ISSN 1995-4255, Contemporary Problems of Ecology, 2014, Vol. 7, No. 7, pp. 838–854. © Pleiades Publishing, Ltd., 2014.
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Multispectral Remote Information in Forest Research

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Received August 16, 2013

Abstract—The article proposes approaches to the use of multi-spectral remote information in basic research on the spatiotemporal organization of biogeocenotic cover with and without the use of ground field measurements. It is postulated that remote measurements reflect the biophysical condition of biogeocenotic cover defined by the absorption and conversion of solar energy and can be considered as its properties. The measurements are interpreted from the perspective of thermodynamics of dissipative open systems. When combining remote information and ground measurements in accordance with the concepts of synergy, order parameters are selected. They are discussed in relation to the controlling parameter—the relief. The broad possibilities for using the results of basic research in the solution of practical problems related to the management of biological resources are noted.

DOI: 10.1134/S1995425514070087

Multispectral and hyperspectral measurements of the reflected solar radiation from satellites are by far the most informative system of estimating the state of ecosystems in a wide range of spatial scales at different time intervals. The mechanisms underlying the absorption of solar radiation and its conversion into useful work determine the functioning of each individual biogeocoenose and the entire biosphere. These mechanisms that determine the operation of a complex system are likely to be understood only as a first approximation [22, 29, 31, 37]. The conversion of solar energy is connected with all of the hierarchical levels of organization of living matter—from the molecular level to the community. It is specific for each level and depends on both the autochthonous processes and self-organization of living matter, as well as on changes in the state of the medium in time and space. The technical capabilities of multispectral measurements of the reflected solar radiation create new conditions for the development of problems regarding the functioning of a complex biological system, its spatiotemporal self-organization, sustainability, adaptability, and evolutionary trends in a wide range of environmental conditions.

However, the scope of remote measurements historically was mainly associated with the desire to indirectly measure the individual properties of vegetation that are of practical importance: biological products, phytomass, transpiration, pigment content, "health," and the like, as well as to promote the development of maps of the vegetation state. In the development of these areas, there is significant progress. However, they by no means exhaust the opportunities provided for the study of complex systems. The present report discusses some of the possible approaches to the study of the organization of forest vegetation as a complex system. The basis for these approaches is formed by the concepts of synergy, thermodynamics and information theory. The ultimate goal of such research is to identify the forms and rules for the organization of living matter and their underlying mechanisms. Complete exhaustion of the topic is most likely impossible; it is more reasonable to speak of some movement in this direction. It is obvious that some issues are also solved within this fundamental problem, ones that can be regarded as a natural result of the particular common approach. The report addresses two related areas:

1. Analysis of the organization and functioning on the basis of multispectral remote information as a measurement system without the use of ground information collected in field.

2. Integration of remote and ground field measurements of the state of ecosystem components.

In this paper, we demonstrate some of the first results and try to identify the most promising areas of research.

RESEARCH ON THE BASIS OF MULTISPECTRAL AND HYPERSPECTRAL MEASUREMENTS

In world practice in this field, vegetation indexes are the most actively developed, the theoretical basis of which is the presence in various pigments and compounds of specific spectral absorption bands, in which the amount of reflection is largely a function of their content, and bands in which the reflection does not depend on their concentration. The latter are considered as the "zero" count. The difference or the ratio among reflections in these spectral bands is determined by the appropriate index. Division of the difference into the amount of reflection in the two compared bands makes it possible to reduce the dependence of the index on the reception of solar radiation or the impact on the overall absorption of external conditions. The most widely used normalized differential vegetation index (NDVI) is based on the difference between the reflection in the near infrared and red channels [28]. The reflected infrared channel increases in proportion to the development of mesophyll; in red it decreases with an increase in chlorophyll a and b content. Accordingly, the larger the index value, the larger the product. However, this relationship is nonlinear, and the value of the index depends not only on the biological product. Distortions create, in particular, the transparency of the atmosphere, with the soil surface, canopy structure, some species-specificity of index, etc. visible through the vegetation canopy. Efforts in the development of each type of index address the impact of such interference. In general, indexes for evaluating the content of virtually all pigments and water, as well as the general condition of the vegetation, were developed for hyperspectral measurements, and the focus is on their verification. (See, for example, [24, 32, 38]).

S.E. Jorgensen and Y.M. Svirezhev [30] proposed a shift from spectral measurements of reflected solar radiation to the thermodynamic variables—the entropy of the reflected solar radiation (S_{out}), the increment of information (K) and exergy (Ex).

$$S_{out} = \sum_{\nu=1}^{6} p_\nu^{out} \ln p_\nu^{out},$$

where $p_\nu^{out} = \dfrac{e_\nu^{out}}{E^{out}}$ is the proportion of reflected energy in the spectral range ν of the total reflected energy (e_ν^{out} is radiation in reflected ν, E_{out} is the amount of reflected radiation). Based on the entropy information, a measure of organization is introduced [20]:

$$R = 1 - S_{out}/S_{\max}, \quad S_{\max} = \ln D,$$

where D is the number of bands of the solar spectrum, which is measured by solar radiation. In general, a large organization means a more efficient implementation of the objective function of the system.

The Kullback increment of information measures the distance of the system from equilibrium—in our case, from the spectrum of solar radiation (E^{in}).

$$K = \sum_{\nu=1}^{6} p_\nu^{out} \ln \frac{p_\nu^{out}}{p_\nu^{in}},$$

where $p_\nu^{in} = \dfrac{e_\nu^{in}}{E^{in}}$ is the share of arrived energy in spectral range ν from the total received energy. In the first approximation e_ν^{in} is taken to be equal to the solar constant. If the system is in equilibrium, then $K = 0$ and the useful work is identical to the free energy of the system. The larger K, the greater the possible useful work.

The increment of information, as well as the organization, is primarily related to the self-development of the system but also to the functions of the external forces. Useful work of system (exergy) is defined as:

$$Ex = E^{out}\left(K + \ln \frac{E^{out}}{E^{in}}\right) + R,$$

where $R = E^{in} - E^{out}$ is absorbed energy, and E^{out}/E^{in} is albedo. Exergy is work, which is mostly spent on evapotranspiration and only a very small extent on photosynthesis. Thus, the total energy balance equation:

$$R = Ex + STW + DU,$$

where STW is bound energy not used for work (dissipation) is

$$STW = TW \cdot S_{out},$$

where TW is heat flux from the active surface, as measured, for example, by Landsat satellite in the sixth long-wavelength channel. DU is the increase in the internal energy of the system, which is related to the energy cost of the interaction of its components.

The theoretical base, and some of the results of using these variables, were considered by S.E. Jorgensen and Y.M. Svirezhev, Yu.G. Puzachenko and R.B. Sandlersky [19, 34]. Direct measurements in the spectral bands and the indices of integral thermodynamic variables calculated on their basis determine the possible space variables. Different vegetation indices can be regarded as derivatives on the reflection spectrum.

In accordance with the concepts of synergy [21], a complex system is organized by order parameters. Their number is certainly less than the number of input variables, each of which is their function. The order parameters can be viewed as reflections of some relatively independent subsystems, each of which has a physical meaning. In turn, the order parameters depend on the action of external forces—the controlling parameters. A change in the controlling parameters may lead to abrupt changes in an order parameter. Isolation of the order parameters can be carried out by different orthogonal transformations: Gram–Schmidt (Tasseled Cap), principal components, multidimensional scaling. The first two methods are most appropriate for normal populations and linear systems, and the Gram–Schmidt transformation is based on the scalar product, and the method of principal components is based on the covariance matrix. Multidimensional scaling can use different metric distances and is less sensitive to nonlinearities, but it is somewhat more cumbersome in the calculations. The most adequate metric and the most appropriate method of identification of the order parameter should provide the best quality reproduction of variables and the highest dispersion or entropy of order parameters with a minimum of a nonlinear dependence.

A discrete method for studying the spatial organization of the system variables can be organized on the basis of cluster analysis. However, for this it is necessary to formulate criteria for the adequacy of the resulting classification of reality. As well as in the first continuous mapping, mapping of the cluster-analysis depends on the metric, the presentation of variables, and the method of classification. The first two conditions have a physical meaning. Taking the logarithms of the original variables, we come to the reproduction capabilities of the nonlinear space; standardizing, we can assume that the variables have the same weight, etc. The adopted metric directly reflects the geometry of space. Having accepted these conditions, it is possible, based on the consequences of the theory of information, to organize the classification algorithm, which in fact measures the amount of information contained in the system that is given by the initial variables or order parameters for a given metric.

