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Exergy as an indicator: Observations of an aquatic ecosystem model

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ABSTRACT

Exergy is considered as a goal function or ecological orientor. Normally at the edge of oscillation exergy reaches to its maximum value when the ecosystem had no adaptation on it. To study the variation of exergy in different states of ecosystem, a simple three species (phytoplankton, zooplankton and fish) food chain model has been considered. From the model it is shown that the system moves from steady state to chaotic state by decreasing zooplankton body volume in turn increasing its grazing rate. By the property of self-adaptability the system tries to overcome this situation. Two such possible processes are described here: (i) by the toxic effect of phytoplankton and (ii) by reducing half saturation constant of fishes. In both this cases exergy value reduces and the system reaches to stable state. Through the analysis of exergy variation in all these situations this paper shows that the system chose the process in which the reduction of exergy will be the minimum.

1. Introduction

1.1. Ecosystem and its stability

An ecosystem is a biological environment in which both living and non living factors interact nonlinearly and influence each other by direct as well as by indirect processes (Tansley, 1935). The spatial distribution and temporal evolution of species and habitats are highly dependent on these nonlinear interactions. This makes ecosystem network very much complex and attractive to the scientists from several areas like biology, physics, chemistry or even mathematics to study its behavior.

One stable ecosystem may be disturbed in several ways and depending on the strength of the disturbance the system can stay to its original state or keep developing towards a maturating state or shifts to another stable state (May, 1973; Scheffer et al., 2001). Even non recurring bounded situation may also arise for different reasons in ecosystem. This situation is called chaotic situation. Systems at the edge of chaos are adaptable to the most complex behavior (Kauffman, 1993). The characteristic of chaos and its presence in nature are much discussed in ecology (Godfray and Grenfell, 1993; Hastings et al., 1993; Jørgensen, 1995; Perry et al., 1993).

Mathematical models predict that species interactions such as competition and predation can generate chaos. However, experimental and field survey demonstrations of chaos in ecology are scarce, and have been limited to simple laboratory systems with short duration and artificial species combinations (Huisman et al., 2006). Benincà et al. (2008) have revealed 'naturally' chaotic population dynamics by performing their experimental study of marine community comprising of bacteria, several phytoplankton species, herbivorous and predatory zooplankton species isolated from the Baltic Sea.

As the ecosystem is the self organizing system, the chaotic system always tries to come back to its stable state. The properties of an ecosystem to adapt for its changed conditions are rooted in the interplay between self-organization and selection. One such self organization happens by the toxin production phytoplankton (TPP) (Ives, 1987; Turner and Tester, 1997; Wolfe et al., 1997). Study on the toxin production by phytoplankton particularly in marine environment and the effects of toxin in the food chain is nowadays is an important topic in plankton research (Chattopadhyay et al., 2002; Franks and Anderson, 1992; Lanora and Miralto, 2010; Sarkar and Chattopadhyay, 2003; Jester et al., 2009; Smayda and Reynolds, 2001; Sournia, 1995).

1.2. Necessity of general rule

As the dynamical process in ecology is dominated by causality and contingency (Gould, 1989), an ecosystem can evolve in several pathways. Therefore, it is difficult to identify a general rule for studying ecosystem dynamics and hence there is a growing demand for holistic indicators that integrate ecosystem processes (M¨uller and Leupelt, 1998). These indicators could be useful in the detection of the ecosystem growth and development or for the quantification of the ecosystem state and maturity at a given moment (Christensen, 1995;

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Jørgensen, 1992a, 1992b; Odum, 1969; Ulanowicz, 1986). Also these could be useful as a tool for policy making or ecosystem risk assessment.

1.3. Different indicators

For assessing the ecosystem development, several indicators such as emergy, exergy, ascendency, structural exergy, indirect effect etc. are proposed by different researchers (Jørgensen, 1995; Odum, 1988; Patten, 1995; Ulanowicz, 1997). Emergy and exergy are based upon thermodynamic principle. Emergy considers how much solar radiation it costs to build a considered organism (Odum, 1983) whereas exergy considers the workable free energy (level of information) of the biomass, embodied in the structure (Jørgensen, 1992a, 1992b). Emergy and exergy both increase with increasing concentrations of nutrients. Structural exergy is defined as the exergy relative to the biomass or nutrient level (Jørgensen, 1992a, 1992b). Ulanowicz (1986) introduced the concept of Ascendency, to account the throughflow of energy in an ecosystem. Most of these goal functions are mutually consistent, suggesting a common pattern for system development. But, among all these principles, exergy has successfully been applied in many cases (Coffaro et al., 1997; Jørgensen and de Bernardi, 1998; Jørgensen and Padisak, 1996).

