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GEOGRAPHY

Estimation of the Thermodynamic Parameters of Land Cover from Multispectral Measurements of Reflected Solar Radiation (Landsat) in Terms of Nonextensive Statistical Mechanics

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Abstract—This paper substantiates the use of the nonadditive statistical mechanics equipment to estimate the thermodynamic variables of an ecosystem in terms of the multispectral measurements of reflected solar radiation. The parameter q is accepted as corresponding to the Förster maximum organization conditions. The remote information (Landsat) has been used to calculate the entropy, Kullback information, Förster organization measure, free energy, exergy, related and internal energy, and the energy consumption for evapotranspiration and photosynthesis for the q index measured for each pixel of the satellite images. It is proved that the seasonal dynamics of the q index and the organization measure is fully consistent with the implications arising from the open nonequilibrium system theory, and the thermodynamic variables accurately reflect the current state of the ecosystem.

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The theoretical background of the biosphere thermodynamics based on the Boltzmann–Gibbs–Shannon (BGS) statistical mechanics for nonequilibrium systems is considered in the works of Yu.M. Svirezhev [1] and S.E. Jörgensen [2]. They propose to estimate thermodynamic variables from the multispectral remote information received from satellites. The model of the adequacy for reality can be proved by considering the variation of thermodynamic variables in time and space. As follows from the analysis of remote measurements from the Landsat and MODIS satellites [3–7], their variations in time and space are in good agreement with the nonequilibrium system theory [8–11].

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The biosphere entropy is minimum, while the Kullback information and exergy are maximum in the period of maximum vegetation and, all other things being equal, are proportional to the rate of solar radiation and the weight of functioning vegetation.

The use of a more general model of nonextensive statistical mechanics (NSM) developed by Tsallis is a natural development of the theory and methods of assessing the biosphere and thermodynamic parameters of the ecosystem in terms of multispectral remote information [12, 13]. It is implemented under the assumption of nonlinear interactions between the system components. The BGS model is a special case. The parameter q in NSM determines the nonlinear relationships between components. The meaning of all thermodynamic variables remains unchanged: entropy, Kullback information, exergy, and related and internal energy. As in the BGS model, the greater the Kullback information, the more nonequilibrium the system and the higher its effective work.

The parameter q in NSM reflects, in particular, the scale of correlations between the system components. The more q is than unity, the higher the internal correlations and the more organized the system. At $q < 1$ the system is under disorganization [12]. This paper demonstrates the thermodynamic variables estimated in terms of the Tsallis nonextensive statistical mechanics and proves that they deepen the understanding of the functioning of the biosphere at the land cover level.

THERMODYNAMIC VARIABLES IN THE NSM SYSTEM

It is postulated in nonadditive statistical mechanics [13] that the system entropy is as follows:

$$S_q = \frac{1 - \sum_{q-1}^{k} p_i^q}{q - 1},$$

where p_i is the probability of state i and $S_q^{\max} = \ln_q k$ is the entropy maximum at $p_i = \frac{1}{k}$, where k is the number of classes.

The Kullback information evaluating the "distance" between equilibrium and nonequilibrium states of the system is as follows:

$$K_q = \sum_{i=1}^{k} p_i \frac{[p_i/p_i^{\mathrm{ecv}}]^{q-1} - 1}{q - 1},$$

where p_i^{ecv} is a probability of class i for the equilibrium state, and at $q = 1$, it is identical to information in the BGS thermostatics.

Information in the Tsallis system, as well as entropy, is nonadditive, but the general interaction remains the same as in BGS:

$$R = Ex_q + TWS_q + DU_q,$$

where R is the absorbed reaction, Ex_q is the exergy (effective work), TWS_q is the related energy (TW is the thermal flow and S is the entropy), and DU_q is an internal energy increment.