The maximum amount of information in the sample is $I = \log_2 N$. This value represents the maximum number of steps to a binary choice. They are necessary in order to find any element we are interested in. It follows that the classification should be obligatory dichotomous. Unambiguous separation into two sets can be accomplished by the method of K-medium with $K = 2$. Thus, the original set is divided by K-mediums into two, then each subset also into two, etc. Accordingly, the maximum possible diversity is 1 bit at the first level, 2 bits at the second, etc. The metric with maximal variety is recognized as the one defining the geometry of space (the principle of maximum entropy).

The problem of the geometry of space biosphere was formulated by V.I. Vernadsky [2]. In accordance with his views, homogeneous space–time implies independent processes of the position of a material body in space, which is obviously not realistic. Real space–time is anisotropic, but assigning to it a homogeneous space—time as an ideal state is a good base of studying its real structure. Geometry is an idealized image of real space, which determines the place of "points" of movement, interaction, and forms in the system. Geometric mapping of space-time gives a model of motion and evolution of system.

"We know a lot of different geometries, i.e. different spatial singularities can be countless. Three branches of geometry—the geometries of Euclid, Lobachevsky, Riemann—can approach all of the geometric manifestation of nature around us. Each branch can theoretically include infinite or nearly infinite number of geometries. Two branches—Euclidean geometry and the geometry of Lobachevsky—spatially are not limited. In Riemann geometry, there is its manifestation, which are always limited" ([1], p. 183). "We now have the right to accept the manifestation of geometric properties that meet all three forms of geometry—Euclid, Lobachevsky, and Riemann in a space in which we live" ([2], p. 26). V.I. Vernadsky proposed to regard Euclidean space as a geometric model of reality, which includes Riemannian spaces that describe embedded organisms. In general it can be assumed that in Euclidean space there is movement, in Lobachevsky space there is interaction, and in Riemann space there is symmetry. Between these spaces should be exchanges of energy or, in other words, they are implemented in the overall energy flow. The geometry of space is determined by the metric, which actually describes the shape of the parts, and the interaction of the particles in the system. The Euclidean metric is determined by linear methods of orthogonal decomposition or relevant metrics at classification. The vector space reflects the geometry of the interaction. Taking the logarithm of the original data, or by using the proper metrics, we proceed to Lobachevsky space. Moreover, the modern thermodynamic system considers two types of interaction: each particle to another particle, and each particle with a plurality of particles, including the ones very remote from it in space and time. Such systems have memory [5]. The first type corresponds to thermodynamics with Gibbs-Shenon entropy with appropriate rank distributions and the additivity of entropy and thermodynamics with Renyi entropy; the second corresponds to the thermodynamics of nonextensive systems with Tsallis entropy, for which the entropy is nonadditive. Systems with Gibbs-Shannon entropy correspond to the rank probability distribution $p_i = \exp(\lambda + \beta_i)$ (i is class rank $p_1 > p_2 > \ldots > p_k$). Renyi entropy corresponds to a fractal thermodynamic system with rank distribution of Zipf $p_i = \exp(q\ln i + \lambda)$. Tsallis entropy corresponds to the rank distribution $p_i = q^{(\lambda + \beta i)}$ [9].

The parameter q is directly related to the fractal dimension. The geometry of space of the system and possible relationships between the elements is a necessary condition for the description of complex systems. It is arbitrarily possible to say a lot about organization, self-organization, and functioning, but only natural measurements can give an idea of the actual processes of transformation of complex systems in time and space and make it possible to move towards a deeper and more adequate perception of reality. It is necessary to draw attention to the fact that the thermodynamics of nonextensive systems is a fairly new approach in the theory of nonequilibrium thermodynamics, which is currently under active development.

As an example, we give an analysis of one scene of Landsat 5 for June 21, 2002, reflecting the state of eco-

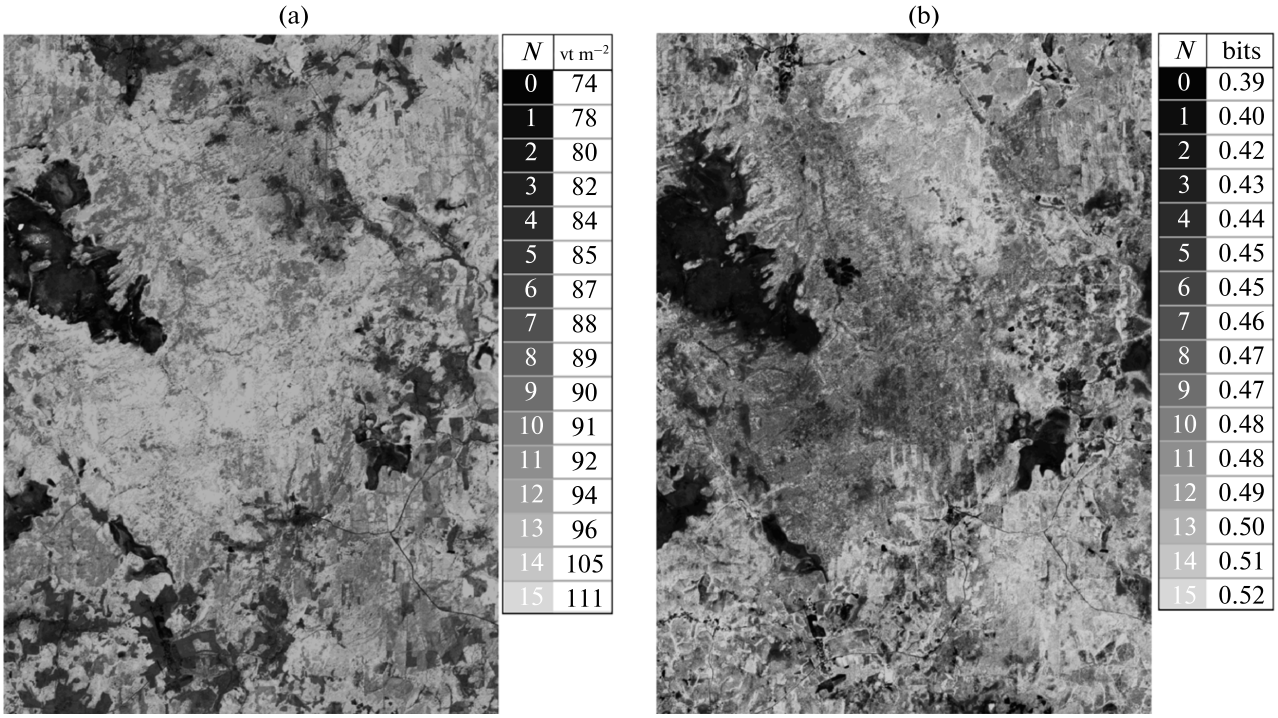

Fig. 1. Thermodynamic variables for June, 21, 2002: (a)—exergy, (b)—organization.

systems in 11 hours 23 minutes, for the territory of the Central Forest Biosphere Reserve (56°30′ N, 32°53′ E).

Figure 1 shows the spatial variation of exergy and actions of the organization. The highest exergy is typical for forests, especially for old-growth spruce forest. In the meadow communities, it is lower, and it is minimal on the bogs. Maximal organization is typical for secondary small-leaved forests, meadows, and clearings, the minimum is typical for raised bogs. Old small-leaved and spruce-fir forests have an average value. Basically, the value of the organization is determined by the ratio of the energy reflection in the red and near-infrared channels. Organization increases with the reflection in the second and a decrease in the first reflection, which corresponds to an increase of the index NDVI. Figure 2 demonstrates the increase of exergy and the organization for 18 min. The increment is obtained when comparing the two scenes for June 2002: from Landsat-5 for June 21 (11 h 23 min) and Landsat 7 for June 20 (11 h 41 min). The weather conditions in these two days were the same, and we can assume that all differences are an increase of solar radiation. On average, the exergy is 90.5 W m^{-2} with organization of 0.47 bits at 11 h 23 min. At 11 h 41 min, the values are 92.5 W m^{-2} and 0.49 bits, respectively. In the bogs exergy and organizations decreased during that time interval (Fig. 2). The greatest increase of exergy was noted in spruce forests, and that of organizations was found in small-leaved forests and meadows. Exergy and organization increase to the greatest degree on the border of bogs and forests in the northern and northeastern parts of the marshes and decrease in the southern part, which is obviously the result of significant changes in the arrival of direct solar radiation on the edge of the forest. Figure 3 shows the evolution of exergy and organizations for forest during the year (on twenty Landsat scenes for different years). If exergy increases relatively gradually from early spring to summer, the organization increases dramatically with the beginning of the active growing season in May, which shows the relationship of these variables with relatively independent subsystems. Thus, exergy and organization values, calculated on the basis of multispectral measurements, open up new, previously unobserved features of the functioning of ecosystems.

