes which lie from oligotrophic to hyper-eutrophic conditions. The adequacy of the proposed indicator has been tested and discussed along two different ecological series: the seasonal progression of phytoplankton and the trophic gradient. The results confirm that the ratio is an appropriate indicator of ecosystem maturity and support the hypothesis that its minimization is one of the primary ‘‘goals’’ of ecosystem development [62,99,100].

Ecosystem integrity at the North Sea was also investigated with the use of exergy parameters, and application of these functional integrity indicators appeared feasible for coastal seas at larger spatial scales, and for the coast would form a useful addition to the indicators presently proposed in the Water Framework Directive (WFD) [84]. Exergy was used in a novel integrated approach to environmental impact assessment, appropriately named SUstainability Multicriteria Multiscale Assessment (SUMMA), aimed to overcome the inherent shortcomings of all single-criterion approaches [102]. Another new concept, agricultural productivity on ecosystem scale (APES), was defined. APES of the agroecosystem is the aggregated contributions of all components to mankind and its habitat in uniformed dimensions, it may be expressed in material, energy, information, organization, pollution

and damage, *etc.*, positive or negative, and calculated based on exergy methods. A related index agroecological coupling degree (ACD) shows sustainability [103]. Exergy capture and exergy dissipation were included into successful theory based indicator set to indicate ecosystem integrity on the basis of holistic information on the environment state [104].

11. Use of Exergy for Lake Baikal Ecosystem State Assessment

The exergy applications to the Lake Baikal ecosystem has passed the same way the eco-exergy studies around the world.

The first works were fulfilled with the use of mathematic models. The eco-exergy content of Lake Baikal plankton ecosystem was demonstrated to increase with the addition of nutrients and to decrease with addition of toxic substances, with the use of ecosystem deviation model [89]. More detailed study demonstrated less resistance of higher trophic levels (seal, fishes, carnivorous zooplankton) to intoxication than lower ones (phytoplankton and herbivorous zooplankton), consequently higher sensitivity of structural exergy, than exergy itself, to toxication. Different sensitivity of under-ice and open water plankton communities to additions of exergy was also demonstrated: the decrease of under-ice community eco-exergy and increase of open water eco-exergy after the same disturbances. This can be related to: 1) differences in abiotic environmental conditions (temperature, light regime *etc.*); 2) the different species composition of phytoplankton, as the dominant species of the spring community are shown to be less resistant to pollutants than those of the summer; 3) different structural exergy content in planktonic community (mainly due to different biomasses of zooplankton). Exergy buffer capacity seems to be a more realistic measure for pliability of ecosystem reaction to external factors than biomass buffer capacity [58].

As throughout the world, the field studies of the benthic community of Lake Baikal exergy changes followed the mathematical modeling. The structural exergy of benthic communities at control (pristine) site, and in the region of Baikalsk Pulp and Paper Combine wastewaters discharge region at the same depths and kind of sediments was shown to differ strongly (structural exergy in polluted area was much lower than in pristine one), while biomass and total exergy behaved in not such an expressive way [92,105]. The next step was the analysis of exergy and structural exergy of plankton community response to different chemical stressors analyzed in mesocosms experiments. Results obtained with microcosms 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 [92,105].

Here we present the results of exergy calculations for natural plankton community of the lake Baikal.

Calculations were fulfilled on the basis of “PLANKTON” database of the Institute of Biology, containing a valuable amount of data.

