



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



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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 biophysical “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.

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1. Introduction

One of the top priorities of modern 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).

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

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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)”;
- (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 Boltzman–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 contains Earth surface albedo measurements taken at 21 distinct moments of time (about 2 times per month) during the year with the resolution of 0.5° (ftp://daac.ornl.gov/data/islscp.ii/vegetation/modis_albedo_2002_xdeg/data/). Additional data on thermal flux

Table 1

Relation between MODIS reflectance bands and biological substances in vegetation. Values in Table are estimates of the surface spectral reflectance for each band as it would have been measured at ground level if there were no atmospheric scattering or absorption (http://modis.gsfc.nasa.gov/data/dataproduct/dataproducts.php?MOD_NUMBER=09).

Band number	Name	Central wavelength (nm)	Bandwidth (nm)	Reproduced pigments and properties
3	Blue	469	459–479	chlorophyll, carotenoids
4	Green	555	545–565	anthocyanin
1	Red	645	620–670	chlorophyll, red edgy
2	NIR (near infrared)	858.5	841–876	mesophyll, leaf mass
5	Short-wave infrared 1	1240	1230–1250	water
6	Short-wave infrared 2	1640	1628–1652	lignin, starch
7	Short-wave infrared 3	2130	2105–2155	sugar, protein

from the earth surface for each month of the same year are taken from another dataset – MODIS Terra Land Surface Temperature and Emissivity (LST/E) for 2002 (https://lpdaac.usgs.gov/lpdaac/products/modis_products_table/land_surface_temperature_emissivity/monthly_l3_global_005_cmg/mod11c3).

Table 1 shows relationship between the reflectance in different MODIS channels and concentration of different vegetation pigments and biochemical compounds. Reflectance in the bands related to Photosynthetically Active Radiation (PAR, <700 nm) is a measure of photosynthetic activity, which produces adenosine triphosphate (ATP) – universal source of energy for biochemical processes (Kiang et al., 2007a,b). The relation between reflectance in different bands and biological substances is derived from a number of publications: chlorophyll Darvishzadeha et al. (2008), anthocyanin Neill and Gould (1999), mass of leaves and water content Palmer and Williams (1974), proteins и carbohydrates Fourty et al. (1996).

Absorption in the near infrared channel (NIR) is connected with the concentration of mesophyll and leaf mass and hence biological productivity. Bands 5–7 measure water content and other photosynthetic products.

In summary, the multispectral measurements contain essential information about functioning of different subsystems of vegetation cover, which in turn is the major functional part of the biosphere. The second option of representing the biosphere system is via thermodynamic variables such as: absorbed radiation (R), exergy (Ex), heat flux (T), entropy (S), Kullback’s information (K), bound energy (ST), and internal energy (U).

The balance of absorbed radiation could be described as follows:

$$R = Ex + ST + U \tag{1}$$

The absorbed radiation is also a function of incoming radiation and reflective properties of the surface:

$$R = \sum_{i=1}^{i=7} (1 - \alpha_i) E_i^{in} \tag{2}$$

where α_i – albedo in channel i , E_i^{in} - incoming solar radiation in i -th channel.

Exergy is calculated based on Jorgensen and Svirezhev (2004) as follows:

$$Ex = (E^{in} - R) [K + 1n \frac{E^{in} - R}{E^{in}}] \tag{3}$$

where E^{in} – incoming radiation in different channels.

$$E^{in} = \sum_{i=1}^{i=7} E_i^{in} \tag{4}$$

Kullback’s information is calculated as:

$$K = \sum_{i=1}^{i=7} p_i^{out} \ln \frac{p_i^{out}}{p_i^{in}} \tag{5}$$

where p_i^{out} – share of reflected radiation in the i -th channel relative to combined reflected radiation

$$p_i^{out} = \frac{\alpha_i E_i^{in}}{\sum_{i=1}^{i=7} \alpha_i E_i^{in}} \tag{6}$$

and p_i^{in} – share of incoming radiation in the i -th channel relative to total incoming radiation.

$$p_i^{in} = \frac{E_i^{in}}{\sum_{i=1}^{i=7} E_i^{in}} \tag{7}$$

According to the theory of non-equilibrium systems (Stratonovich, 1985), the greater is the information increment – the further the system is from equilibrium and the greater is the level of exergy.

The value of entropy of solar reflected radiation is calculated using traditional Shannon formulation:

$$S = - \sum_{i=1}^{i=7} p_i^{out} \ln(p_i^{out}) \tag{8}$$

Bound energy is estimated as the product of temperature and heat flux, while internal energy is equal to the difference between absorbed radiation and the sum of exergy and bound energy. As we showed in our previous paper the assessment of entropy based on solar spectrum is thermodynamically correct (Puzachenko et al., 2011).

The level of biosphere “organization” at a specific moment of time in two alternative systems of representation can be evaluated according to Foerster (1960)

$$R = 1 - \frac{S^v}{S_{max}^v} \tag{9}$$

where S^v – entropy of a given variable v and $S_{max}^v = \log_2 k$, where k is the number of possible classes (categories) of variable v .

If $\frac{dR}{dt} > 0$ then the system is in the process of self-organization; its level of organization is increasing due to receiving information from outside. In an opposite case, the system undergoes “disorganization”.