The order parameters for the system were determined by the Tasseled cap method with the Erdas Professional program by the principal components method without rotation, as well as by the method of multidimensional scaling with rotation with the distance based on Spearman correlation and Euclidean distance. The first method is an inadequate description of the variation of variables and can be rated as an inadequate organization of the system. Two stands of the order parameter based on other methods stand out in system (see Table 1).

Table 1 implies that the joint entropy of the order parameters is maximal with the application of distance on the basis of Spearman correlation but at a very low quality of reproduction of variables. In view of this criterion, the method of principal components with rota-

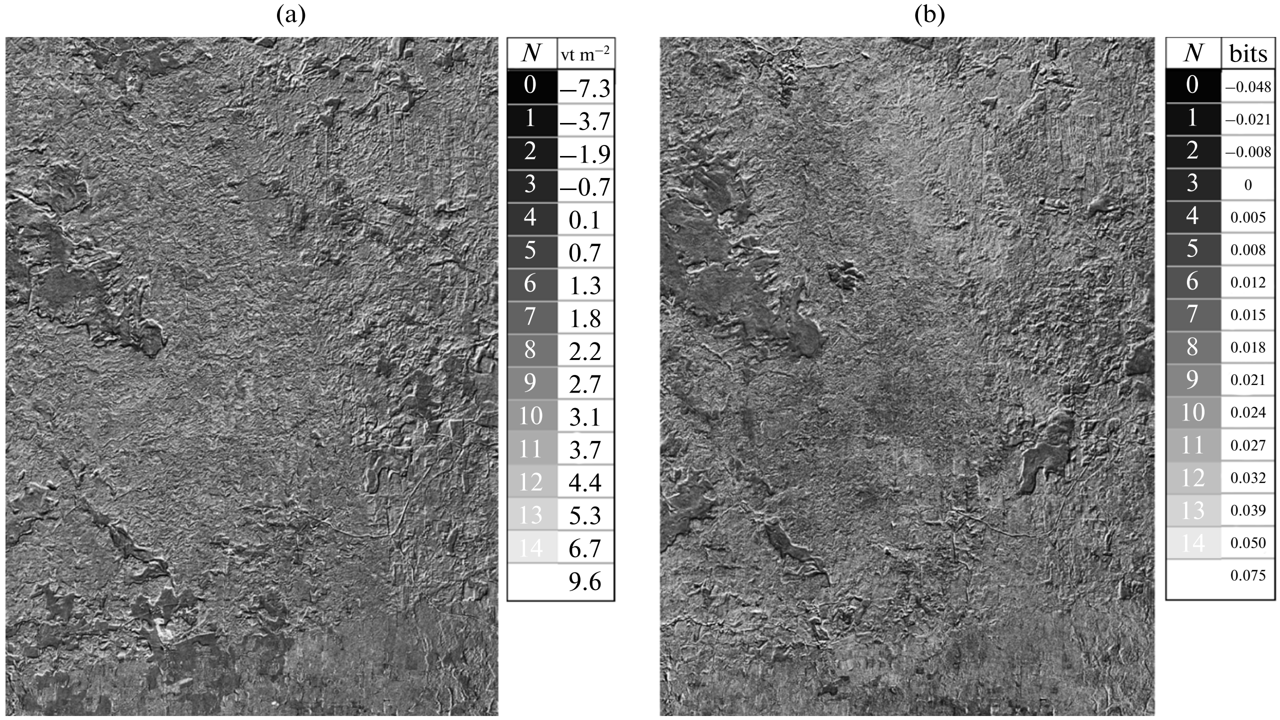

Fig. 2. Increment of thermodynamic variables from 11 h 23 min (June, 21, 2002, Landsat 5) to 11 h 41 min (June, 20, 2002, Landsat 7): (a)—exergy, (b)—organization.

tion is the most appropriate for the system. It follows from Fig. 4 that the first order parameter determines the visible and far-infrared part of the spectrum, and the second determines the near-infrared, which is associated with the reflection of the mesophyll.

On Fig. 5 order parameters for the same area are presented according to the data of the Hyperion satellite (198 channels, spatial resolution of 30 × 30 m, 25 on May 2012). In this case, there are also two parameters with the same relationships of variables. Note that all of the indices based on hyperspectral measurements are based on the differences in the nearest spectral band maxima for the first and second order parameters (a description of the most used indices in the ENVI User's Guide is presented in the section of Vegetation Indices [25]). Thus, there are two significant independent subsystems in the system that converts solar energy, though in general there can be both fewer or more of them. So, if we add indices to the considered variables and consider multiple timing measurements, the number of order parameters can reach five, which is determined by the presence of the subsystems that manage derivatives over the spectrum and the influence of external variables that are manifested at different stages of observation [7].

Four versions of the classification are tested: the one based on Euclidean metric, normalized scalar product of vectors, order parameters determined by principal components without rotation and with rotation, method of multidimensional scaling in the Euclidean distance (Table 2). Entropy is estimated for the eighth level of the dichotomous classification, respectively, with a maximum possible value of 8 bits.

For all classifications rank distributions are taken from the Tsallis thermodynamics. Other models have a

Table 1. Assessment of the quality of transformations for extraction of the order parameters

No.	Method	Distance	Quality of determination, R^2	Entropy, bits	Conjugacy, bits
1	Multidimensional scaling	Euclidian distance	0.234	12.589	0.066
2		Euclidian distance	0.920	12.184	0.579
3	of principal components	Without rotation	0.950	12.153	0.514
4		With rotation	0.950	12.213	0.203

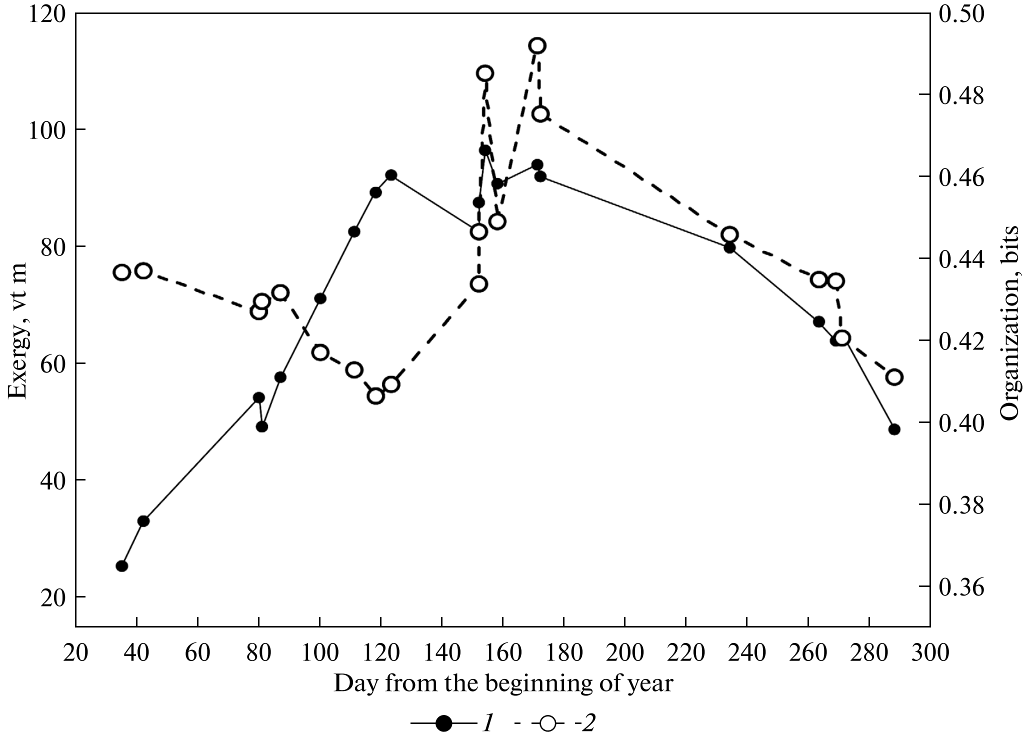

Fig. 3. Increment of exergy (*1*) and organization (*2*) from 11 h 23 min (Landsat 5 from June, 21, 2002) to 11 h 41 min (Landsat 7 from June, 20, 2002).