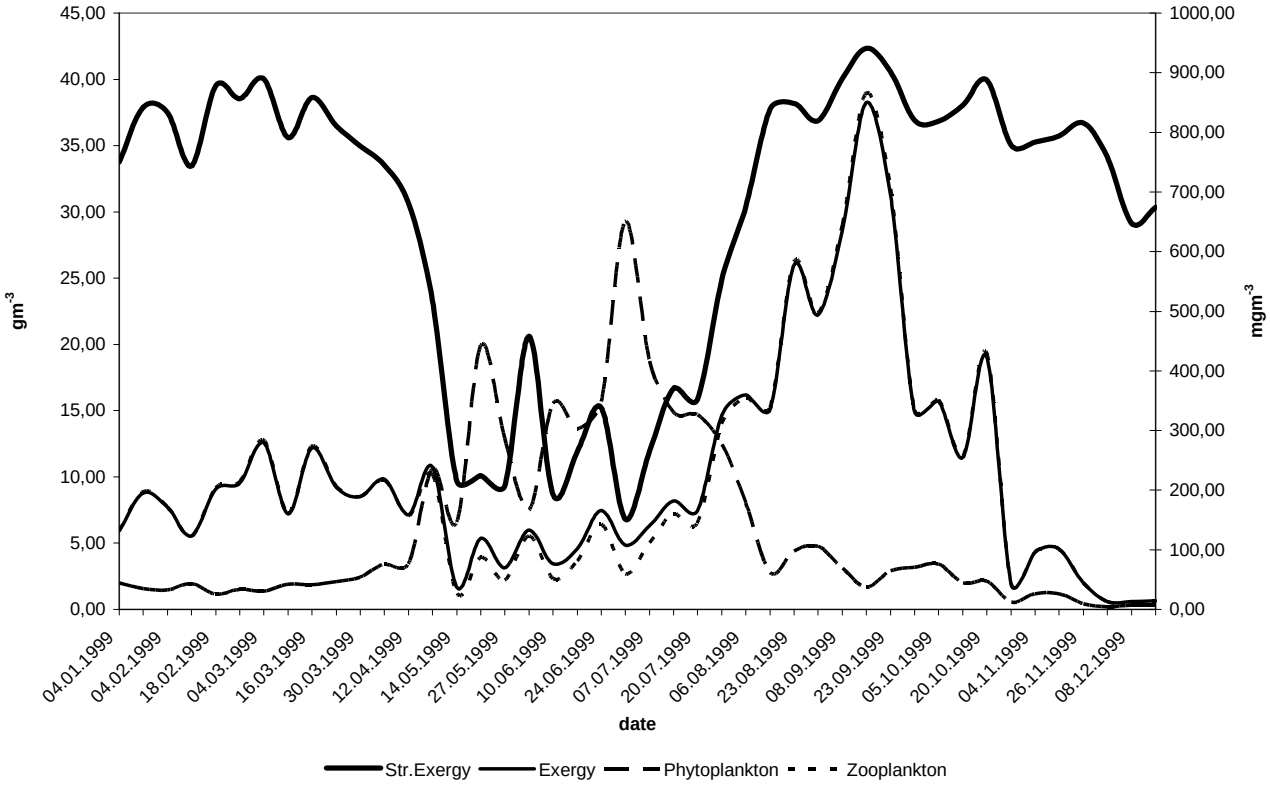
The data have been collected since 1945, at least monthly, generally every 7–10 days, in depth profiles from the surface to 250 m at a single main station (Point #1) in the Southern basin approximately 2.2 km offshore from Bol’shie Koty (51° 54′,195 N и 105° 04′,235 E) where water depth is approximately 900 m. Thin ice prohibits collection in some months, usually January. Water temperature is measured using a mercury thermometer in samples retrieved on deck with a Van Dorn bottle. Secchi depth, the depth at which a standard white disk disappears from view in the water

column, is routinely measured as an index of water quality. Phytoplankton samples are enumerated at the species level. Discrete depths of 0, 5, 10, 25, and 50 m are targeted for measurement of abiotic variables and sampling of phytoplankton with a 10 L Van Dorn bottle. Zooplankton samples are enumerated at the species level and also identified by age class. Single zooplankton samples are collected with a closing plankton net (37.5 cm diameter, 100 мm mesh) from depth layers of 0–10, 10–25, and 25–50 m. Zooplankton samples have been fixed and stored in formalin throughout the long-term monitoring program.

Calculations of exergy and structural exergy were fulfilled with the use of three Baikal plankton components–diatom phytoplankton, cyanobacteriae and the rest of phytoplankton and zooplankton (which in Baikal is represented practically by monoculture of Epischura baicalensis). All biomasses were computed on the basis of direct count of samples. Coefficients f were accepted 66 for diatom phytoplankton, 15 for cyanobacteria, 20 for the rest of phytoplankton, 240–for zooplankton.