Based on multispectral remote information using the standard formulas [14], we can calculate the reflected solar radiation e_i^{out} in each spectral channel i, W/m^2, the energy incoming to the surface e_i^{in}, which is accepted as equal to a solar constant in the channel i at the measurement time and

$$p_i = \frac{e_i^{\mathrm{out}}}{\sum_{i=1}^{k} e_i^{\mathrm{out}}}.$$

The formula to estimate the exergy (effective work) proposed by Svirezhev [1] for BGS in NSM will be as follows:

$$Ex_q = E_{\mathrm{out}} \left(K_q + \frac{(E_{\mathrm{out}}/E_{\mathrm{in}})^{1-q} - 1}{1 - q} \right) + R,$$

where $E_{\mathrm{out}} = \sum_{i=1}^{k} e_i^{\mathrm{out}}$ is the total reflected radiation in multispectral channels, $E_{\mathrm{in}} = \sum_{i=1}^{k} e_i^{\mathrm{in}}$ is the incoming radiation total, and $R = E_{\mathrm{in}} - E_{\mathrm{out}}$. At $K_q = 0$ the system is in equilibrium, and $Ex_q = F_q$ is the Gibbs free energy.

REAL DATA ANALYSIS

The physical meaning of the NMS theory as applied to remote information can be verified by comparing the direct measurements with their predicted behavior in time and space defined by the theory of nonequilibrium thermodynamics.

Such verification is carried out by analysis of the spatiotemporal dynamics of q_{org} for twenty-two Landsat images from 1986 to 2011 for southern taiga lands in the Central Forest Biosphere Reserve and its protected zone. It is assumed that each pixel of a satellite image corresponds to a specific ecosystem with a corresponding solar radiation reflection spectrum in terms of which all thermodynamic variables are estimated.

Figure 1 shows the seasonal course of q_{org} and R_q. Obviously, their variations are completely governed by the theory of self-organizing open systems. In winter, from December to early April, at a landscape average $q_{\mathrm{org}} < 1$ the system is under disintegration. With the beginning of the vegetative season, $q_{\mathrm{org}} > 1$, reaching a maximum in June, is indicative of active self-organization processes. Variations in the organization time correspond to the Klimontovich S theorem. The organization has two maxima corresponding to the conditions of the steady-state system: in winter and summer with two transition periods in October–December and in April. The analyzed dependence of the average landscape q_{org} on the incoming solar energy and the weather shows an almost unambiguous dependence on the accumulated temperature total for 24 days and incoming radiation; meanwhile, the intrinsic influence of incoming radiation is insignificant and lies on the verge of certainty.

The statistical model involves the following parameters: current temperature, accumulated temperature, and precipitation for 3, 6, 12, 24, and 36 days. The resulting relation is relatively natural. The system goes into the self-organization state, when the temperature total accumulated for 24 days becomes more than 100°C (4.1°C per day, on average) at over 120 W/m^2 of solar radiation in six channels.

Figure 2 shows variations in the q index and the measure of organization depending on the state of vegetation in June in the maximum seasonal growing period. The minimum q index with a relatively low organization is typical of old spruce forests. Its value becomes somewhat higher in the overgrown windfallen areas and reaches a maximum in the young forests. Then, as the forest becomes older, the q index and