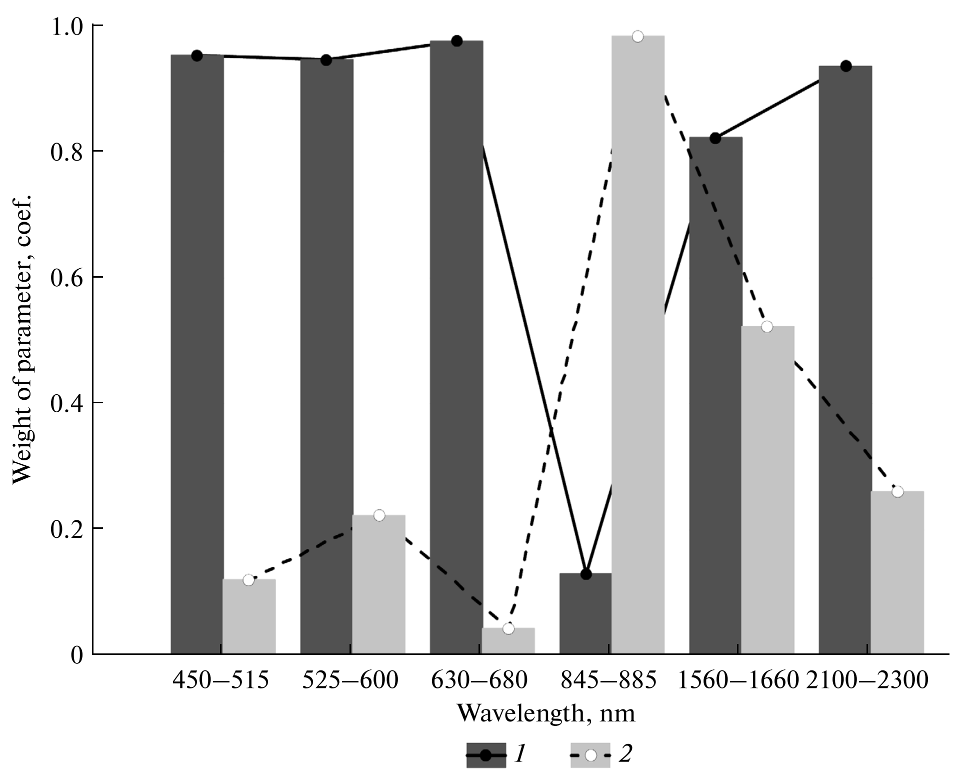

Fig. 4. Ratio of the order parameters and reflection in spectral channels for Landsat 5 (June, 21, 2002): *1*—the first order parameter; *2*—the second order parameter.

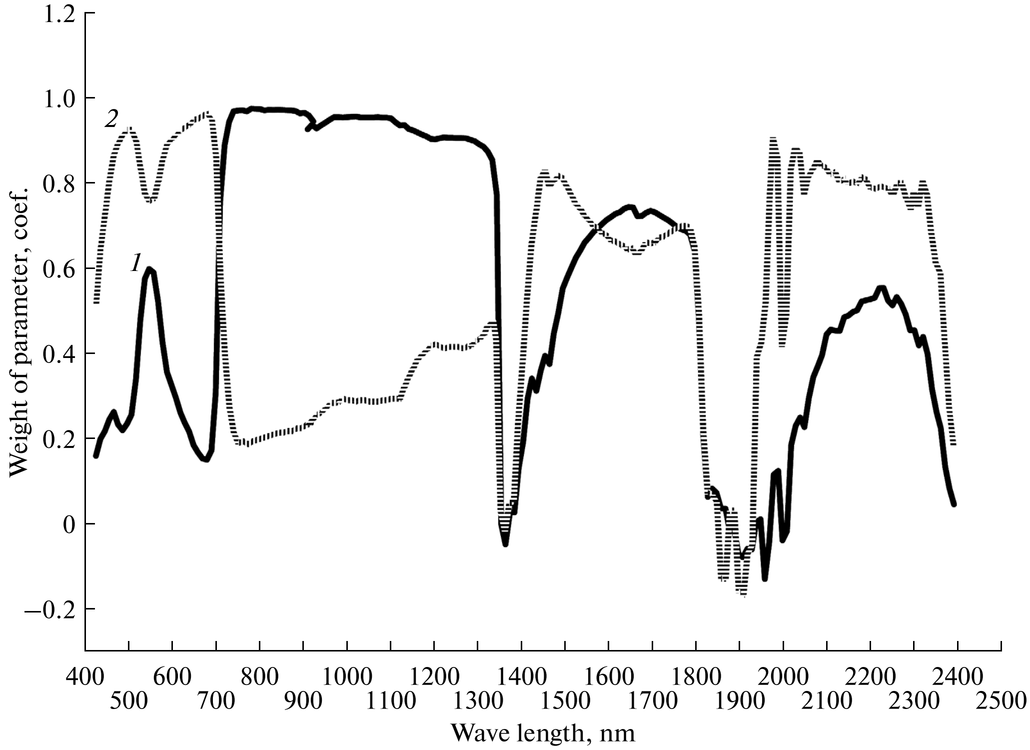

Fig. 5. Ratio of the order parameters and reflection in spectral channels for Hyperion (May, 25, 2012): *1*—the first order parameter; *2*—the second order parameter.

significantly worse quality of the description or are not reproduced by nonlinear estimation at all. Accordingly, it can be assumed that the scheme of interaction of each biogeocoenose operates with all those in the system and/or that the effect on memory in the system is significant. The greatest entropy gives a classification based on the metric of the normalized scalar product of vectors. However, the rank distribution obtained on the basis of this classification has the lowest coefficient of determination and a high value of χ^2-test, indicating a significant difference between the actual distribution and the model distribution that reflects the structure in an equilibrium system. The second largest entropy is the classification based on the parameters of the order obtained by principal components without rotation (the minimum increment of the information and the maximum value of the coefficient of determination of the real rank distribution model). The minimal increment information indicates that this version of the geometric model of a space is the one most in equilibrium with respect to the actual data. Thus, two of the used variants of metrics and baseline conversions can be considered as the most appropriate (Type 2 and Type 3). They provide the highest entropy and create a mapping that is closest to equilibrium. Figure 6 shows the rank distributions for two classifications. Classification based on the scalar product of vectors gives a higher probability for the first two ranks. Formally, the maximum entropy is an absolute criterion, and we must admit that in this case the system is subject to the geometry of the vector space of Euclid, and the system is nonequilibrial because of high values of χ^2-test and increment of information. On the other hand, the classification based on the ranking of Euclidean space generated by the method of principal components may also be acceptable for practical purposes. Its high quality in accordance with the criteria suggest that the relations in the system are largely linear. Comparing the model with real rank distributions, we can distinguish the state of biogeocenotic cover to the greatest extent dis-

Table 2. Dichotomous classification parameters for the eighth level

Type	Entropy, bits	R^2, %	Increment of information, K	χ^2-test
1	7.041	99.0	0.067	24989
2	7.274	95.7	0.066	49732
3	7.178	98.9	0.058	29708
4	6.848	97.6	0.089	98672
5	7.162	97.7	0.141	59016

Type of classification: 1—Euclidian distance, 2—distance based on normalized scalar product of vectors, 3—main components without rotation, 4—main components with rotation, 5—multidimensional scaling on Euclidian distance.