When representing seasonal dynamics of exergy, the decrease of structural exergy during spring phytoplankton bloom is clearly seen (Figure 1).

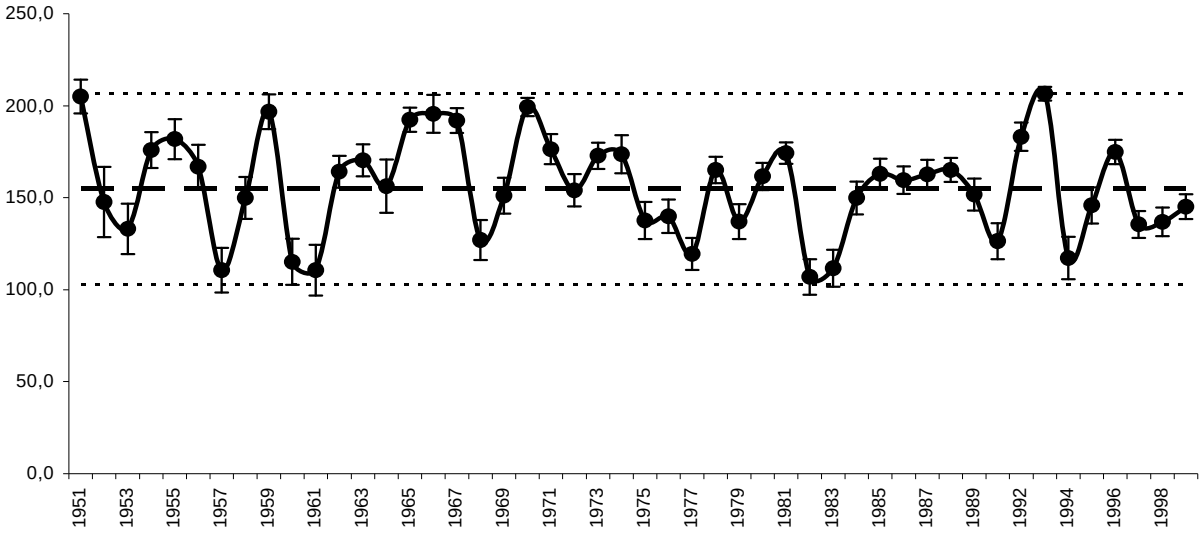
Figure 1. Dynamics of exergy (g·m^{-3}) and structural exergy (left scale) and phytoplankton and zooplankton biomasses (mg·m^{-3}; right scale) for the typical year 1999 in Lake Baikal.



Yearly average values of structural exergy during 1951–1999 varied from 107.0 ± 9.7 (1982) to 206.6 ± 3.7 (1993) with a long-term average of 154.9 ± 1.5 and median 165.1 (Figure 2).

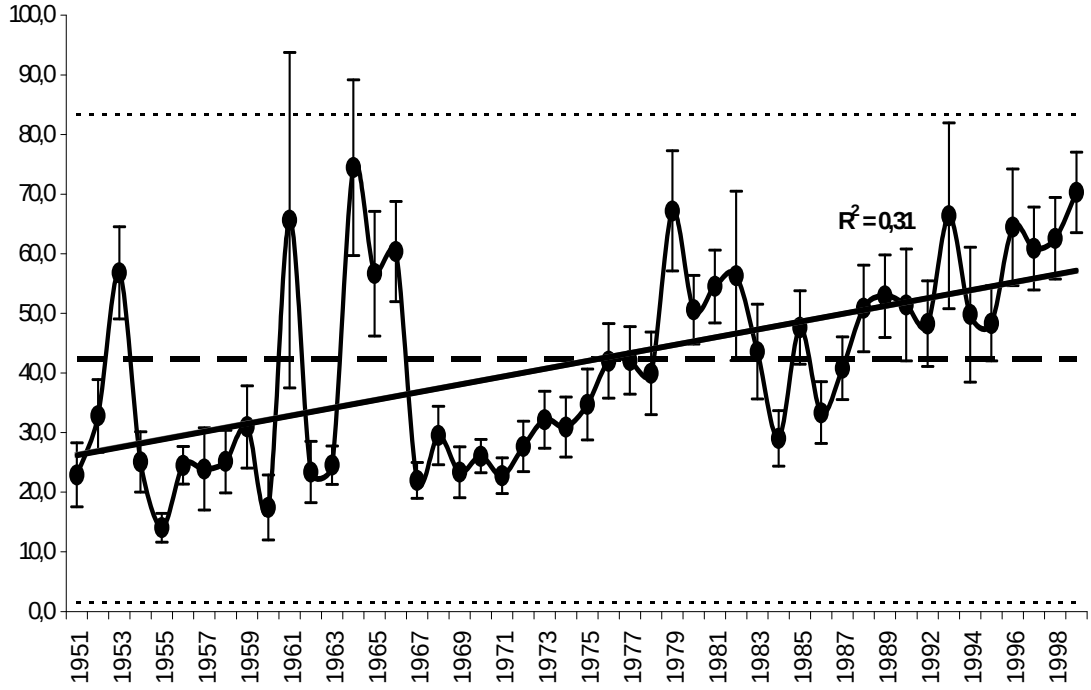
Yearly average values of structural exergy during 1951–1999 also fluctuated around their long-term average within the limits “long-term average ± mean square deviation” without any trends.