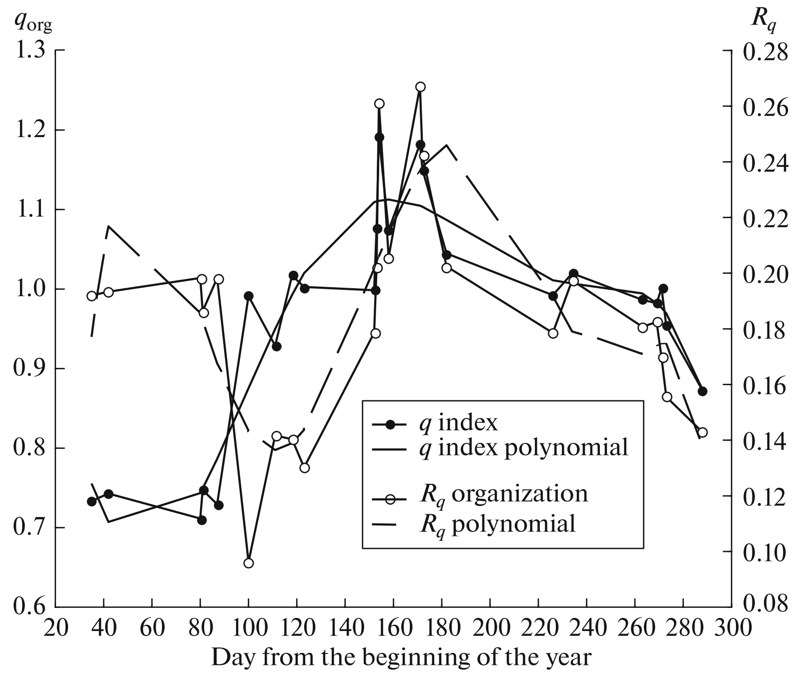

Fig. 1. Seasonal course of the q_{org} index and R_q (organization).

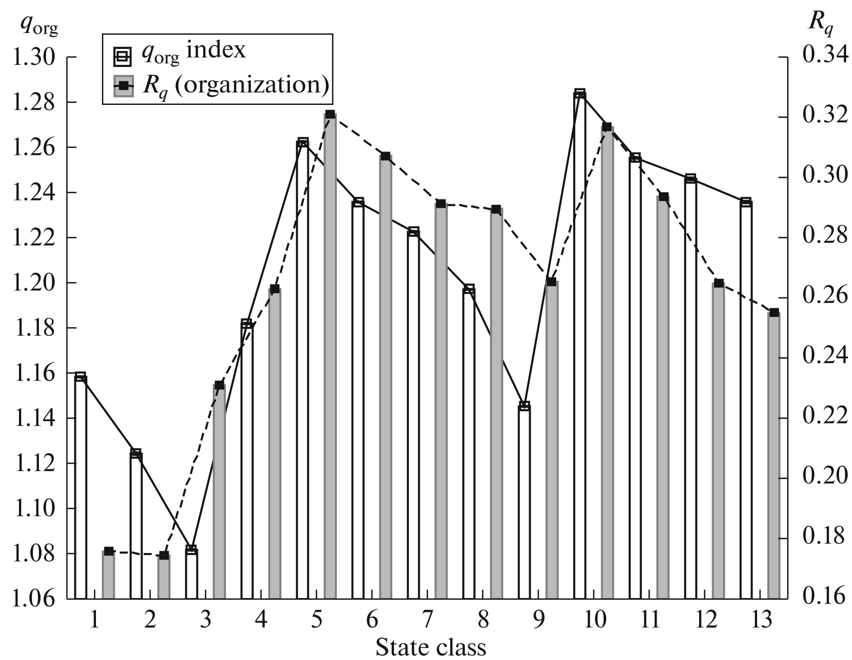

Fig. 2. Variations in the q index (q_{org}) and organization (R_q) depending on the state of vegetation cover in June: (*1*) high bog, (*2*) high bog with pine, (*3*) old spruce forest, (*4*) overgrown windfallen and cut trees, (*5–9*) age stages of spruce forest recovery, (*10*) meadows, (*11*) overgrown cut forests, (*12*) meadows replacing arable land, (*13*) arable land and settlements.

organization values gradually decrease. The q index reaches an absolute maximum in the meadow communities. The organization value and the q index decrease when passing from relatively fresh cut forests to arable lands and settlements. The high bogs are unique formations with a minimum organization and low q index, while the q index is lower in a bog with pine. The obtained ratios, on the one hand, reflect differences in the ability of bog, forest, and meadow communities to self organize, and, on the other hand,