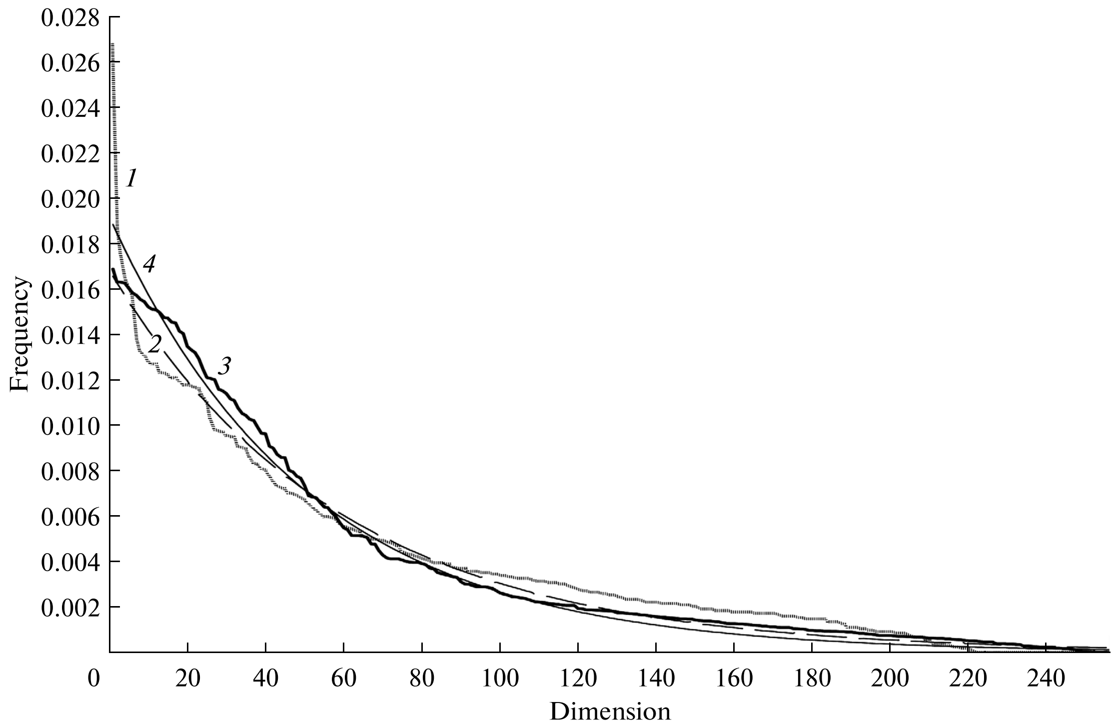

Fig. 6. Rank distributions for classification: *1*—rank distribution for the classification based on the scalar product of vectors; *2*—model of rank distribution for *1*; *3*—rank distribution for the classification based on two order parameters; obtained by analysis of principal components without rotation; *4*—model of rank distribution for *3*.

turbing the equilibrium and on this basis make assumptions about the possible direction of the dynamics: the state, the frequency of which is much greater than the equilibrium norm, must decrease during self-development, and vice versa.

Figure 7 shows the classification results for the space of order parameters obtained by the method of principal components. On the first level there are two main classes, forest and nonforested areas; on the second, there are closed forests, destroyed forests (wind falls, river valleys with woody vegetation destroyed by beavers, etc.), and open areas with meadow and shrub vegetation and wetlands. Subsequent classification levels are of appropriate detail. Since each class since the first layer is divided into two, an elementary knowledge of the territory can reliably determine their meaning, at least up to the fifth level, i.e. to distinguish thirty-two states of vegetation. Reflectance spectra, which are specific to each class, make it possible to improve the reliability of the determination of their meaning. As a result, we obtain an analog of the vegetation map or, in the general case, a land-cover type [7], which may be of practical importance when solving problems related to the design of various forms of economic activity. According to the final level of classification, we can assess the diversity of the territory for a sliding square, highlight the unique status, assess fragmentation, etc. [4, 12]. These estimates are useful for the design of protected territory [33] and the planning of field surveys, for example, to calculate the optimal placement of field measurements, to assess the diversity of vegetation and forest-taxation states [4]. Of particular interest may be the operation of allocating the borders on the basis of the violation of reflection similarity in spectral bands for adjacent pixels. Similarity can be assessed, for example, with the correlation coefficient for a sliding square of a given size. It is obvious that the larger the average or the maximum correlation between the pixels of a given square, the more pronounced the border. With a 30 m Landsat pixel size, only rough borders can be identified on its basis. This procedure is more efficient on RapidEye satellites with a resolution of 6.5 m. Figure 8 shows an example of the selection of borders of the territory of the Central Forest Reserve. The territories, which are almost homogeneous in the structure reflection of solar radiation, are allocated by white background. The larger image shows the existence of ecosystems with discrete borders. We call attention to the fact that the forest spatial structure in natural forests is much more complicated than in the wild felled areas of 1960–70s. Finally, wide opportunities for assessments of change in the vegetation state exist on the basis of a comparison of scenes for various periods of time [14, 23].

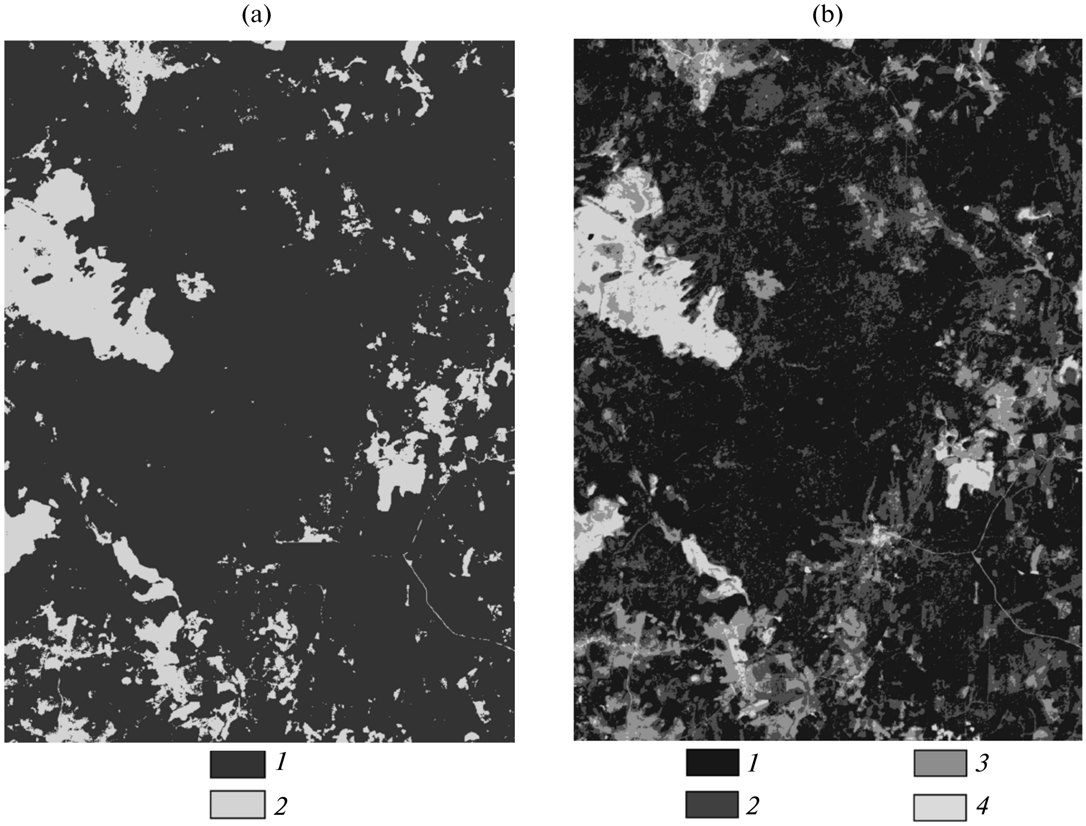

Fig. 7. The first two levels of the dichotomous classification. (a)—first level: *1*—forests, *2*—nonforested areas; (b)—second level: *1*—closed forest, *2*—destroyed forests, *3*—open forests with developed vegetation, *4*—the same ones with sparse vegetation (mainly up-river bogs).

RESEARCH WITH THE USE OF REMOTE AND GROUND MEASUREMENTS

A forest is a complex biological system; research on its organization has scientific significance. The category of organization can be understood to include the mutual placement of species in an ecological space or in the space of environmental conditions, interaction of the vegetation with soil and climate conditions, the formation of coherent organism-like ecosystems, mechanisms of autochthonous and allochthonous dynamics, stability borders for climate variations, the nature of this stability, etc. These studies should obviously be based on modern technical means of measurements in nature, allowing collection of the necessary information at the lowest cost of labor. In setting up this type of research, two schemes of observations may be selected: regularly spaced sampling of uniformity on linear transects on the basis of descriptions from the centers, obtained on the basis of the aforementioned classification of multispectral measurements and, conversely, measurement in the border areas. The first circuit comprises quasi-continuous information on changes in ecosystems in space; the second makes it possible to maximize coverage of the existing diversity [3]. The first scheme also makes it possible to investigate boundary effects; to conduct a one-time measurement of dynamic variables, such as soil moisture, acidity, sheet index, air temperature, atmospheric composition, and others; to repeat measurements promptly; etc. General and methodological bases of research, in which ideas for coordination are developed, are discussed in several papers [10, 16, 18]. Here, let us focus on the results of the simplest combination of remote and ground measurements for the Landsat satellites. As an example, consider the transects laid directly through the forest with the use of a laser level, with tmeasurement of the excess after every 5 m in laying relevées after 20 m (Fig. 9). In 2007 86 descriptions were performed and 38 were added in 2012 (area 20 × 20 m). At each point, we measured sum of the areas of the cross sections by tree species and the height of the forest (with a RC3H Masser dendrometer), projective cover of shrubs, and bushes; an estimate of their share was estimated for a site of 5 × 5 m (summer 2010). Soil moisture was measured with a TDR-300 (Spectrum), and acidity was measured with an IQ 150 pH-meter (Spectrum) on June 27, 2013. Data on the surface temperature of the soil, humidity, and air temperature was also taken into account (measured in August 2010). The transect passes around the tower, which was implemented by

