Ecological Modelling 341 (2016) 27–36

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Analysis of spatial and temporal organization of biosphere using solar reflectance data from MODIS satellite

Y.G. Puzachenko, R.B. Sandlersky*, A.G. Sankovski

A.N. Severtsov's Institute of Ecology and Evolution RAS, Moscow, Russia

ARTICLE INFO

Article history:
Received 4 April 2016
Received in revised form 28 August 2016
Accepted 24 September 2016
Available online 3 October 2016

Keywords:
Non-equilibrium thermodynamics
Goal functions
Absorbed solar radiation
Exergy
Entropy production
Increment of information
NDVI
Seasonal dynamics

ABSTRACT

The paper addresses the spatio-temporal dynamics of biosphere reflected by the multispectral MODIS images. The hypotheses of different goal functions are examined and principles of biosphere function are tested. It is demonstrated that one of the major bishopric "goal functions" is the maintenance of the stable solar radiation absorption in the PAR range during the vegetative season. This is also associated with stabilization of biological production, which is supported by advanced accumulation of internal energy. It is shown that the biosphere can be viewed as a non-equilibrium system with two stationary states – winter and summer separated by transition periods associated with the maximal spatial information.

1. Introduction

One of the top priorities of modem ecology is empirical and theoretical justification of "goal functions" in the ecosystem evolution at different temporal and spatial scales (Müller and Fath, 1998). These "goal functions" are described by internal system parameters, which should be maintained at a certain level in order to ensure the existence and sustainable development of self-organizing thermodynamical system (Nielsen et al., 1998). It is widely assumed that such "goal functions" define the system organization and interaction between its parts.

Description of "goal functions" in terms of empirical laws is a traditional natural science approach. For instance, the "goal function" of natural selection is the "maximization of survival for species and populations". A Russian scientist Karl Ernst von Baer (1792–1876), member of the Russian Academy of Sciences, a co-founder of the Russian Geographical Society, and the first President of the Russian Entomological Society (also a distinguished Baltic German scientist) could not agree with the natural selection model and instead postulated an immanent goal of evolution – progressive improvement of life forms. He has also formulated the "frugality" law – natural organisms retain chemical elements in the biological cycle.

V.I. Vernadsky defined "living matter" as a statistical assemblage with many elements: «I will call living matter a combination of organisms taking part in geochemical processes. Organisms will be part of this living matter. We will pay attention only to such living matter properties as weight, chemical composition and energy. When defined like this, living matter becomes a new object of science». (Vernadsky, 1976). In addition, Vernadsky introduced a key concept of "organization" «A notion of a living being cannot be equal to the notion of mechanism both in philosophical and scientific sense. I will use the word "organization" a common property of all organisms. This property can be defined as a spatio-temporal co-relation between living organisms and their environment. Organization is not a mechanical property since it is changing and emerging every moment by internal movements of smallest material and energy particles» (Vernadsky, 1934). Based on these definitions in 1925 Vernadsky formulated two principles of living matter functioning in the biosphere (defining its goal function): «1) biological migration of atoms of chemical elements in the biosphere tends to conduct work based on embedded free energy and 2) the species evolution during geological time leading to the creation of various stable life forms goes in the direction of increasing biogenic migration of atoms» (Vernadsky, 1925).

---

* Corresponding author.
E-mail address: srobert_landy@mail.ru (R.B. Sandlersky).

http://dx.doi.org/10.1016/j.ecolmodel.2016.09.022
0304-3800/

Clearly, these principles are closely related to the "maximum power principle" for evolutionary systems Lotka (Lotka, 1922). In addition, E. Bauer in 1935 formulated so-called principles of "stable non-equilibrium" and "maximum effect of external work" for biological systems (Bauer, 1935). A similar principle of "maximizing exergy" was formulated by Kay (Kay and Schneider, 1992; Kay and Fraser, 2001) and Jorgensen with co-authors (Jorgensen, 2008; Jorgensen et al., 2000; Jorgensen and Svirezhev, 2004) as part of the modern thermodynamics and even as its Fourth Law. The development of ecology and non-equilibrium thermodynamics provided an ample foundation for formulating alternative goal functions for ecological systems (Nielsen et al., 1998; Patten, 1995; Silow and Mokry, 2010; Burkharda et al., 2011). It should be noted that some of these functions contradict each other. For instance, the principle of maximum entropy production (MEP) (Kleidon and Lorenz, 2005) for systems far from equilibrium (which is used by many authors for substantiating fundamental ecosystem relations and properties) contradicts the principle of minimum entropy production (MinEP) of Prigogine and S-theorem of Klimantovich (1983). This theorem proves that if a process of self-organization could be represented as a phase change into a more orderly state with lower symmetry then the production of entropy in this less symmetrical state is lower than in the previous state. The MEP principle also contradicts Haken's informational theory (Haken, 1996) stating that in the vicinity of non-equilibrium state the information flows and effectiveness of self-organization is increasing exponentially as a function of energy intake. At the same time in the areas far from non-equilibrium e.g., close to equilibrium both of those variable attain minimum values (I-theorem). Finally, the MEP principle (MEPP) contradicts the criteria of system organization proposed by Foerster (1960) according to which $dR/dt > 0$ (where R is the level of "organization"), so that in a general case while the level of organization (R) grows and a distance to equilibrium increases, the system entropy declines.