1.4. Exergy as an indicator

Exergy is now a major tool for indicating the performance and organization of ecological system. It reflects the degree of ecosystem development or complexity. The most perspective use of exergy parameters in recent ecology is as ecosystem health indicators. The application of exergy in ecological, environmental, and related studies are multiple and various. Some researchers try to capture sustainability through exergy analysis (Hellström and Kärrman, 1997; Kanoglu, et al., 2008). Exergy is used for the analysis of economics, where the money is supposed to serve as "social exergy" (Spiegelman et al., 2007). Many researchers are using this concept in industrial ecology (Koroneos et al., 2003; Rosen and Dincer, 1997; Yang et al., 2006). To describe the effects of environmental impact and sustainable development the relations between exergy, sustainability and environmental impact are illustrated (Kanoglu et al., 2008). Exergy is used to describe the consequences of global change (Ayres, 1997; Hermann, 2006). This is used to describe and imitate the growth of forest (Alexandrov, 2008). This has also been used as ecological indicators of coastal areas (Jørgensen, 2000).

1.5. Difficulties

Level of exergy and development of an ecosystem are correlated. Ecosystem development can be described mainly in three ways: (i) structural development, (ii) network development and (iii) gain of information. It is better to express the exergy principle as follows: the ecosystem attempts to get the highest possible exergy under the prevailing conditions. By considering the development of ecosystem which implies moving towards most stable/ordered state, this paper will address one theoretical example (movement from chaos to order), where decreasing exergy implies system's development towards ordered state. Keeping it in consideration, the aims of the present work are to solve few questions arise with this. Is it violation of exergy principle? If "Yes" then how can we explain this? If "No" then how does exergy principle still valid?

1.6. Attempt to answer

To search answers of above questions, a simple ecosystem model of phytoplankton, zooplankton and fish has been considered here. Although the model is purely theoretical, the ideas in this model are taken from the several experimental works of marine environment and therefore, the present model represents the planktonic food chain of marine ecosystem. The variations of exergy level in three different situations of the system have been studied. First we have considered the situation when the system develops towards stable state. In the second stage the system shifts from stable state to chaotic state due to increase of grazing pressure of zooplankton (or decrease of half saturation constant of zooplankton) and finally we have considered the situation when the system recover from chaotic state to stable state by some self organizing processes of the system.

In first two stages, it is shown in this paper that, the system obeys classical exergy principle which says that the exergy value is the maximum at ordered state and gradually reduced at chaotic state. The earlier mentioned question comes in the third stage when the system recovers from chaotic state to ordered state. From experimental works by many authors we have identified two possible self organizing processes through which the system can achieve the ordered state: (i) by liberation of toxin by phytoplankton and thereby reducing the effective grazing pressure on it and (ii) by reducing the half saturation constant of the fishes (Chattopadhyay and Sarkar, 2003; Ives, 1987; Jester et al., 2009; Lanora and Miralto, 2010; Mandal et al., 2006; Turner and Tester, 1997; Wolfe et al., 1997). According to Peters (1983) the half saturation constant and grazing/feeding rate of organisms are directly and indirectly proportional to body size respectively, thereby by reducing half saturation constant in the model the smaller fish can be selected and in turn predation rate of fish also be increased by which zooplankton grazing rate be decreased. During recovering from chaotic to order state either by the above mentioned processes, the exergy value reduces. The main objective of the present study is to identify theoretically the better option out of these two above mentioned processes where the system will prefer minimum reduction of exergy and obey the exergy principle. The description of the model of phytoplankton, zooplankton and fishes and its parameters are given in Section 2. Section 3 describes the methodology of incorporation of body size of zooplankton in the model. Section 4 briefly describes the concept of exergy. The detail analysis of the system behavior through exergy is described in Section 5. The last section deals with the conclusion of this work.

2. Mathematical model

Several mathematical models have been developed to detect chaotic system dynamics using time-density data (Chattopadhyay and Sarkar, 2003; Hastings et al., 1993). Here a mathematical model has been developed by considering the interaction between different aquatic species of phytoplankton, zooplankton and fishes. Suppose p_i represents the ith species of phytoplankton community, z_j represents the jth species of zooplankton community and f_k represents the kth species of fishes and the number of species in phytoplankton, zooplankton and fishes are N_1, N_2 and N_3 respectively. Therefore the total number of species of the system is $N = N_1 + N_2 + N_3$. Consideration of all these species interactions separately it makes the model very much complicated and needs N number of equations to describe the whole system. As this paper does not aim to study the behavior of each species component separately, we can simplify our model equations by considering each community as a single variable P, Z and F corresponding to whole community of phytoplankton, zooplankton and fishes. In this case the basic mathematical model transformed to modified Hastings - Powell model (Hastings and Powell, 1991) and can be represented as a set of three ordinary differential equations describing the change of phytoplankton (P), zooplankton (Z) and fish (F) over time.

$$\frac{dP}{dT} = R_0 P\left(1 - \frac{P}{K_0}\right) - \frac{C_1 A_1 PZ}{B_1 + P}$$