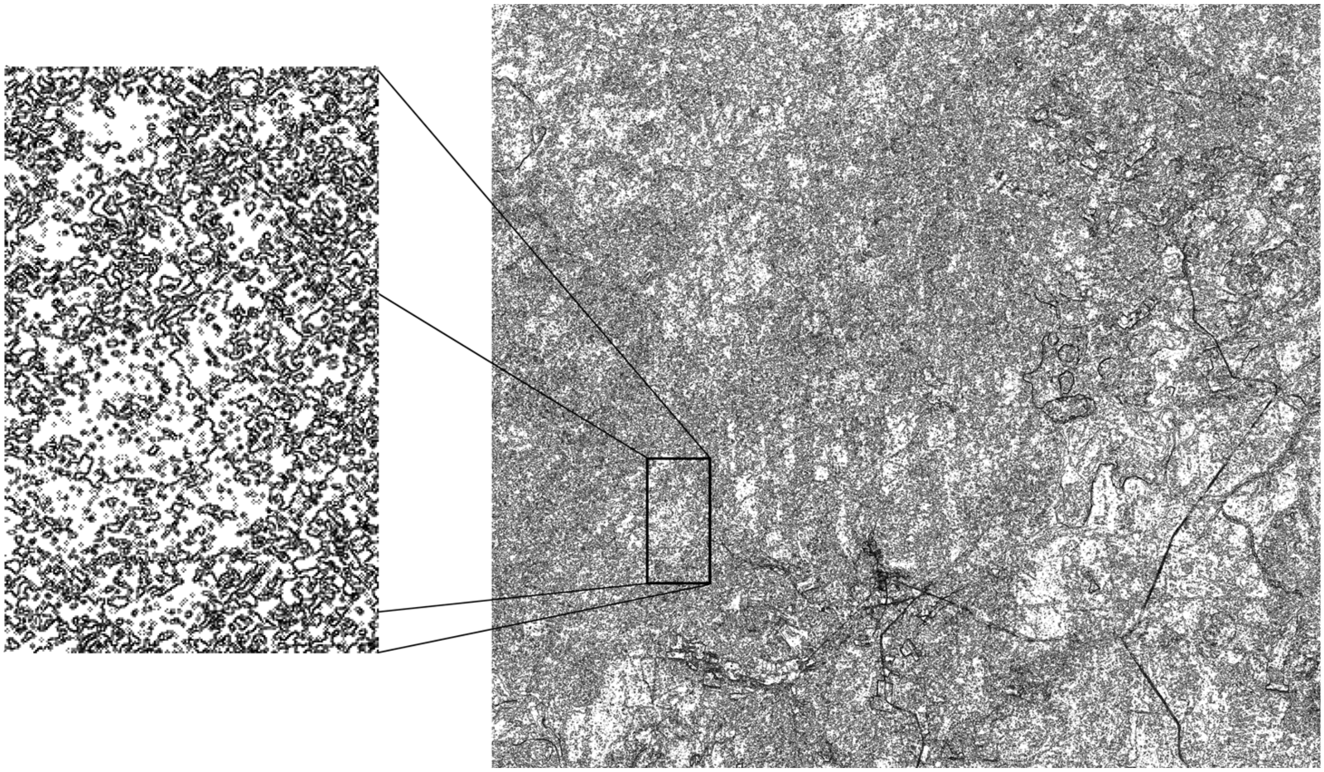

Fig. 8. Borders with a width of 18 m marked by the RapidEye satellite (September, 9, 2009).

the measurement program EUROFLUX [26]. The leaf index (LAI) was estimated using a digital camera with an aperture of 180 degrees in June 2007 and in July 2012, followed by calculation with the program Hemisfer [27]. The first term of measuring LAI defines the second, with a coefficient of determination of 0.6. It is obvious that many of the properties of the biogeocoenose are very dynamic and we can expect reliable reproduction of only the most stable relationships when comparing them with the remote measurement giving a cross-sectional dimension.

In general, the system under study is determined by the variables measured in the field study, and the variables are calculated based on the distance information for the time closest to the time of ground measurements. In addition to remote data, a digital elevation model is also considered as environmental conditions. The relief is submitted through the hierarchical levels [15, 36]; The slope, exposures, laplacian, longitudinal and transverse profile convexities,and the maximum and minimum curvature are estimated for each. Their calculation can be performed in the software package ENVI. The relief is regarded as a factor determining the spatial redistribution of precipitation and mineral nutrients, respectively. In analyzing the data, there are two approaches: continuous and discrete. In contrast to the analysis above, variables obtained from ground measurements, such as the leaf area index and total area of the cross sections of trees at each measurement point, should be added to the remote system. Next, we highlight the order parameters and assess their physical meaning and their base to determine the spatial variation of the measured variables, regardless of the distance information. The quality of the relevant statistical models will assess the extent of their involvement in the system. The order parameters can be considered representative if their base reliably describes the variables, including those not included in the original system. Continuous mapping relations between the order parameters and variables reproduce the equilibrium relationship, deviation from which is traditionally treated as random. "Nonrandomness" of deviations is proven by appropriate methods and is most often associated with latent nonlinearities or a material breach of equilibrium. The latter implies the action of some external or internal factors. The areas of equilibrium disturbance are determined by statistically significant series of significant positive or negative deviations. The discrete approach involves classes of status integrating a combination of values of type variables. If these variables belong to a system, they must be reproduced by its other variables, i.e. variables considered as "inputs." We can estimate this relationship by using the discriminant analysis. As part of this analysis, we obtain an estimation of the quality of the reproduction of variables in classes, analogs of the order parameters describing the variables that make up classes; we can also estimate the probability of a par-

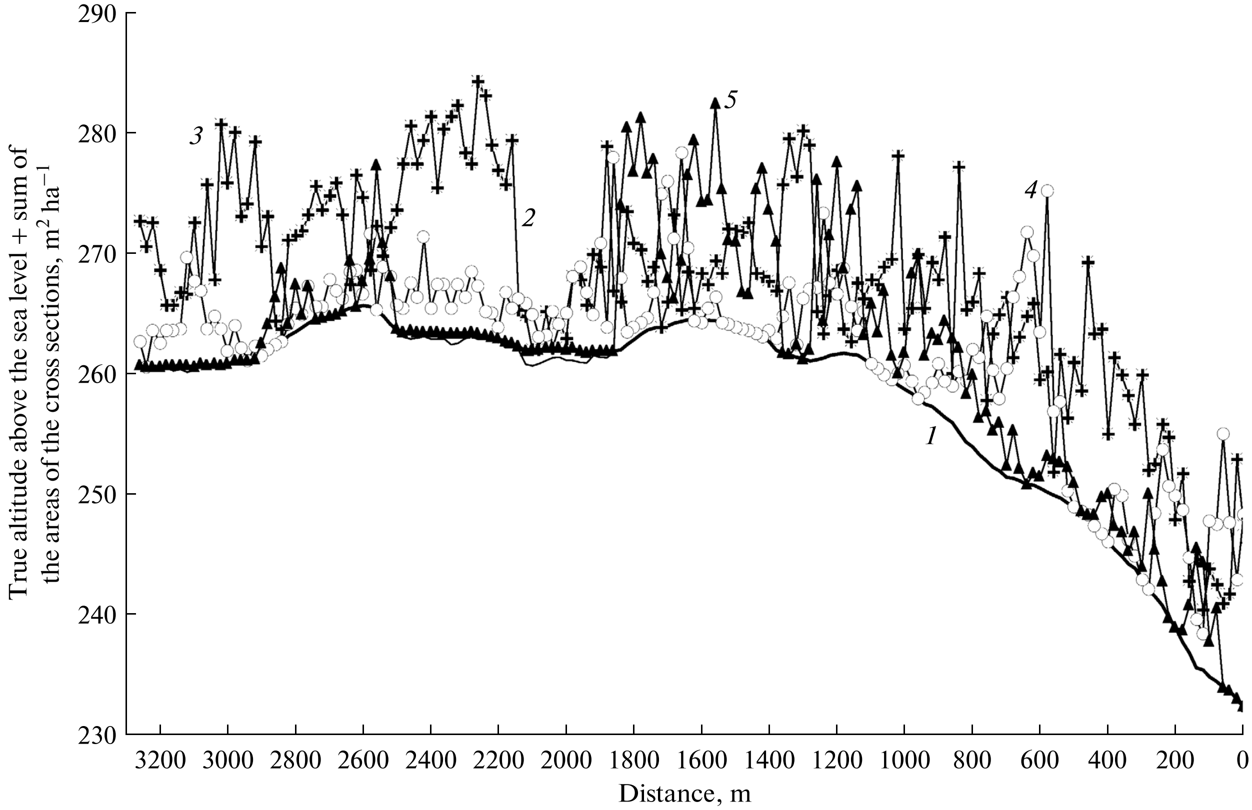

Fig. 9. Transects with step descriptions of 20 m. *1*—true altitude of the earth's surface, *2*—altitude of the bedrock, *3*—sum of the areas of the cross sections of spruce, *4*—sum of the areas of the cross sections of small-leaved species, *5*—sum of the areas of the cross sections of broad-leaved species.

ticular observation belonging to each class, and finally, the external variables that have an appropriate weight in the description of variation. Discriminant analysis has some advantages over continuous mapping, as it is less sensitive to disturbances of linearity. In the future, the use of other methods of multivariate analysis will be possible.