Martyushev and Seleznev (2006) studied the theoretical foundations of MEP principle (MEPP) and concluded that it is applicable only in limited conditions with small deviation from equilibrium. However, the authors also note that the intuitive simplicity of MEPP leads to its wide use. In their next paper Martyushev with co-authors studied the minimum entropy production principle (MinEP) and (Martyushev et al., 2007) demonstrated that:

(1) "the MinEP principle may be used if two or more thermodynamic forces, some of which are invariable, are available";
(2) "the kinetic coefficients should not depend on flows and forces, but they may depend on thermodynamic parameters (e.g., the temperature)"; and
(3) "the minimum entropy production implies the stationary state of the system and vice versa: the stationary state of the system implies the minimum entropy production". Finally, in another paper Martyushev (2010) state that the maximum entropy production principle cannot be strictly proven and its correctness should be checked by comparing it with reality.

It could also be true that the differences in opinion (in particular, about the conditions when the principle of maximum and minimum entropy production should be applied) stated above are related to the approach to defining the systems subjected to the analysis (Martyushev et al., 2007). For instance, let's consider a classic example – a hydro power plant (HPP). Clearly, the system is far from equilibrium. Its exergy in the form of electric power is channeled away from the system and in order to keep this channel stable the HPP structure should be maintained at a required level and the entropy increment of an HPP itself should be kept close to zero. This result is achievable when a certain amount of energy and information is spent to keep the structure in a stationary non-equilibrium state (the law of necessary variety by Ashby (1956)). It should also be noted that a given HPP will not be economically feasible if the energy expenditure to maintain it operational will be similar to the amount of useful work. Naturally, all the exergy produced by this HPP somewhere outside it will be turned into a "bound" energy or entropy and the more HPPs will be built – the higher level of final entropy will be produced.

In relation to ecosystems with their daily and seasonal trajectory of energy transformation the MEPP incorporates both the entropy of bound energy (heat flux) and the entropy of «hidden» heat flux (evapotranspiration). In such a case, the MEPP is equivalent to the principle of maximum exergy production. Such calculation of entropy does not include biological production and internal energy, which in the end are transformed into entropy. It should be noted, however, that the hidden heat flux resulting from condensation will produce entropy far away from a given ecosystem borders and consecutively such entropy production should be treated as part of a system at a higher hierarchical level. On the other hand, in dissipative systems the energy flux supporting a given structure and corresponding entropy production should increase along the system drift towards a local stationary area. At the same time the Boltsman-Gibbs-Shannon entropy reflecting the system structure (for instance in Bernard cells) will be reducing. This apparent contradiction is removed if we consider a two-level system: at a level of heat processes, the system maximizes its entropy flux, while at a microscopic level of structural organization – it minimizes entropy production. In such a case, a portion of incoming energy is used for maintaining the system structure and then the structure itself contributes to the maximum entropy generation.

The literature review presented above suggests that the goal of a system in non-equilibrium conditions is to maximize exergy and minimize production of entropy and information in the stationary state. At the same time, the production of entropy related to energy attains maximum values.

When the dynamic properties of real systems are studied these goals can be studied as "zero hypotheses". On the other hand, we do not have to define a goal function *a priori* but instead try to find it following the hypothesis of homeostasis and regulation formulated by Ashby (1956). According to this hypothesis, the goal function of a system is defined by variables that show the minimum variability in time. The minimum variability is supported by large variability of regulator variables.

In the current paper, we examine seasonal variation in the temporal and spatial organization of the biosphere using multispectral measurements from the MODIS satellite. The satellite measurements reflect the biosphere state via reflectance of solar radiation in different channels. Images obtained from these channels show functional properties of different plant cover subsystems. We use Jorgensen-Svirezhev model (Jorgensen and Svirezhev, 2004) for evaluating thermodynamic variables for each grid cell of the Earth surface.

We treat biosphere as one system and measure combined and partial entropy of selected variables and the level of their organization separately for the cases of reflected solar radiation and thermodynamical system at different time scales. We also check hypotheses about potential goal functions and independently seek the goal function based on the Ashby (1956) approach. Such an analysis has significant exploratory power due to the "objectivity" of initial data.

2. Data and methods

The current study is based on satellite Terra MODIS images from the International Satellite Land 63 Surface Climatology Project ISLSCP for 2002 (distributor – ORNL DAAC, 2016). The database