Figure 2. Long-term variability of structural exergy of lake Baikal plankton in 1951–1999 in 0-50 m layer



More interesting is the picture for exergy for the same period. It also fluctuated within "long-term average ± mean square deviations" but simultaneously exergy demonstrates well expressed linear trend with r2 = 0.31 (Figure 3).

Figure 3. Long-term variability of exergy ($g \cdot m^{-3}$) of lake Baikal plankton in 1951–1999 in 0–50 m layer



It is necessary to note here that ecosystems can develop in the direction of exergy maximization *via* realization of three strategies [65, p.24]:

(1) Development of a physical – biological structure that is able to capture solar exergy. The bigger the physical structure, the more solar exergy captured.

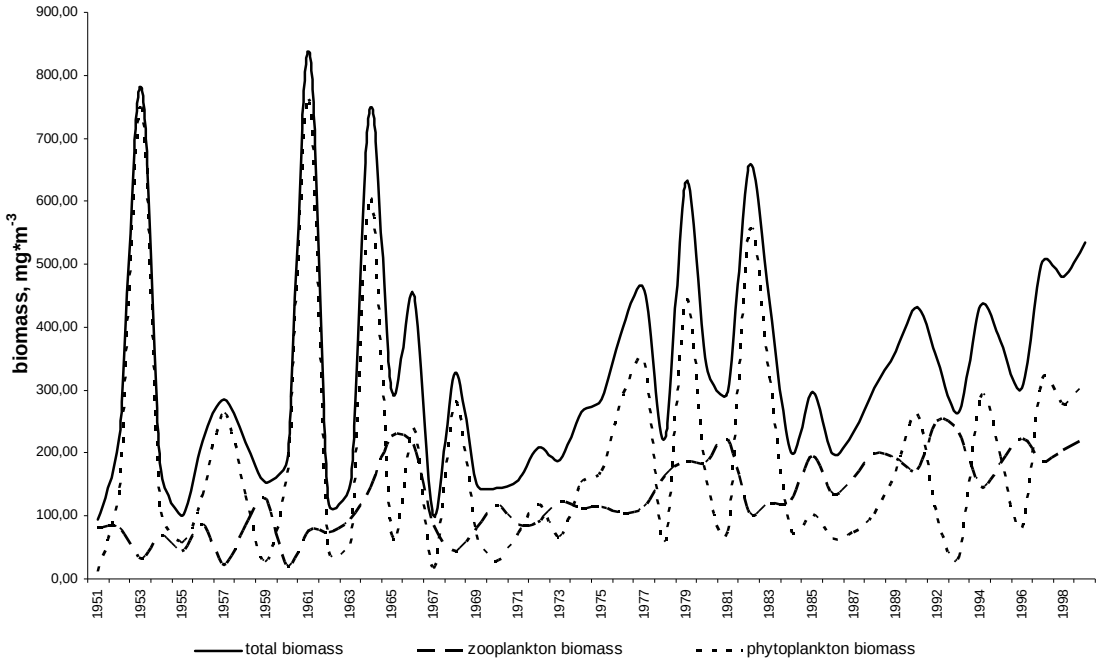
(2) The components of an ecosystem are linked in an ecological network that cycles the mass, energy and information. As the number of components in an ecosystem generally is increasing over time, and as more and more links are established among the components, the ecological network is increasing in complexity, and thereby the flows of mass, energy and information. The mass and energy cycling in the network will increase too, and it becomes possible for the ecosystem to move further away from thermodynamic equilibrium by a better utilization of the solar exergy. It implies that the ecosystem gains more eco-exergy.