In both cases, we describe the system in terms of several variables and need to calculate their joint entropy in space:

$$S(v_1, v_2, v_3, \dots, v_n) = - \sum_{i=1}^k \sum_{i=1}^k \sum_{i=1}^k \dots \sum_{i=1}^k p(v_1^i v_2^i v_3^i \dots v_n^i) \log_2 p(v_1^i v_2^i v_3^i \dots v_n^i) \tag{10}$$

where $p(v_1^i v_2^i v_3^i \dots v_n^i) = \frac{n(v_1^i, v_2^i, v_3^i, \dots, v_n^i)}{N}$ – is the probability of combinations of variables 1 to n taking values from 1 to k . In our case,

variables are the values of albedo in 7 MODIS channels and N is the total number of pixels.

The total number of “states” of each variable is assumed to be $k = \log_2 N - 1$, where N – is a sample size. In our case, $k = 11$ (states).

We have developed a simple computer program where each variable was evenly broken into 11 classes. Then the program calculated all permutations, $(S(v_i))$ for all variables and also computed

partial entropy – $S(v_i)$, where $S(v_i) = -\sum_{j=1}^{k=11} p(v_i^j) \log_2 p(v_i^j)$ and joint

entropies $S(v_1, v_2, v_3, \dots, v_n)$ according to Eq. (10).

Information in a multidimensional system was calculated as:

$$I(v_1, v_2, v_3, v_n) = S(v_1) + S(v_2) + S(v_3) + \dots + S(v_n) - S(v_1, v_2, v_3, \dots, v_n) \quad (11)$$

We also applied two measures of “organization”: the level of organization measured after H. von Foerster (1960):

$$R_F = 1 - \frac{S(V_1, V_2, V_3, \dots, V_n)}{n \log_2 k} \quad (12)$$

and the level of organization based on information:

$$R_i = 1 - \frac{\sum_{i=1}^{i=n} S(v_i)}{\sum_{i=1}^{i=n} S(v_i)} = \frac{I}{\sum_{i=1}^{i=n} S(v_i)} \quad (13)$$

To summarize, information (multidimensional combination of variables) is directly related to the level of system “organization” – greater informational content of a system reflects the greater level of its “organization”.

3. Analysis of seasonal changes in albedo measured in multi-spectrometer channels and thermodynamic variables in the Northern Hemisphere

Our prior research showed (Puzachenko et al., 2011) that the trajectories of seasonal changes in thermodynamic variables in the Northern and Southern Hemispheres have similar shapes but are opposite in direction. Relatively small land area in the Southern Hemisphere increases the sensitivity of analyzed parameters to weather conditions, while the absence of boreal forests and tundra zones reduces the amplitude of variables’ dynamics. Hence, the analysis presented here is based solely on the Northern Hemisphere data.

Fig. 1 shows the seasonal dynamics of average albedo in seven spectral channels. Changes in albedo in the first three channels reflect Photosynthetically Active Radiation (PAR). Seasonal variations in the blue channel are the greatest followed by green and red channels. Fig. 2 shows co-relation of albedo (A), incoming radiation (E^{in}) and absorbed radiation (R) in all seven channels from Table 1. As one can see, most of the absorption occurs in the first four channels.

As it is commonly known, the main part of energy used in the biosphere is associated with PAR. During about 80 days starting from the second half of May to August the albedo in the PAR range is nearly stable. As it can be seen from Fig. 1 changes in albedo in the PAR channels in the first and second halves of the year could be described by parabolic equations with different signs of the first and second derivatives (Table 2, Fig. 1). In the first half of the year, the increment of albedo second derivative (parameter c in Table 2) is negative and an increment of albedo in response to increasing incoming energy is reducing (Fig. 3).

Therefore, it can be concluded (from Figs. 2 and 3) the seasonal change in albedo in the PAR range is “asymmetrical” to the incoming solar radiation. In spring, the albedo increment is greater than

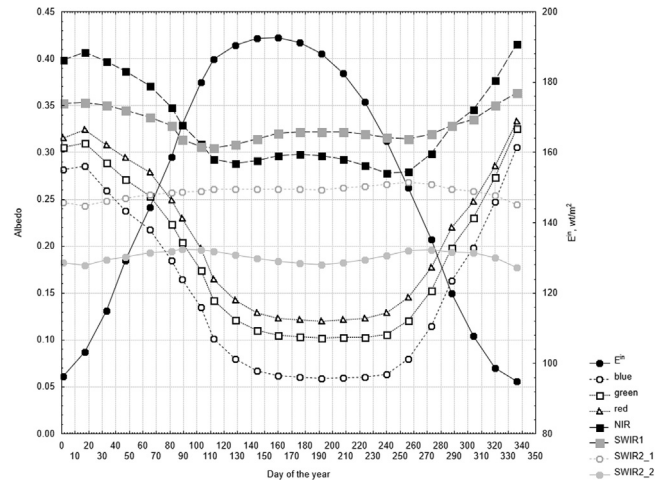


Fig. 1. Seasonal dynamics of albedo in seven MODIS TERRA spectral channels for the Northern Hemisphere.