Let us demonstrate the simple results of the application of these methods with the example of the given transect. Let us include in the system of te total area of the cross sections the tree species measured on the transect and the leaf area index (July, 2012), the reflected solar radiation measured by the Landsat 5 satellite (August, 22, 2007), and the corresponding thermodynamic variables. The order parameters are calculated by the method of principal components (Table 3).

Three order parameters reflect the linear part of the relationship in the system, which describes 54.85% of the total variation. The three types of trees, the LAI, most of the variables, and Landsat are described very satisfactorily, and four species of trees (with a coefficient of determination of more than 0.4) are described satisfactorily. Reflection in the near-infrared channel, the increment of information, the exergy, and the NDVI have a leading role in the system. The first order parameter is associated with reflection in the near- and mid-infrared regions of the spectrum and with virtually all thermodynamic variables other than temperature. In plants, they correspond to spruce with a negative sign and to linden and ash with a positive sign.

The second parameter is defined by the visible part of the spectrum, the far-infrared band and temperature. The higher the value, the lower the humidity and the higher the temperature. The parameter with a positive sign significantly determines the leaf index; with a negative sign, it is pine; with a positive sign, it is rowan, alder, and elm. The third parameter is negatively related to the blue channel and determines birch, rowan, maple, and ash. The very weak mapping placement of aspen is noteworthy. Most likely, it is mostly determined by regrowth restoration in the area of an old spruce forest; consequently, its distribution is closely related to a founder tree. If we add the height of the forest and growing stock to the parameters of the order, the coefficient of determination for aspen grows to 0.4, and the considerable sum of the areas of the cross sections of aspen indicates old forests by a large margin.

Table 4 shows the relationship of the order parameters for variables that are not included in the analysis. Given the discrepancy between the dates of field mea-

Table 3. Weight and influence of the sign of the order parameter to a variable

Variables		Order parameter 1	2	3	R^2
LAI of tree layer		0.05	**0.77**	0.04	**0.602**
Sum of the cross sections	*Pinus sylvestris*	0.13	**–0.73**	–0.03	**0.637**
	Picea abies	**–0.67**	0.26	–0.01	**0.616**
	Betula pendula	0.23	0.23	**–0.55**	0.403
	Populus tremula	0.26	–0.24	–0.33	0.180
	Sorbus aucuparia	0.09	**0.71**	**0.79**	0.418
	Alnus incana	–0.04	**0.66**	–0.14	0.436
	Salix sp.	–0.13	0.14	0.07	0.359
	Tilia cordata	**0.63**	–0.13	–0.22	0.494
	Acer platanoides	0.33	0.20	**0.49**	**0.617**
	Fraxinus excelsior	**0.60**	0.10	**0.54**	0.368
	Ulmus glabra	0.15	**0.37**	–0.29	0.262
Landsat channels, (nm)	Blue (450–515)	0.00	**0.43**	**–0.49**	0.432
	Green (525–605)	–0.25	**0.73**	–0.11	0.607
	Red (630–690)	–0.12	**0.78**	0.17	0.662
	Near-infrared (770–900)	**0.95**	0.24	0.04	**0.979**
	Average infrared (1550–1750)	**0.73**	0.48	0.05	0.778
	Far-infrared(2090–2330)	0.46	**0.66**	0.06	0.659
Physical	Entropy	**–0.86**	0.26	–0.01	**0.824**
	Increment of information	**0.98**	–0.05	0.05	**0.966**
	Exergy	**–0.82**	–0.53	–0.01	**0.958**
	Temperature	–0.36	0.65	–0.12	0.576
	Bound energy	**–0.86**	0.34	–0.02	**0.856**
NDVI		**0.96**	–0.04	0.01	**0.937**
Dispersion		6.97	4.34	1.69	
Share of the described variation		0.29	0.18	0.07	

The highest values are in bold.

surements and satellite measurement dates, a multiregression linear model can be considered as quite satisfactory. The second parameter is the leader in the description of soil temperature and contributes significantly to the other variables. The first parameter with a negative sign, like exergy, determines soil moisture; with a positive sign, it determines its acidity. The characteristics of vegetation are also mainly determined by the second parameter, and only the closeness is simultaneously connected to the second and the first. Thus, the linear model has been satisfactorily tested in variables not included in the analysis. It should be noted that many of the non-inear relationships and the correction value corresponding to the description (determination coefficient) is increased by an average of 0.05 units. On the other hand, some of these variables, of course, can be attributed to properties not of communities but of biogeocenoses, which allows the use of remote multispectral information for the study of all its components, including the animals [13].

The measured variables clearly belong to the same system, and the order parameters can be both their own and a function of exogenous variables. Terrain and soil-forming rock can be recognized as the external variables. As an example, we will show the dependence of the order parameters on the relief properties The first parameter describes a terrain with a coefficient of determination of 0.881, the second has a value of 0.800, and the third has a value of 0.641.

Thus, the first two parameters are almost entirely a function of the relief, while the third parameter may present autochthonous component defined by a fall with successional shifts arising from them.

On the basis of a dichotomous classification for the transect, we can distinguish five well-defined classes: 1—7S2B1Asp + L; 2—4B3L2S + Asp, M, E;

Table 4. Reproduction of variables not included in the analysis by order parameters

Variables	Date of measurement	Order parameter			R^2
		1	2	3	
Air temperature, °C	August, 7, 2010	**–0.423**	**–0.568**	–0.035	0.499
Air humidity, %		**0.469**	**–0.470**	–0.117	0.478
Soil temperature, 5 cm		–0.129	**0.728**	–0.014	0.545
Soil temperature, 15 cm		0.145	**0.671**	0.006	0.472
Soil temperature, 20 cm	July, 27, 2013	0.193	**0.466**	0.120	0.269
Soil humidity, 10 cm	August, 7, 2010	–0.368	**0.419**	0.205	0.386
	August, 18, 2010	**–0.419**	0.345	0.0262	0.300
	July, 27, 2013	**–0.513**	0.370	–0.058	0.403
Soil acidity	August, 7, 2010	**0.303**	0.120	0.0521	0.108
	July, 27, 2013	**0.469**	**–0.467**	0.044	0.440
LAI of tree canopy	August, 7, 2010	0.245	**–0.722**	–0.245	**0.695**
LAI of grass layer		–0.171	**0.305**	–0.012	0.122
LAI in total		0.217	**–0.690**	–0.264	**0.646**
Height of forest	Summer 2007	0.214	**–0.569**	0.168	0.372
	Summer 2012	0.194	**–0.621**	0.023	0.422
Density	Summer 2007	**0.453**	**–0.542**	–0.194	**0.577**
Reserves of forest stand		0.287	**–0.526**	0.187	0.365
	Summer 2012	0.274	**–0.570**	0.083	0.401

The highest values are in bold.

3—4S1B1L1R3 (M, Ash, E); 4—6S2S2B; 5—8R2B, where S is spruce, P is pine, B is birch, Asp is aspen, E is elm, M is maple, L is lime, R is rowan, and Ash is ash. After the discrimination of classes from Landsat and terrain variables, we find that the spatial structure of the tree layer is described by 91% of the relief. Landsat variables added only 7.2%, reflecting the states that do not depend on the topography (Table 5). Similarly, the placement of the majority of species is determined by the terrain, and the conversion of solar energy as a property of the vegetation makes only a small correction to the basic relationship. All in all, species placement is mostly defined by different variants of curvature and convex surfaces, first and foremost in the forms of relief with average linear dimensions of the order of half a kilometer (Table 6).