(3) The growth of information is a third possibility for ecosystems to develop. K-strategists replace r-strategists, which means that less energy is wasted on the offspring. Bigger organisms are replacing smaller ones and the specific maintenance energy (respiration) decreases with increasing body mass. More information means also that more and more feedbacks can regulate the various biological processes, and better regulation means higher eco-exergy efficiency. The result is that the ecosystem moves further away from thermodynamic equilibrium.

Exergy was shown mathematically to develop on total biomass and ecosystem complexity by Y.M. Svirezhev [45,111] on the basis of Jørgensens' principle of exergy maximization. Exergy increases if either one of these components increases, or both increase.

Dynamics of pelagic plankton biomass in Baikal for 1951–1999 is given in Figure 4. There is no demonstrated directional change of total biomass, or biomasses of different components (only slight positive trend of zooplankton biomass). Long-term oscillations of individual components are easily observed.

Figure 4. Long-term variability of biomass (mg·m-3) of lake Baikal plankton in 1951–1999 in 0-50 m layer.



Taking into account all discussed above and remembering the constancy of the total biomass of pelagic plankton, we can try to explain the tendency of its exergy to increase according to S.E. Jørgensen principles through the growth of solar exergy assimilation activity and the complexity of

plankton community. According to the first principle it is the primary production increase, based on the mass development of small sized alga in summer period [112]. According to the second principle it might be some recently observed structural changes in the plankton community [113,114], and the third principle is realized through the share of growth of larger zooplankton, like Cladocerans [115].

The calculated values of Exergy Index and structural exergy in the lake Baikal plankton for the second half of XX century, on the basis of long-term monitoring data, fluctuate within their natural limits (long-term average ± mean square deviation) and do not demonstrate any positive or negative trends. This points to the lack of expressed unfavorable changes in the lake Baikal pelagic.

Total biomass of plankton community and its individual components remains constant, while the total exergy of the community tends to increase. This increase can be explained with the principle of S.E. Jørgensen–the principle of exergy maximization *via* the growth of solar exergy consuming capacity, sophistication of ecosystem networking and increase of ecosystem information storage.

12. Conclusion

Multiple goal functions have been applied to describe the state of ecosystem during the XX century. One of them, exergy, is understood in ecology, since Exergy is the distance between the present state of the system and its state when in thermodynamic equilibrium with the environment, measured in the units of energy. 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 the ecosystem to accept and utilize external fluxes of energy. It reflects the degree of ecosystem development or complexity, and has advantages over the total exergy such as independence from the total biomass of the ecosystem and possibility to serve as an indicator This demonstrates the level of evolutionary development of organisms in the ecosystem. It is now becoming clear that the movement away from thermodynamic equilibrium, and the subsequent increase in organization during ecosystem growth and development, is a result of system components and configurations that maximize the flux of useful energy and the amount of stored exergy. Both empirical data, as well as theoretical models, support these conclusions.

Exergy is widely used in ecology to analyze theoretical problems and to solve applied tasks. The most perspective use of exergy parameters in recent ecology is the use of them as ecosystem health indicators. Exergy, and, especially structural exergy, is shown to be a good health indicator for ecosystems in many model, experimental, field and complex case studies. A number of other ecosystem health indices are developed on the basis of exergy.

Exergy was applied for the analysis of the lake Baikal ecosystem state and its possible changes under the influence of cultural stressors. Exergy was used in mathematical modeling of the lake ecosystem, analysis of benthic community state, behavior of plankton community in mesocosms experiments. Presented here, the application of exergy calculations to long-term dynamics of the lake Baikal plankton demonstrates the steady state of plankton community structural exergy and well observed increase of its total exergy.

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