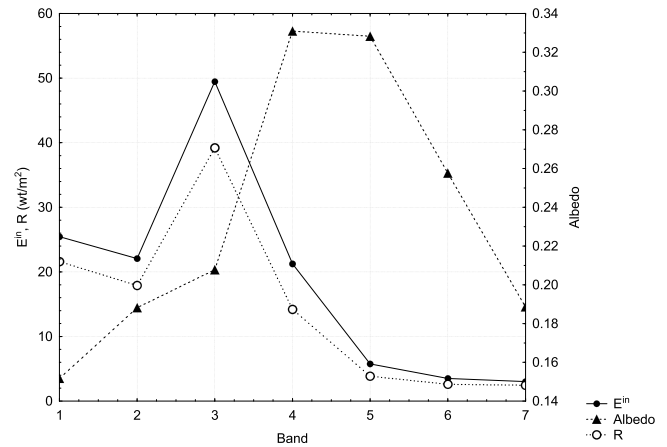


Fig. 2. Average incoming radiation (E^{in}), albedo, and absorbed radiation (R) in the seven radiation channels.

Table 2
Parameters of the polynomial equation $-B_i = a + bE_i^{in} + c(E_i^{in})^2$, where B_i = i-th channel, E_i^{in} - incoming radiation in channel i, a, b, c – equation parameters.

Channel	Halves of the year	R ² %	a	b	c
Blue	First	99.20	0.283	0.0053	-0.0003
	Second	97.55	1.072	-0.069	0.0012
Green	First	99.46	0.264	0.0101	-0.0005
	Second	97.76	1.024	-0.073	0.0014
Red	First	99.42	0.195	0.0083	-0.0001
	Second	98.08	0.953	-0.027	0.0002

increment of incoming solar radiation. In the summer, albedo is quite stable despite changes in radiation. Finally, in the fall the negative derivative of the albedo function is either lower or equal to the derivative of solar radiation function. Since, the albedo in the PAR range is inversely proportional to the concentration of corresponding photosynthetically active pigments, one could assume that the global ecosystem is “trying” to maximize the required level of radiation absorption (1-albedo), then tries to maintain it during the entire vegetative season (even through the fall) at an optimal level. Therefore, the maximization of solar radiation absorption could be viewed as a “goal” function of the entire system.

The albedo dynamics in other channels with a longer wavelength channels is different. In the winter, when a considerable part

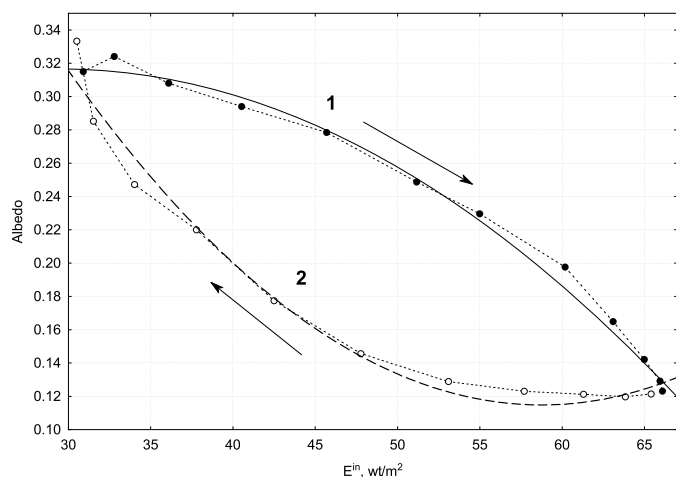


Fig. 3. Relation between albedo in red channel and incoming energy. 1- first half of the year, 2- second half of the year.

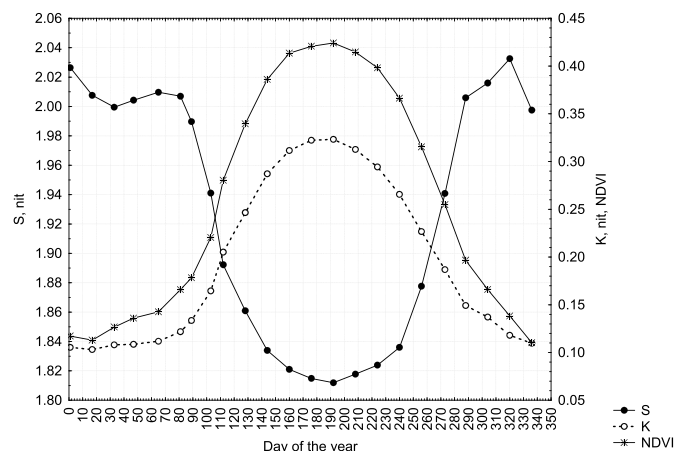


Fig. 5. Average seasonal changes in entropy (S), Kullback's information (K), and NDVI in the Northern Hemisphere.

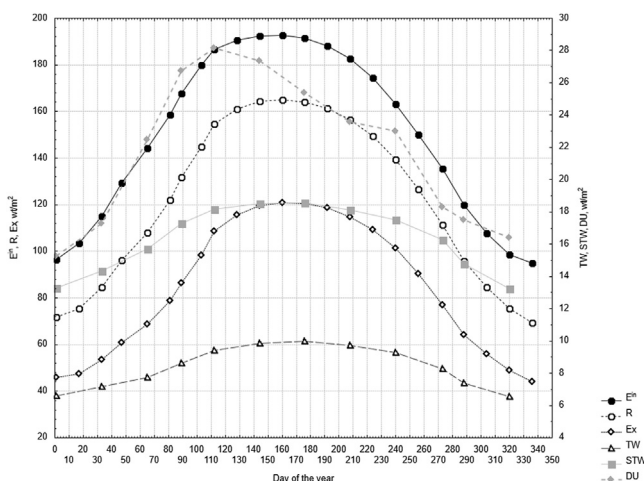


Fig. 4. Seasonal changes in thermodynamic variables in the northern hemisphere. E^{in} – incoming solar radiation, R – absorbed solar radiation, Ex – exergy, TW – heat flux, STW – bound energy, DU – internal energy.

of the Northern Hemisphere is covered in snow and lacks photosynthetically active vegetation cover the average albedo in long-wave channels is maximal. The NIR channel has the minimum albedo levels in spring and fall and a local maximum in June, reflecting high levels of mesophyll and maximum biological production.