Within discriminant analysis, we get the opportunity to evaluate the considered discrete representation of vegetation on the basis of the probability vector of belonging of a specific description to each class. On the basis of the probability vector, we calculate the uncertainty of reference of a specific point to a particular class (the uncertainty is calculated as the entropy). If uncertainty is equal to zero, then the class within discriminant analysis is determined unambiguously. The higher the uncertainty, the less unambiguous identification of the class. Figure 10 shows the reproducibility of the classes in the discriminant analysis on the terrain and remote measuring. In general, 85% of the sample is reproduced correctly. Figure 10 implies that the first (spruce), second (linden), fourth, and fifth grades (pine and birch on raised bogs) may be represented by almost discrete territorial structures with an uncertainty of discrimination at each point that is close to zero. The third class with the greatest diversity of species, apparently, is a continuum almost everywhere, so the uncertainty in the domain of definition everywhere is nonzero. It is obvious that the maximum uncertainty corresponds to the borders of relatively discrete communities. The width of the border between the discrete communities varies from one to three pixels.

Table 5. Reproduction quality of total area of the cross sections of the forest stand by the scene of Landsat for August, 22, 2007, with morphometric characteristics of relief and joint order parameters calculated through discriminant analysis classes of tree layer

Types of trees	Coefficient of determination, R^2		
	landsat	relief	vegetation and relief
Total	0.742	0.915	0.938
Pinus sylvestris	0.567	0.835	0.835
Picea abies	0.405	0.414	0.508
Betula pendula	0.069	0.152	0.154
Populus tremula	0.074	0.219	0.327
Sorbus aucuparia	0.034	0.098	0.215
Alnus incana	0.094	0.119	0.217
Salix sp.	0.377	0.371	1.000
Tilia cordata	0.375	0.426	0.554
Acer platanoides	0.124	0.133	0.270
Fraxinus excelsior	0.343	0.249	0.343
Ulmus glabra	0.026	0.000	0.099

Table 6. Variables of relief determining the structure of vegetation to the greatest degree

Hierarchical level of relief, linear dimensions, m	Morphometric characteristics	Significance	Fisher test
3810	Longitudinal convexity	0.495	18.6
	Planned convexity	0.652	9.8
1050	Planned convexity	0.769	5.5
450	Transverse convexity	0.746	6.2
	Maximum curvature	0.539	15.6
	Laplacian	0.629	10.8
270	Planned convexity	0.766	5.6
	Profile convexity	0.621	11.1
	Laplacian	0.661	9.3

The two systems of analysis are interrelated, and the order parameters of the linear space that displays the organization of vegetation are almost entirely displayed in the parameters of discriminant analysis (Table 7).

The axis of discriminant analysis of the placement of Landsat classes almost completely describes the first two order parameters obtained by the method of principal components, which are equally linked directly with vegetation and Landsat variables. The third parameter, which is associated with Landsat in the smallest degree, (Table 3) is also not displayed in the system of discriminant analysis. The axes of discriminant analysis of classes of forest stand on the relief contribute somewhat less to the description of the variation of the order parameters than just the topography (Table 7) but the ratios are generally similar. The third order parameter, just as in the first variant, is mainly described by the relief, though there appears to be some autochthonous component of the spatial variability of woody vegetation, which is reflected neither in any terrain, nor in any solar energy conversion.

Table 7. Reproduction of order parameters of the first model by parameters of discriminant analysis, the coefficient of determination R^2

Order parameter	Landsat	Relief	Landsat and relief
1	0.857	0.611	0.895
2	0.843	0.633	0.883
3	0.028	0.314	0.321

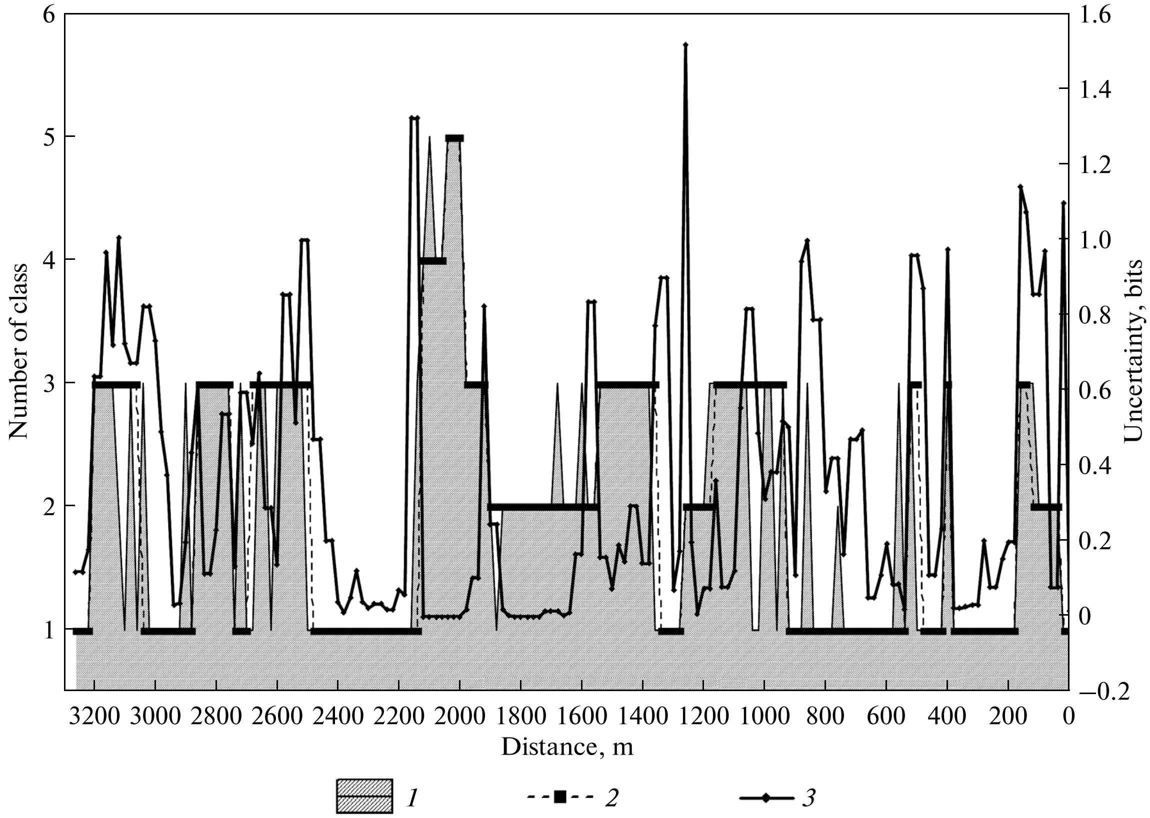

Fig. 10. Reproducibility of classes of forest stand content from the relief and remote measuring in the discriminant analysis: *1*—classes, *2*—reproduction of classes, *3*—uncertainty.

Apparently, this component is determined by the placement of birch, maple, and ash, the least-defined parameters of two reproduction options. In accordance with the results of the analysis, we can assume that the system is close to equilibrium with respect to the relief and can be defined as discrete-continuum. Species' individual relationships with the environmental conditions that determine their relative independence create a basis for the placement of species in space, and discreteness is determined by edificating possibilities of spruce and linden and swamping processes, which determining the spread of pine.

CONCLUSION

In accordance with the theme of the article, some possibilities are shown for the use of multispectral remote measurements as proxies for the conversion of solar energy by elementary units of biogeocenotic or vegetation cover, the dimensions of which correspond to the scale of the survey. These demonstrations are meant to illustrate the various forms of data conversion in accordance with the objectives of the study and do not contain complete, validated results. The latter is achievable through the use of multiple scenes in different seasons of a year; estimates of the dynamics of the phenomenon under investigation are thus improved, and a higher quality of reproduction of field measurements is achieved. It should be borne in mind that remote information, as well as any measurements, includes noise and distortion that are often specific for each channel. In the general case, a three-dimensional terrain model can be obtained on the basis of radar remote measurements. In particular, the standard SRTM product can be used for analysis [35]. It is obvious that a sufficiently complete reproduction of biogeocenosis properties with distance information based on topography makes it possible to build maps of its integral order parameters and the state of individual variables, with the use of the interpolation method discriminant, multiregress analysis, and neural networks, based on the limited number of field measurements proportionally covering the states of biogeocenotic cover. [6, 8, 11, 17].

ACKNOWLEDGMENTS

The study was carried out with support from RFBR (projects nos. 12-05-00060-a and 13–05–12003-ofi_m).

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Translated by S. Avodkova