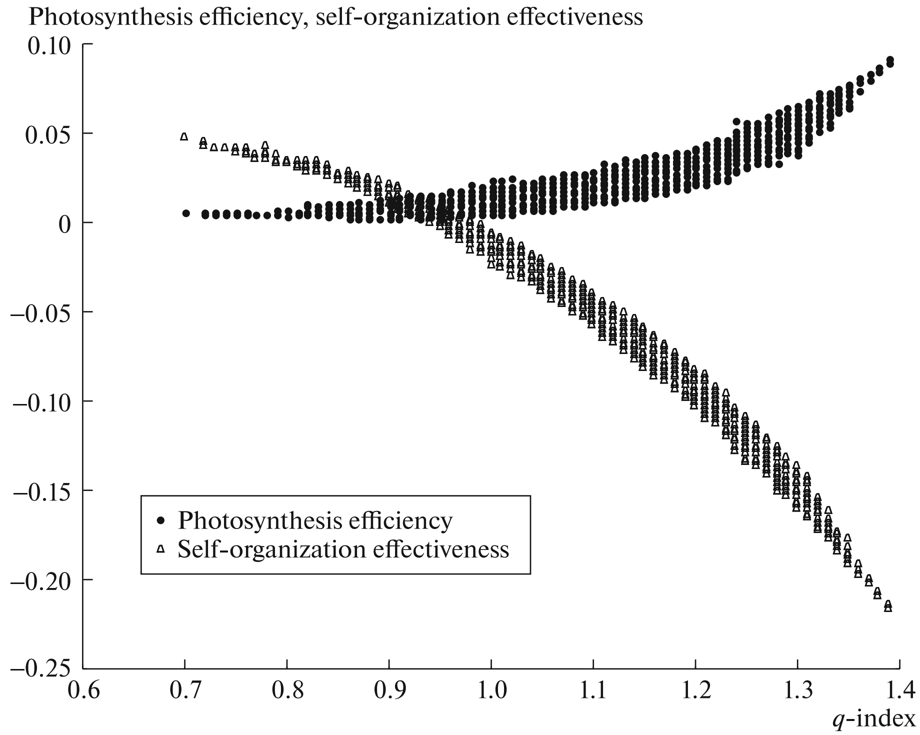

Fig. 3. Dependence of the efficiency ofphotosynthesis as a self-organization nonequilibrium and efficiency function reflecting the difference in heat consumption for evaporation relative to $q = 1$ on the q index value.

forest communities demonstrate a decrease in the ability to self-organization when they become older. At the extreme limit, the forest system tends to the state when the q index is close to unity.

The average values of entropy and exergy in the BGS system are higher than those in the NSM system, and the Kullback information is less, but in all cases, the variance of all variables and the amplitude are higher in NSM. In general, the higher q, the lower exergy and entropy, but the higher the Kullback information. In terms of the self-organization, it is evident that the growth of an organization value is accompanied by a decrease in the effective work of the system.

By comparing Ex_q and $Ex_{\text{bgs,}}$ we obtain variations in exergy depending on q. This value can be written as follows:

$$\Delta_q = Ex_q - Ex_{\text{bgs}},$$

it can be given as a fraction of incoming solar radiation E_{in}

$$\eta\Delta_q = \Delta_q / E_{\text{in}}$$

and termed as “self-organization effectiveness.” Exergy involves mainly two forms of work such as moisture transport and biological products. If we assume that evapotranspiration is subject to the classical laws of thermodynamics, then it is provided by the Gibbs free energy consumption, and biological products are ensured by the system deviation from equilibrium, i.e., by the Kullback information. Then, the free energy is as follows:

$$F_q = E_{\text{out}} \frac{(E_{\text{out}}/E_{\text{in}})^{1-q} - 1}{1 - q} + R$$

and the energy consumption for biological products reaches

$$E_{\text{fot}} = Ex_q - F_q.$$

The energy theoretically spent for photosynthesis can be estimated through the efficiency:

$$\eta F_q = \frac{F_q}{E_{\text{in}}}.$$

Figure 3 shows the dependence of the self-organization effectiveness and the photosynthesis efficiency on q. As follows from the real data on June 21, during the maximum seasonal growing period, the energy consumption for transpiration decreases exponentially with increasing q, and the system uses less moisture with an exponential increase in the efficiency of photosynthesis. Hence, in the class of systems considered, self-organization described by a growing q improves the system efficiency by the fact that it reduces the energy consumption for supporting processes such as moisture transport from the soil to the atmosphere. As follows from Fig. 4, high bogs and old spruce forests evaporate moisture almost at the level of free energy consumption, on average, with a minimum photosyn-