The fifth channel (short-wave infrared 1), which indicates moisture content, has the minimal albedo levels in spring and fall, when the moisture content is maximal and has a local minimum in summer months.

The albedo of the next far infrared channel (short-wave infrared 2), which indicates the presence of lignin and starch, does not vary significantly throughout the year, with maximum levels in the fall. Finally, the albedo in short-wave infrared 3 channel has two maximums – in spring and fall. It should be noted, that the overall role of infrared channels in energy transformation by plant cover is insignificant. Those channels indicate concentrations of intermediate and final photosynthetic products.

The seasonal changes in thermodynamic variables averaged across the entire Northern Hemisphere surface are displayed in Figs. 4 and 5 and the relation of these variables with the incoming and reflected solar radiation are shown in Table 3.

The second derivative in the equation that connects the absorbed solar radiation (R) with incoming radiation (E^{in}) is posi-

tive during first half of the year and negative – during the second half (Table 3). Thus, during the first half of the year, the absorption is steadily increasing (opposite to albedo in the PAR range), while in the second half the absorption declines slower than incoming radiation.

One could say that the system “tries” to maintain the maximum absorption of the solar radiation that could be interpreted as a “goal function” directly connected with maintaining the constant albedo in the PAR range during the vegetation season. This absorbed radiation is then subdivided into exergy (including both energy used for evaporation and biological production) and bound energy, which primarily consist of heat flux.

Dynamics of exergy (Ex) is similar to the dynamics of absorbed radiation with the positive value of the second derivative of exergy during the first half of the year (and summer) and linear relationship between these variables during the second half. Such “linearity” means that these two variables are in equilibrium relations. During the entire year, the heat flux (T) depends linearly from the absorbed energy and comprises around 3–4% of its value at the given parameter levels. Such a proportion shows that the biosphere “maintains” a relatively low and constant level of heat flux to the atmosphere during the entire year, which changes proportionally to the incoming energy flow.

The internal energy is calculated as the “end term” of the thermodynamic balance. It demonstrates sharp growth at the start of the year peaking in April. Later it gradually declines being used for maintaining the stationary nature of solar radiation absorption in the PAR area, consequently keeping photosynthesis at maximum levels.

Fig. 5 shows the dynamics of entropy and Kullback's information associated with reflected solar radiation averaged over the $0.5^\circ \times 0.5^\circ$ grid in the northern hemisphere. As one could see from the figure, the entropy is maximal during the winter period – from the second half of October to the end of March. The level of Kullback's information demonstrates that the northern half of biosphere is closer to equilibrium in December-February and starts to depart further from the equilibrium starting in April. The departure from equilibrium becomes maximal in June, when entropy is at the minimum level. Such relations demonstrate that the biosphere thermodynamics is governed by the “minimum entropy” rule, S-theorem of Klimantovich (1987) and informational theorem by Haken (1988).

Table 3
Parameters of polynomial functions $y = a + bE^{in} + cE^{in2}$ describing thermodynamic parameters as a function of albedo. R – absorbed radiation; Ex – exergy, T – heat flux.

Function	Half of the year	R ² %	a	b	c
R = f(E ⁱⁿ)	First	99.91	60.833	-0.294	0.004
	Second	99.97	-40.66	1.265	-0.001
Ex = f(E ⁱⁿ)	First	99.95	28.686	0.008	0.003
	Second	99.97	-13.07	0.816	-
T = f(E ⁱⁿ)	First	99.59	4.129	0.034	-
	Second	99.67	1.728	0.074	-0.0002
T = f(E ⁱⁿ)	All year	98.51	3.941	0.036	-

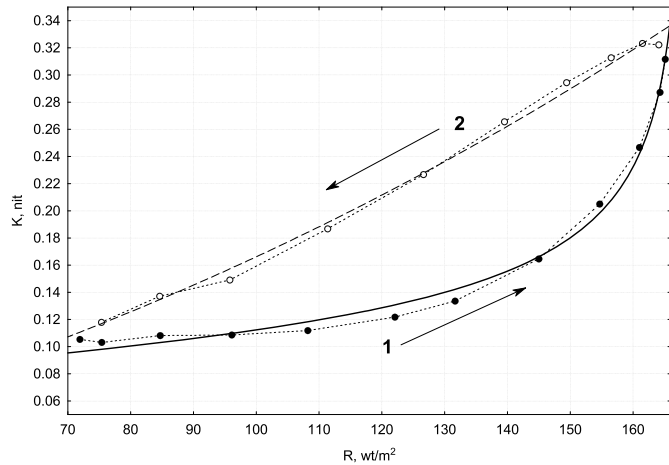


Fig. 6. Relationship between Kullback's information (K) and absorbed solar radiation (R) 1–first half of the year, 2–second half of the year.

The seasonal changes in Kullback's information (K) are asymmetrical (Fig. 6). In the first half of the year, its level depends on the absorbed solar radiation (R) according to the following function:

$$K_{0.5} = (10196 - 1988 \ln R)^{0.31} \quad (14)$$

During the second half of the year, this relationship looks like this:

$$K_{0.5} = (3.420393 - 0.42065 \ln R)^{-4.55} \quad (15)$$

The maximum increment of information corresponds to the maximum of internal energy. Correspondingly, during the first half of summer Kullback's information is increasing with an increase in incoming energy in a nearly exponential mode, while during the second half of summer the system tends to an equilibrium state in a linear fashion.

It is typical that intensive accumulation of internal energy is coinciding with high entropy and low information, or in other words is associated with the equilibrium state of biosphere in the start of the year. We could assume that during the second half of the year the decreasing information and absorption of solar radiation is "supported" by the internal energy accumulated earlier in the year.

The Normalized Difference Vegetation Index (NDVI) is closely linked to Kullback's information:

$$NDVI = 0.29 + 1.26K^{0.5} \quad (16)$$

Such relationship is quite understandable since the variation of reflectance in the red and infrared channels has the major impact on information level and determines NDVI. Since NDVI is a measure of productivity, one could conclude that the maximum biological productivity is reached when the system is far from equilibrium.

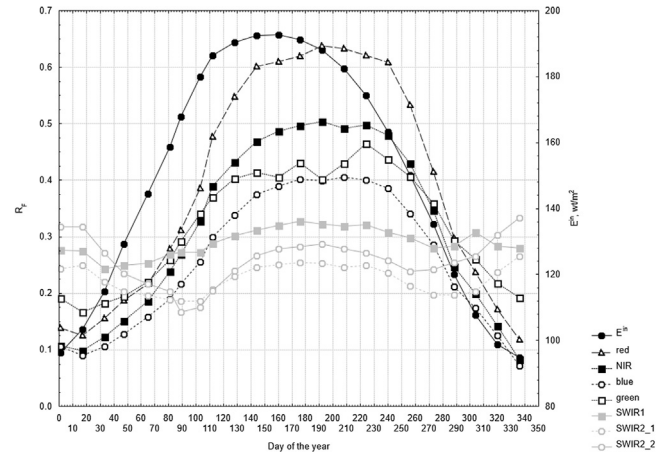


Fig. 7. Seasonal dynamics of spatial organization (R_F).

4. Seasonal dynamics of spatial organization

If the biosphere is treated as a unified system then its spatial organization should reflect its adaptive behavior as a whole to the incoming solar radiation. In any case, the level of system organization is inversely related to the level of entropy. As one can see from Fig. 7 the maximal level of one-dimensional organization (R_F , Eq. (12)) is demonstrated by reflected solar radiation in the red channel, which means that the biosphere tends to maximize its absorption of solar radiation in this channel. The second highest level of organization is demonstrated by the NIR channel, then green and blue. The maximum in these channels is achieved in September. A relatively high level of biosphere organization in the area of PAR is maintained throughout the vegetation season. The level of organization in three other channels does not change significantly reaching minimum levels in spring and fall.

Fig. 8 shows the dynamics of the multidimensional spatial Foerster's organization and information of reflected radiation in the seven MODIS channels. The level of multidimensional spatial organization dynamics is similar to the one for individual channels. The multidimensional information (I) could serve as a non-parametric metric of correlation of between albedo in seven channels. Unlike the level of Foerster's organization (R_F , Eq. (12)), the multidimensional spatial information (R_i , Eq. (13)) is minimal during the vegetative season (Fig. 8), which means that albedo in the seven MODIS channels is changing independently. Hence, it could be concluded that biosphere functions as a whole in such a way that albedo in each point in space is approaching a local optimum, while the combination of albedos in space tends to be maximally diverse. It can be further concluded that different types of vegetation cover have different ratios of albedo in different channels, which reflects their adaptive behavior leading to the reduction of multidimensional organization in vegetative season.

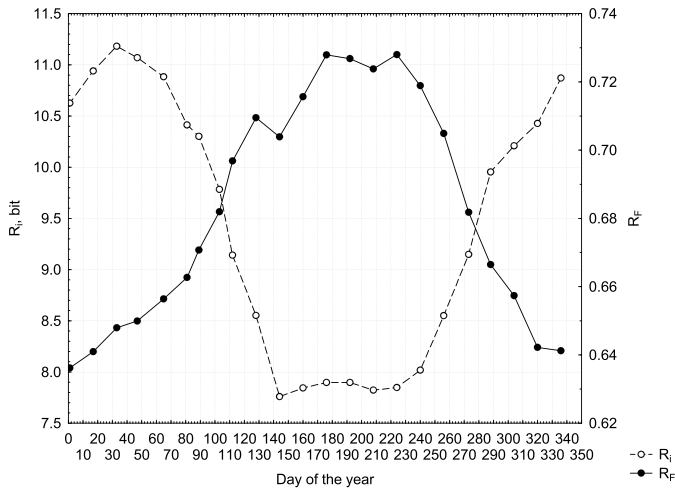


Fig. 8. Seasonal dynamics of multi-dimensional level of organization (R_F) and information (R_I).