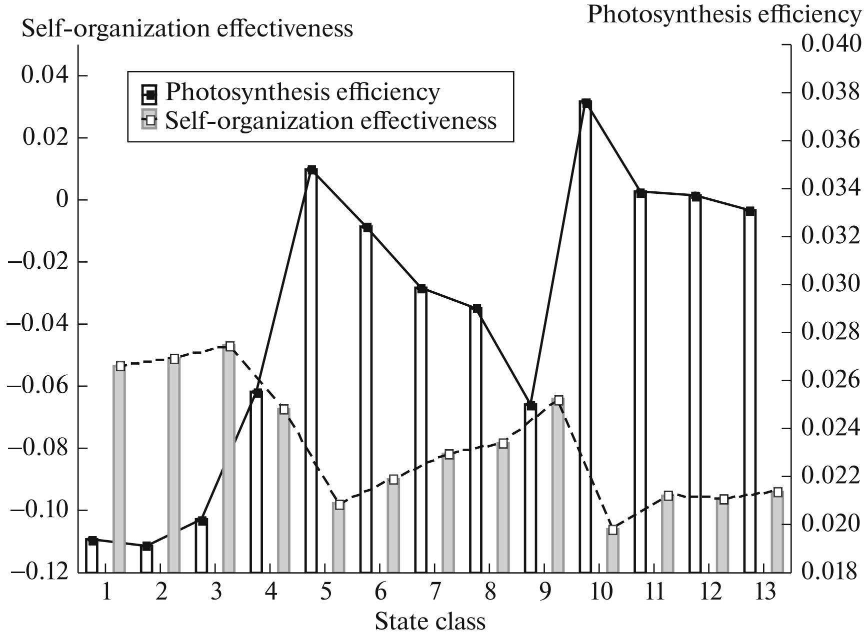

Fig. 4. Variations in the efficiency of photosynthesis and the self-organization effectiveness depending on the vegetation cover state in June: (*1*) high bog, (*2*) high bog with pine, (*3*) old spruce forest, (*4*) overgrown windfall and cut trees, (*5–9*) age stages of spruce forest recovery, (*10*) meadows, (*11*) overgrown cut forests, (*12*) meadows replaced arable land, and (*13*) arable land and settlements.

thesis efficiency. In the young forests, the photosynthesis efficiency for forest communities is maximum, while the heat consumption for evaporation is substantially lower than in the old forests. As the forest becomes older, the photosynthesis efficiency and the effectiveness of self-organization decrease. Against this background, the highest efficiency and minimum heat consumption for evaporation are observed in the meadow vegetation, which from the standpoint of self-organization can be considered as the most perfect community. It should be noted that the average photosynthesis efficiency under the given calculation scheme of energy consumption for photosynthesis is about 2%, which is totally consistent with the typical average effectiveness estimates of this process.

We should also note the great information capacity of R_q, which was used for the first time in the analysis of remote data on the organization measure; in particular, it is highly different for high bogs and meadows, which are hardly distinguishable when comparing their spectral images.

The theoretical grounds considered for the application of nonadditive thermodynamics for multispectral remote information analysis and real data analysis demonstrate the adequate representation of the theoretical ideas of behavior of open nonequilibrium self-organization systems by the NSM parameters. The multispectral remote measurements in the proposed interpretation make it possible to estimate the functional state of the ecosystem for each pixel, to determine the degree of self-organization of the ecosystem, the efficiency of photosynthesis, and the efficiency of moisture use, and to express them in energy and relative measurement units. The proposed approach to the multispectral measurement transformation differs from the approach based on the use of various semi-empirical vegetation indices in the physical validity of each variable obtained under the general open non-equilibrium system thermodynamics theory.

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