In order to check this hypothesis we made a classification of reflecting surface of the Northern Hemisphere based on albedo. The classification was based on hierarchical dichotomy approach analogous to K-mean classification method. The distance between pixels was determined using scalar (inner) vector product (Cauchy–Schwarz inequality). The resulting map is shown on Fig. 9. Clearly, the classification based on albedo differs from analogous classifications of landscape cover. The third type of surface corresponds to grassy tundra, meadows (steppe) and grassy savanna. Forest types are based on the degree of density (canopy closure) without taking into account their zonal position. The resulting classification demonstrates that albedo depends on the level of density of plant cover without consideration of different biomes.

Fig. 10 shows spectrums for all the identified vegetation types with exception of glaciers. The spectrum types 2, 8, 9, 10 and 11 are very different from each other and the rest of spectrums. In arctic tundra, the albedo is very high for visible spectrum part and near infrared radiation. In dry steppe and desert, the spectrums are more alike but in steppe, the reflectance in the short-wave infrared 1 and short-wave infrared 2 channels is lower than in deserts. In elevated steppe and semi-desert spectrums are similar to steppe and desert, respectively but the albedo in elevated ecosystems is lower. Spectrum types 3 to 7 form a sequence in which the reflectance in different channels changes in different direction. In a sequence from meadows to dense forests, there is certain reduction in the reflectance in the visible part of the spectrum and a certain increase in the reflectance in the near infrared channel.

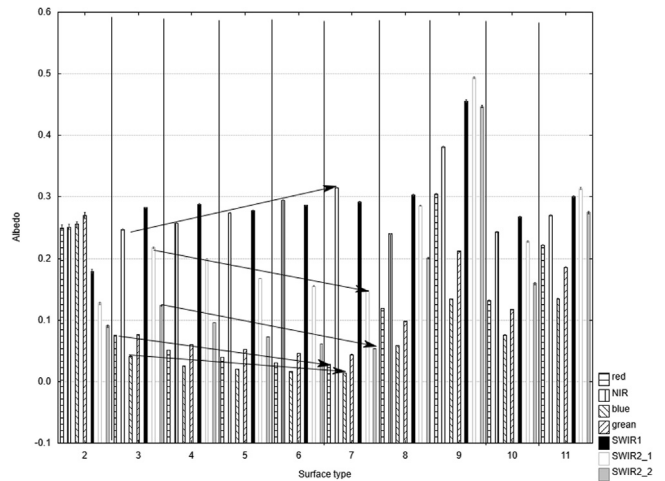


Fig. 10. Albedo spectrums for surface types described on Fig. 9.

The albedo in the short-wave infrared channel that reflects the water content in the vegetation cover is nearly constant, while the albedo in other far infrared channels declines in the sequence of cover types from 3 to 7.

Our analysis shows that the albedo in the visible part of the spectrum (responsible for photosynthesis) and short-wave infrared channel (showing water content) is not varying much in a wide range of conditions from tundra to steppe to closed canopy forests. At the same time, in other channels, changes are greater and multidirectional, which is explained by changes in the concentration of mesophyll and other biochemical compounds. The latter reach maximal concentrations in forests and lower concentrations – in grasslands. Such multidirectional and multiscale changes in the albedo of different channels lead to the reduction of inter-channel correlation during the vegetation season.

In the winter when large parts of the Northern Hemisphere are covered in snow the multidimensional spatial information is increasing as a result of greater similarity of different properties of the reflective surface. At the same time, during grater vegetation activity due to the adaptive behavior of biological systems the structure of albedo in different channels becomes more diverse and spatial coherence reduces.

The spatial organization (r) of thermodynamic parameters of the biosphere was analyzed for absorbed solar radiation, exergy, heat flux, entropy, Kullback’s information, and NDVI. As it follows from Fig. 11 in the winter the spatial organization of radiation absorption; exergy and heat flux is very low (minimum in February) and then starts to grow rapidly with the maximum in May–June. The increment of entropy in the areas far from the equilibrium conditions is minimal (Fig. 12).

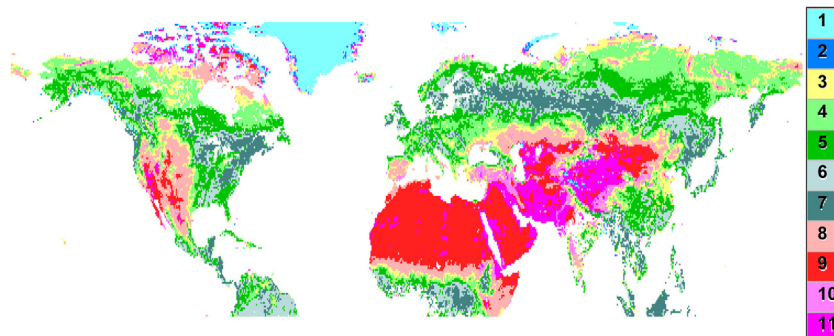


Fig. 9. Map of surface types of the Northern Hemisphere in June. 1–glaciers, 2–arctic tundra, 3–tundra, meadow, savanna, 4–sparse forests, 5–medium-dense forests, 6–dense forests, 7–highly dense (closed) forests, 8–dry steppe, semi-desert, 9–desert, 10–elevated dry steppe, semi-desert, 11–elevated desert.

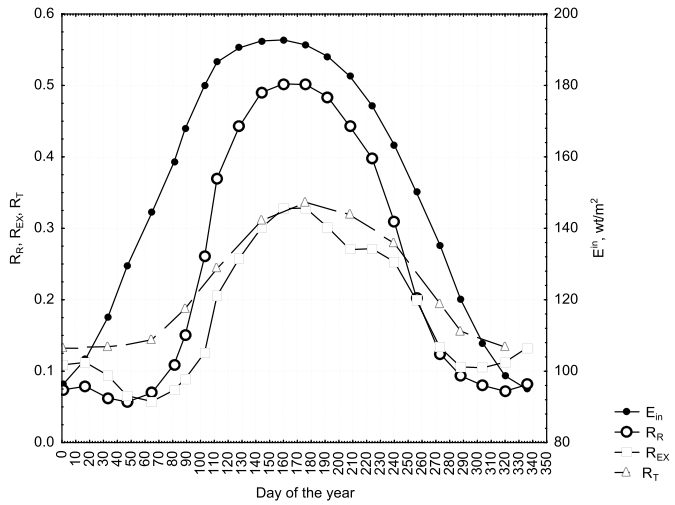


Fig. 11. Seasonal dynamics of the spatial organization of absorbed radiation (R_R), exergy (R_{EX}) and heat flux (R_T).

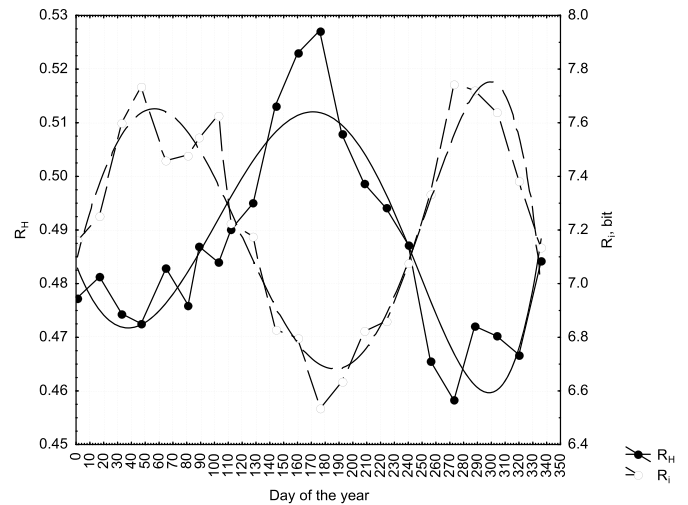


Fig. 13. Seasonal changes in the spatial organization of all thermodynamic variables (R_H) and information (R_I).

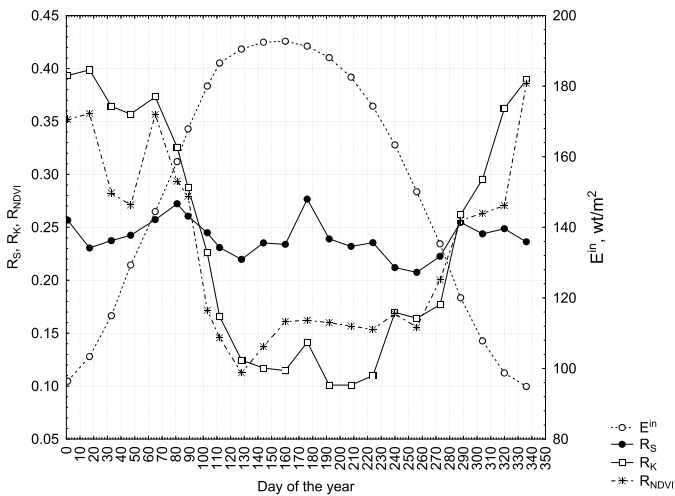


Fig. 12. Seasonal dynamics of the spatial organization of entropy (R_S), Kullback's information (R_K) and NDVI (R_{NDVI}).

The seasonal changes in the organization of selected thermodynamic variables are quite asymmetric – the biological system “attempts” to keep the maximum level of organization when the incoming solar radiation is reducing.

Overall, the dynamics of spatial organization for entropy, Kullback's information and NDVI is quite different (Fig. 12). The spatial organization of entropy during the season has 3 peaks – days number 81, 176, and 256 (March, June, September). Perhaps, these peaks reflect the moments of certain restructuring of the albedo structure. However, the magnitude of variation is not too high, so it can be related to irregular gaps in the initial data. Unlike entropy, the spatial organization of Kullback's information and NDVI fluctuate along a clear seasonal trajectory with the minimums at days 128 and 224. These days also correspond with the minimums of spatial organization of entropy. It appears that the average Kullback's information (Fig. 5) and spatial Kullback's information are changing during the season in a similar fashion. The average maximums of Kullback's information and NDVI (Fig. 5) in the Northern biosphere are determined by an increase in spatial variability, when the biological production in each pixel of the Earth surface attains its maximum value in accordance with its type and climatic conditions.

Let's examine the generalization of the multidimensional spatial organization of the thermodynamic system (Fig. 13). The aggregated spatial organization reaches its first maximum in June and the second less pronounced maximum in January. The seasonal dynamics of the multidimensional spatial information changes in reverse. Such relations could be seen as very clear manifestation of the Haken information theorem and S-theorem of Klimantovich – biosphere has two stationary states with maximums of organization (minimum of entropy) in the winter and summer seasons. According to S-theorem the transition between these states takes time with the minimum of entropy production in the stationary states and with the maximum of information production in non-stationary states (according to Haken information theorem). It should be mentioned that this effect is observed only for the level of entire biosphere and when the system is represented by thermodynamic variables.

5. Discussion

The analysis conducted for this paper shows that the *goal function* of the biosphere is to maintain the absorption coefficient in the area of PAR at an optimal level during the vegetative season. At the same time, the system tries to maintain the maximal possible absorption when the incoming radiation is reducing, during the fall. It could be further concluded that the attainment of this goal function is made possible by the internal energy accumulated during the spring season with its subsequent utilization for supporting mechanisms that regulate energy absorption in the PAR range.

The dynamics of the exergy flow could be assessed by comparing derivatives for exergy and NDVI in the first half of summer. A simple comparison of Fig. 4 and 5 shows that during the first half of summer the accumulation of biological production is preferable to the overall increase in exergy, which mostly takes place in the form of energy use for evapotranspiration.

The heat flux during the entire season is proportional to the absorbed radiation and could be treated as “thermal noise”. Consecutively, the goal function during the process of allocating energy received in the PAR diapason is the maximization of biological production.

One could apply the criteria of identifying goal functions to the analysis of the spatial organization of vegetation cover. The highest level of spatial organization is demonstrated by albedo in the red and near infrared channels, which in combination determine the

potential biological productivity. This high level of organization is maintained during a lengthy period.

The biological system functions in such a way that the level of energy absorption is maintained at an optimal level during the vegetative season (in the PAR range) and then keep it at maximal levels during the fall season. This type of functioning is associated with a certain type of thermodynamics. The analysis of spatial organization shows that the biosphere is a holistic system with two stationary states – in the summer and winter. The transition between these states is achieved according to the Haken information theorem (maximum information) and the production of entropy in these stationary states is minimal (according to S-theorem of Klimantovich).

The organization of biosphere is determined by the variability of states at the local level. In each of those states the system tries to achieve the maximum possible level of PAR absorption and a certain level of incremental information and NDVI depending on the vegetation properties. The variability of allowable relations between the functional parts of solar radiation absorption spectrum leads to the stationary condition of the solar energy transformation. In other words, the vegetation diversity is a condition for the stable functioning of the biosphere.

In fact, the variability of allowable relations between the functional parts of the spectrum of solar radiation absorption determines the stationary nature of the transformation of solar energy by biosphere. The overall plant diversity, while maintaining the general stability of the biosphere, is also a manifestation of the Ashby law of necessary diversity.

It could be concluded that the type of data analysis offered in this paper does not support the principle of maximization of entropy. In space and time, in the states close to stationary, the entropy production is close to zero and heat flux (which is usually associated with entropy) is in equilibrium with the absorbed solar radiation.

Also, the entropy associated with hidden (latent) heat does not reach the maximum level in the stationary state far from equilibrium. We should also mention that the principle of maximization of energy flow or the flow of exergy is only applicable to the biological production. However, there doubts in this case as well. If this principle holds true, it would imply that the coefficient of energy absorption in the PAR range would grow proportionally to the incoming radiation level during the vegetative season, which does not happen in reality. During the vegetative season, the coefficients of absorption stay at about the same level specific to different vegetation types. It appears that the photosynthetic mechanism cannot overcome the internal limits and its work is determined by the principal of “necessary and sufficient”. This effect is also seen in a classic photosynthesis light curve.

6. Conclusion

In this paper, we examined the real functioning of the biosphere based on the analysis of spatio-temporal dynamics of reflected solar radiation in seven spectral channels. These channels describe different aspects of vegetation cover.

The analysis revealed that the goal function of the examined system is maintaining the albedo in the PAR range during the vegetative season at a specific optimal level (with the maximum rate of its growth during the start of vegetative season). One of the mechanisms regulating this process is accumulation of internal energy during the vegetative season. Another mechanism is the significant independence of albedo in different channels, being determined by specific vegetation types and providing global stability of albedo in the PAR range. Such a mechanism looks similar to the Ashby regulator and leads to a hypothesis about the global homeostasis, such as Lovelock's Gaia hypothesis at the local level. The constancy of

albedo in the PAR range during the vegetative season implies that the accumulation of energy in ATP molecules is proportional to the incoming solar radiation and is the function of the solar constant. Based on annual observations one could conclude that the albedo in the PAR range is a regulated variable and cannot be an independent temperature regulator, which is assumed by the Lovelock model (Watson and Lovelock, 1983).

At the same time, as it follows from Fig. 4 the heat flux from the Earth surface has minimal variability during the year and also could be treated as regulated variable. The fast increase in exergy during the first half of summer leads to a decline of heat flux. In the second half of summer, the decrease in exergy maintains the heat flux at a relatively high level, leading to a distortion of the linear relation between heat flux and incoming solar radiation. Such regulative function of evapotranspiration is noted by Kleidon (2002) during the analysis of Lovelock's model.

To conclude, the spatio-temporal analysis of the Earth's surface biosphere based on MODIS annual multi-spectral data leads to a holistic description of a complex system and defines its “orientors” according to the notions of non-equilibrium thermodynamics.

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